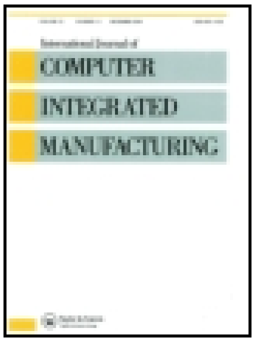

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An Internet of things and cloud-based approach for energy consumption evaluation and analysis for a product

Ying Zuo[a], Fei Tao[a]* and A Y C Nee[b]

[a]*School of Automation Science and Electrical Engineering, Beihang University, Beijing, P. R. China;* [b]*Department of Mechanical Engineering, National University of Singapore, Singapore, Singapore*

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Energy consumption evaluation and analysis (ECEA) of a product entire life cycle is a key issue for realising green and sustainable manufacturing. In this paper, an Internet-of-things (IoT) and cloud-based novel approach for product ECEA is proposed in which the IoT technologies are employed for real-time and dynamic collection of energy consumption-related data, and various ECEA functions are developed and encapsulated into services which are managed in a cloud. An experimental bench and a cloud-based software system are developed, and a case study is provided to test and illustrate the effectiveness of the approach in a product's design and manufacturing processes.

Keywords: product; service; energy consumption evaluation and analysis (ECEA); Internet of things (IoT); cloud

1. Introduction

With the rapid development of new-generation information technology (NGIT), especially the deep integration of NGIT and manufacturing technology, great changes have taken place in the manufacturing service environment. Meanwhile, the energy usage of the manufacturing industry is intensifying, which results in more and more serious energy crisis. On the other hand, the energy consumption of a product in the entire life cycle is mostly decided by the design and manufacture process. So, energy-saving and emission-reduction is a key issue in design and manufacturing processes of a new product which must meet customers' demands and also reduce energy consumption and environmental impact (Zhang and Li 2010). Energy consumption evaluation and analysis (ECEA) refers to the collection of energy consumption data of a product in its entire life cycle, the construction of the corresponding evaluation model, and the visualisation analysis of the evaluation result. Its aim is to achieve statistical management of energy consumption, the analysis of key energy consumption points and to provide data support for decision-making. Thus, an effective ECEA approach of product life cycle is paramount for realising the above aims.

In order to realise accurate ECEA, real-time and dynamic data are needed in the energy management of a product life cycle (Reap et al. 2008; Taisch, Cammarino, and Cassina 2011). However, current research mostly focuses on the way to obtain data from the energy consumption database, such as Chinese Life Cycle Database (CLCD) from China, Econvient from Switzerland, and European Reference Life Cycle Database (ELCD) from the European Union. These data, which come from industry statistics or technical literature, are mainly historical data. It is difficult to provide sufficient support for accurate analysis and decision-making of energy consumption for a current product (Seow, Rahimifard, and Woolley 2013). It has very important impact on product energy-saving. On the other hand, as the ECEA system is established from the perspective of product life cycle, the required data are necessarily related to the enterprise information systems (EISs) in the entire product life cycle. Therefore, in order to ensure data validity, the integration between ECEA system and EISs should also be considered.

From the point of view of realising ECEA, many methods such as life cycle assessment (LCA) (Finnveden et al. 2009; Göschel, Schieck, and Schönherr 2012),economic input–output-LCA (Joshi 1999), life cycle costing (Gluch and Baumann 2004), life cycle simulation (Umeda et al. 2012), life cycle sustainability assessment (Kloepffer 2008), social life cycle assessment (Jørgensen et al. 2008), embodied energy model (Kara, Manmek, and Herrmann 2010) have been proposed to assess the environmental impacts and costs of product entire life cycle stages consisting of material extraction, manufacturing process, use, maintenance, etc. These methods have a very important role for energy-saving in the entire product life cycle. However, from the perspective of the users in practical application processes, the following issues still need to be addressed.

(1) The data or input required in the existing assessment methods and systems are primarily collected manually, the real-time and dynamic requirements

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*Corresponding author. Email: ftao@buaa.edu.cn are not satisfied. Therefore, how to realise real-time, intelligent, dynamic perception and collection of ECEA data generated in the design, manufacturing and service processes of a product needs further studies.

(2) Most ECEA methods or systems are independent of existing EISs such as product data management (PDM), computer-aided process planning (CAPP), enterprise resource planning (ERP), supply chain management (SCM), customer relationship management (CRM), which are widely used in modern enterprises.

(3) Many professional functions, models and algorithms are required in the ECEA process, as well as the actual data on various materials and manufacturing processes. It is impossible for an end user or small enterprise to master and acquire all the necessary knowledge and the resource data. This has hindered wider applications of ECEA methods. A simpler way, akin to the service-oriented method is therefore required. For example, the end user only needs to input the related information to a browser-based interface in a PC or an App interface in a smart phone, the related service request will be sent to a remote ECEA server (e.g. cloud-based) via Internet, and the results will be returned to him in seconds.

Therefore, in order to address the above three issues, enhance the efficiency and intelligence of the ECEA process, and provide better user experience in the product life cycle, the authors have designed a novel approach to compute and analyse energy consumption throughout the entire product life cycle. In the proposed method, the Internet of things (IoT) technologies are employed to achieve real-time and dynamic collection of energy consumption and environmental impact data generated in the entire product life cycle. Various required functions and data in ECEA are encapsulated into services which are managed in a cloud.

The remainder of the paper is organised as follows: Section 2 presents a literature review on ECEA approach and application of IoT and cloud service. Section 3 describes the energy flow and data management of ECEA of product. In Section 4, the architecture and the key technologies of IoT and cloud-based ECEA system is proposed in detail. A case study of ECEA Cloud-based product design optimisation and manufacturing optimisation are analysed in Section 5. Finally, some conclusions and future works are drawn in Section 6.

2. Literature review

2.1. Energy consumption evaluation and analysis approach

In order to realise ECEA for a product, some related works are carried out in academia and industry. For example, from the point of view of the constructed model, an energy factor-based approach for energy-saving in product design has been studied by Zhang and Li (2010), which integrates the axiomatic design and modularity design theories with energy factor. An embodied product energy framework for modelling energy flow during manufacturing was established by Rahimifard, Seow, and Childs (2010). It provides greater transparency on energy inefficiencies and enables a 20–50% reduction of energy consumption. Energy assessment model for machining process and the energy efficiency analysis and evaluation for machine tools, important components, and machining systems were studied by Balogun and Mativenga (2013). Li, Yan, and Xing (2013) proposed a milling process energy consumption model as a function of material removal rate and spindle speed, and the accuracy of this energy model is more than 96%. Hu et al. (2012) proposed an online energy efficiency monitoring model based on the identification of machine tools operating state and power balance equation of spindle system. For energy consumption database, in addition to the existing national database (such as CLCD, Econvient, ELCD), other databases have also been studied. For example, Ono, Motoshita, and Itsubo (2015) established the water footprint inventory database on Japanese goods and services distinguishing the types of water resources and the forms of water uses based on input–output analysis. Papong et al. (2015) developed the social inventory database in Thailand using input–output analysis. For the application of ECEA approach, an energy consumption evaluation of the desktop PC was carried out using a detailed modular LCA based on SimaPro software (Song et al. 2013). Hawkins et al. (2013) provided a transparent life cycle inventory of conventional and electric vehicles (EVs), which applied our inventory to assess conventional and EVs on use phase energy consumption. The integration of LCA into the early stages of process design and optimisation is reviewed and discussed (Azapagic 1999). Mori et al. (2011) studied a new acceleration control method to reduce energy consumption for machine tool by synchronising spindle acceleration with feed system. Jeong, Morrison, and Suh (2015) proposed and developed a case-based reasoning procedure that allows swift and accurate estimates of the ecological effects of a new product. Velden, Kuusk, and Köhler (2015) presented a LCA of a wearable smart textile device for ambulant medical therapy, and used the eco-cost approach to compare the LCA results of the original prototype design against various eco-redesign options. Del Pero et al. (2015) put forward a predictive LCA of a heavy metro train that will operate in the urban area of Rome, and a predictive analysis on recyclability/recoverability at the end of life has also been performed. Besides, some other new evaluation methods and their applications are proposed and described

(Kloepffer 2008; Zhang 2014; Dietmair and Verl 2009; Lake et al. 2015).

From the above literature review, it can be concluded that the current work primarily concentrated on ECEA model, database, and method. The existing models are built by enterprises themselves and the evaluated data are based on the database. Hence, it is difficult to guarantee the accuracy of evaluation and analysis for the use of non-real-time data. Compared with the existing methods, this paper emphasises on the collection and usage of real-time data.

2.2. *Application of IoT and cloud service*

In product life cycle, the collection of real-time data has been a problem for the precision energy consumption evaluation. However, IoT technologies provide a possible solution for this problem. For example, Tao et al. (2014c) proposed the IoT-based intelligent perception and access of manufacturing resource (i.e. hard manufacturing resources, computational resources, and intellectual resources) in cloud manufacturing, which could realise dynamic acquisition of the underlying data in the entire life cycle of manufacturing. He, Yan, and Xu (2014) developed vehicular data cloud services based on IoT, and two modified data mining models, which includes a Naïve Bayes model and a Logistic Regression model, are presented for the vehicular data mining cloud service in detail. Zhang et al. (2015) studied real-time information capturing and integration architecture of the Internet of manufacturing things, which provide a new paradigm by extending the techniques of IoT to manufacturing field. Suciu et al. (2015) analysed existing components and methods of securely integrating big data processing with cloud M2M systems. Based on this, a converged E-Health architecture built on Exalead CloudView was put forward. Kiritsis (2011) introduces a new definition of the notion of intelligent product in the era of the IoT. In addition, the IoT technologies have been widely used for smart cities (Perera et al. 2014), smart home (Li and Yu 2011), smart buildings (Hernández-Ramos et al. 2015), in-home health care (Pang et al. 2015), cloud manufacturing (Tao et al. 2015), SCM (Ng et al. 2015), automation of assembly modelling systems (Wang, Bi, and Xu 2014), LCA of products (Tao et al. 2014d), and so on.

Furthermore, to realise the on-demand use of resources, cloud-based method is intensively studied. For example, Chen and Chang (2015) put forward cloud-based energy management service for distributed renewable energy integration. Li et al. (2012) present a hybrid wireless network integration scheme in cloud services-based EISs. Muñoz et al. (2015) proposed a social cloud-based tool to deal with time and media mismatch of intergenerational family communication. Bi et al. (2015) developed the self-management architecture of cloud data centres with virtualisation mechanism for multi-tier web application services. Based on this architecture, a flexible hybrid queuing model was established to determine the amount of virtual machines for each tier of virtualised application service environments. Tao et al. (2014b) presented a case library and Pareto solution-based hybrid genetic algorithm for energy-aware cloud service scheduling. Liu, Li, and Tong (2015) performed research on queuing model for performance analysis of cloud services. The model considers the resources sharing among VMs, and the service requests are relaxed compared with prior research. Caballer et al. (2015) proposed a software platform to dynamically deploy complex scientific virtual computing infrastructures, on top of Infrastructure as a Service Clouds. Hegazy and Hefeeda (2015) introduced a new industrial automation cloud service, which includes different functionalities from feedback control and telemetry to plant optimisation and enterprise management. Wang, Liang, and Li (2015) designed a multi-resource allocation mechanism, which generalises the notion of dominant resource fairness from a single server to multiple heterogeneous servers. Meanwhile, some new technologies of the cloud and service have been studied in many other aspects (Cheng and Shaw 2015; Fatahi Valilai and Houshmand 2014; Tao et al. 2016, 2017).

From the above analysis, we can know that the IoT and cloud service have gained wide acceptance including manufacturing operations, which have provided a new method for intelligent perception and connection, and on-demand use and efficient sharing of resources (Wang et al. 2014; Tao et al. 2014a).

3. Energy flow and data management of ECEA of product

A product life cycle consists primarily of three phases, i.e. pre-production, production, and post-production. Each phase has a specific manufacturing process unit. For example, at pre-production, it includes design and material obtain unit. During production, it includes manufacturing and assemble unit. In post-production, use, disassembly, recycling, waste, remanufacturing, and reuse are included. Many EISs are widely used to manage the product life cycle data in each phase, such as PDM in pre-production phase, CAPP and ERP in production phase, SCM and CRM in post-production phase. At the same time, the material and energy flow in product life cycle is the root cause of environment impacts from manufacturing activities, as illustrated in Figure 1. It is also the mainstream of most ECEA methods (Finnveden et al. 2009; Göschel, Schieck, and Schönherr 2012; Joshi 1999; Gluch and Baumann 2004; Umeda et al. 2012; Kloepffer 2008; Jørgensen et al. 2008). The energy flow and the product life cycle data have a strong coupling relationship with each other. However, most ECEA methods or systems are

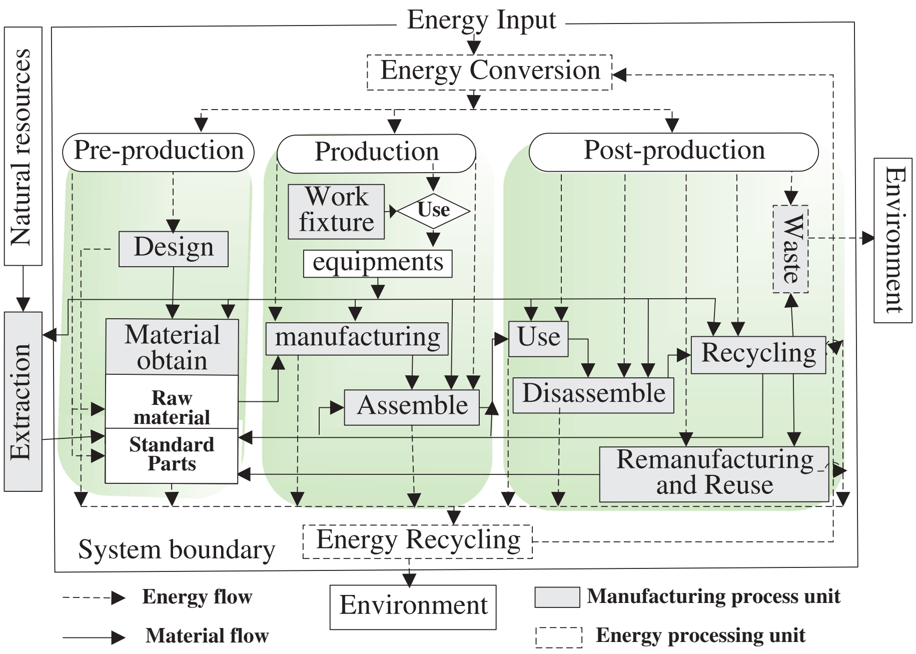

Figure 1. Energy flow in product life cycle.

independent of the above-mentioned EISs. It results in the proliferation of information islands, and the increasing of the enterprise information costs.

To overcome this deficiency, it is useful to introduce the cloud concept to the ECEA process in product life cycle. An ECEA Cloud is proposed based on the service-oriented architecture (SOA), as shown in Figure 2. It can collate and integrate various capabilities and resources from the society. As illustrated in Figure 2, various ECEA functions, models, and algorithms in product life cycle are collated from social providers and encapsulated into services by making use of SOA technology, and provisioned in terms of ECEA services. Among them, the social providers may be a designer, manufacturer, customer, assessment enterprise, optimisation engineer, algorithm engineer, or other social workers. Additionally, energy consumption information from bill of materials, manufacturing processes, standard parts, etc., which is especially important for ECEA, is also maintained in the form of services in ECEA Cloud.

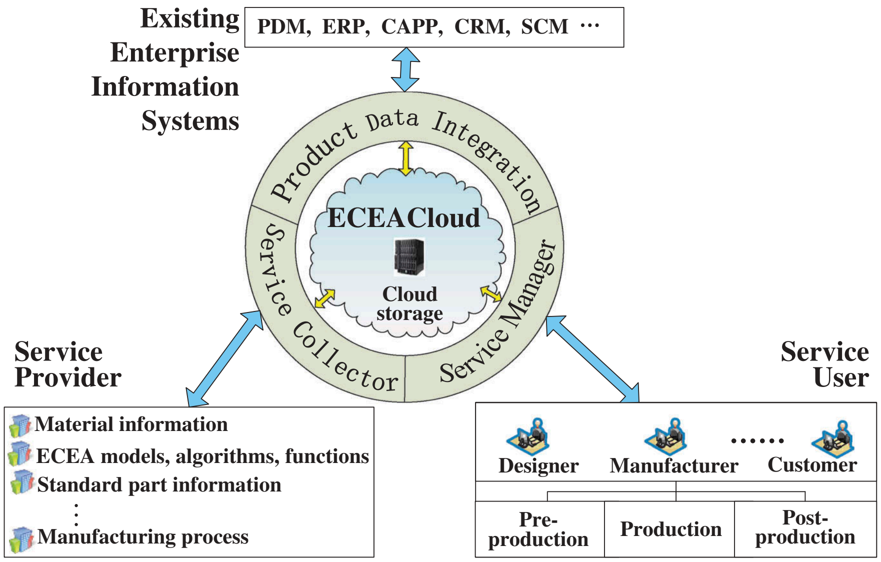

Figure 2. Cloud-based ECEA data management.

The above-mentioned ECEA services are integrated with the product data information that are provided and used in EISs. An ECEA Cloud can therefore provide a good link between an ECEA system and EISs.

These ECEA services can be invoked and accessed by various users in the product life cycle. For example, a designer in the pre-production phase can input or select material information in his design by a browser-based interface or App interface in his smart phone, the ECEA Cloud will feed back to him the ECEA results of the selected material. Based on the results, he can optimise his design and select the energy-efficient material for the new products within their specific function constraints and cost constraints.

4. IoT and cloud-based ECEA system

The six-layered architecture of the proposed IoT and cloud-based ECEA system is depicted in Figure 3. It mainly includes service collection layer, ECEA Cloud layer, service manager layer, user layer, IoT layer, and physical manufacturing lifecycle layer as described below.

Service collection layer collates various ECEA modes, algorithms, energy consumption information of material, manufacturing process, standard part, etc., from the social providers, encapsulates, and documents them into standardised services named ECEA services, which are registered and deposited in ECEA Cloud.

ECEA Cloud layer is the services pool of the collated ECEA services, which can be invoked by the end users in the product life cycle. In addition, it is the comprehensive and standardised data exchange environment that maintains all the information and knowledge throughout a product life cycle.

Service manager layer plays the role of an orchestrator of the ECEA Cloud. It provides functions or services for the users to manage, access, and invoke ECEA services in ECEA Cloud, including publication, discovery, matching, assembly, scheduling, QoS management, charging, evaluation, coordinator and allocator, etc. (Tao, Zhang, and Hu 2012).

The users in user layer are defined as the stakeholders who demand ECEA services. They can be product designers in pre-production phase, manufacturing participants and managers in production phase, end users and customers at the post-production phase. The users are connected to ECEA Cloud at the user layer via browser-based user interfaces, which collects various ECEA

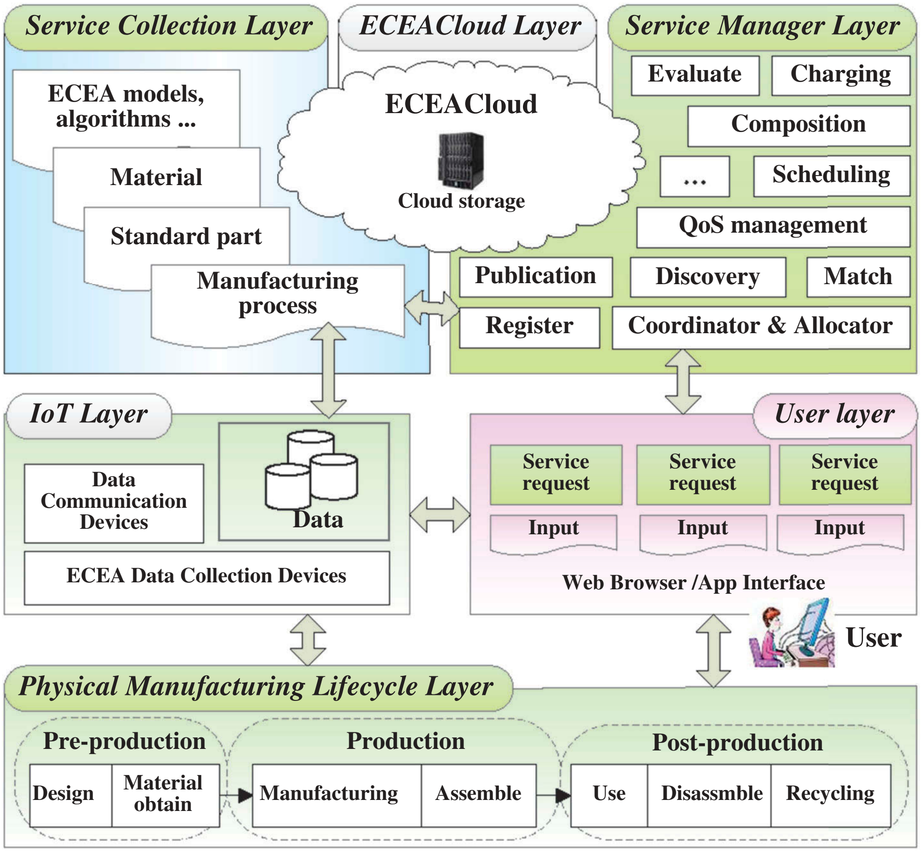

Figure 3. Six-layer IoT and cloud-based ECEA Cloud system.

service requests from users and documents them in a standardised format. The documented service requests are then delivered to the service manager layer.

IoT layer is responsible for sensing the physical product life cycle process, enabling them to be connected to the wider network, and collecting and processing the ECEA-related data and the generated information.

The physical manufacturing lifecycle layer contains the physical environment and physical activities carried out in the entire product life cycle.

In order to implement the proposed system, the IoT-based data collection mechanism and experimental bench, ECEA models and algorithms for a product, ECEA Cloud prototype system, and service management middleware are developed.

4.1. IoT-based ECEA data collection and experimental bench

With the rapid development of information technology, the emergence of IoT has provided a promising opportunity to build powerful industrial systems and applications by leveraging the growing ubiquity of Radio Frequency Identification (RFID), wireless, mobile and sensor devices, embedded object logic, object ad hoc networking, and Internet-based information infrastructure. In the proposed ECEA system, the IoT technology is employed to realise real-time, intelligent, and dynamic perception and collection of the generated data, and an IoT-based intelligent perception experimental bench has been developed by the authors, as shown in Figures 4 (b) and (c). Over 30 different intelligent IoT devices (e.g. smart electronic meters, sensors, and communication devices) have been developed and integrated in the experimental bench. Forty data interfaces (e.g. serial port and USB interface) are developed and provided for data transmission and communication. By using this experimental bench, various parameters and information that are required in the ECEA process, such as the environment parameters (e.g. temperature, humidity, brightness, vibration), power parameters, electric current, voltage can be collected. The collected data are sent to the ECEA software system by using wired or wireless transmission equipment in the experimental bench.

As an example, if a user wants to evaluate and analyse the energy consumption of a computer numerically controlled (CNC) lathe (Figure 4 (a)) when machining a part, he can connect the CNC lathe with the smart power meter (i.e. PM5350 in Figure 4(1)), RFID reader (Figure 4 (2)), and smart water meter (Figure 4 (3)) in the experimental bench. Then the information about power consumption of the CNC lathe (Figure 4(e1)), tool (Figure 4(e2)), and cutting fluid (Figure 4(e3)) can be collected. The collected data are documented in a standardised format (Figure 4 (f)) and transmitted via the Ethernet gateway (i.e. EGX 100 in Figure 4 (4)) to the ECEA software system (Figure 4 (c)). The documented data will be recorded automatically as part of the input of the ECEA service request Figure 4 (5)) which is sent to the ECEA Cloud by the user via browser-based user interfaces. Then, the related ECEA services (Figure 4 (d)) in the ECEA Cloud will be matched and invoked, and the result (Figure 4 (6)) will be evaluated and returned to the user.

4.2. ECEA model for product and ECEA Cloud prototype system

As shown in Figure 1, a product life cycle consists primarily of three phases, i.e. pre-production, production, and post-production. Therefore, a multistage ECEA model for a product life cycle is established, which consists of three parts,

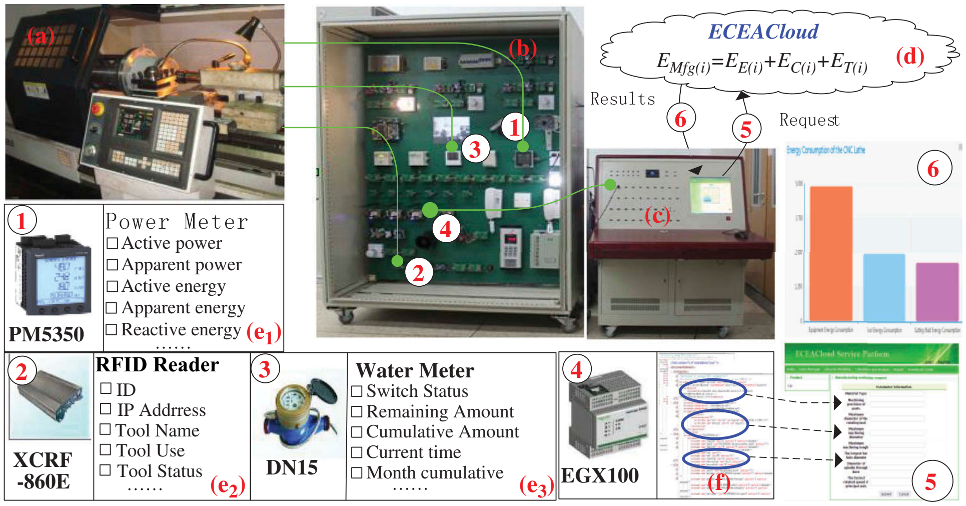

Figure 4. IoT-based data collection experimental bench and its application.

i.e. $E_{Pre\text{-}prod}$, E_{Prod}, and $E_{Post\text{-}prod}$, as depicted in Figure 5. Due to the complexity of manufacturing and assembly processes, energy consumption at this stage includes the main energy consumption of the process and the auxiliary energy consumption of the process. The main energy consumption refers to the energy consumed by the equipment during manufacturing operations such as forming and machining, auxiliary energy consumption refers to the energy required by the supporting activities and auxiliary equipment for the selected process (e.g. generation of vacuum for sand casting, or pumping of coolant for machining) (Seow, Rahimifard, and Woolley 2013).

(1) $E_{Pre\text{-}prod}$ is defined as the energy required in a product's pre-production phase, including product design stage, material obtained and transportation stages (Figure 1), as depicted below:

$$E_{Pre-prod} = E_{Des} + E_{Mos} + E_{Tra}, \tag{1}$$

where E_{Des}, E_{Mos}, and E_{Tra} represent the energy consumption in design stage, material obtain stage and transport stage, respectively. The E_{Mos} consists of the energy consumption of raw material obtained (E_{Rmo}) and standard parts obtained (E_{Sta}).

(2) E_{Prod} is defined as the energy consumption in a product's production phase, including part manufacturing stage, and component and product assembly stage, as depicted below:

$$\begin{aligned} E_{Prod} &= E_{Part(i)} + E_{Comp(j)} + E_{Product} \\ E_{Part(i)} &= E_{Mfg(i)} + E_{Tra(i)} + E_{AE(i)} \\ E_{Comp(j)} &= E_{Ass(j)} + E_{Tra(j)} + E_{AE(j)} \\ E_{Product} &= E_{Ass} + E_{Tra} + E_{AE}, \end{aligned} \tag{2}$$

where

- $E_{Part(i)}$ is the total energy consumption in the manufacturing stage for the ith (i = 1,2,3,. . .) part, it consists of the energy consumption of the manufacturing process ($E_{Mfg(i)}$) and transportation ($E_{TranS(i)}$), and the auxiliary energy consumption ($E_{AE(i)}$) in manufacturing the ith part.
- $E_{Comp(j)}$ is the total energy consumption in the assembly stage for the jth (j = 1,2,3,. . .) component, which consists of the energy consumption of assembly ($E_{Ass(j)}$) and transportation ($E_{Tra(j)}$), and the auxiliary energy ($E_{AE(j)}$) for assembling the jth component.
- $E_{Product}$ is the total energy consumption in the assembly stage for the final product, and it consists of the energy consumption of assembly (E_{Ass}) and transportation (E_{Tra}), and the auxiliary energy (E_{AE}) for assembling the product.

(3) $E_{Post\text{-}prod}$ is defined as the energy required in a product's post-production activities, including use, disassembly and recycling, etc. (Figure 1), as depicted below:

$$E_{Post-prod} = E_{Use} + E_{Dis} + E_{Rec}, \tag{3}$$

where E_{Use}, E_{Dis}, and E_{Rec} represent the energy consumption in use stage, disassembly stage, and recycling stage, respectively. The energy consumption in the use stage is determined by the use characteristics of a product. For example, the energy consumption of a car is estimated by multiplying its rated power and the service life time. But if a product is passive product such as a book shelf, the energy consumption in the use stage is 0.

$$E_{Prod-Life} = E_{Pre-prod} + E_{Prod} + E_{Post-prod}. \tag{4}$$

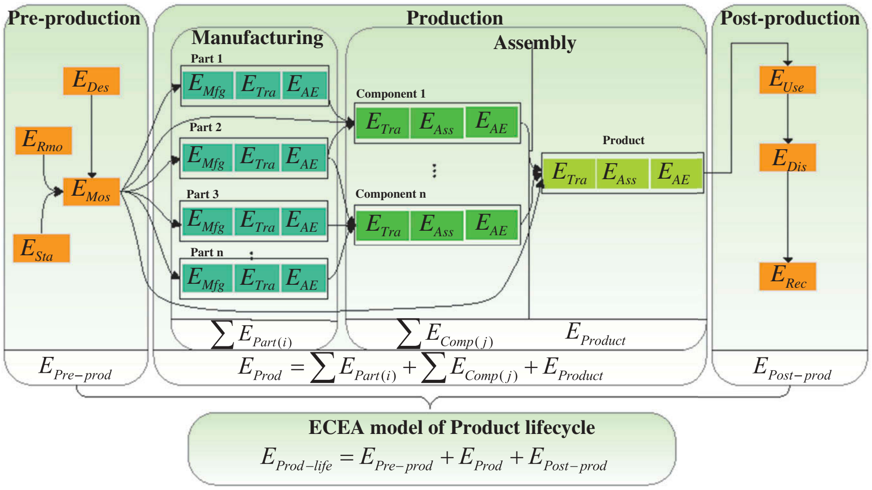

Figure 5. ECEA model for a product life cycle.

Then the total energy consumption of a product life cycle is as formula (4). The detailed formulations and methods for energy consumption in each stage are collected from social providers, and are encapsulated into service and registered in ECEA Cloud. For example, the detailed energy consumption models and methods for the tool (Figure 6 (a)) and cutting fluid (Figure 6 (b)) used in the CNC lathe in Figure 4(a) can be provided by community professionals or companies in the field of tools and cutting fluid. They are encapsulated into services using SOA technology, which are published and registered in the corresponding service list (Figure 6(d)) in ECEA Cloud. In the ECEA process, after the ECEA Cloud system receives the related service requests (Figure 6(g)) from an end user, it searches and invokes these services, and the related ECEA models and algorithms in these services will be executed together with the collected data in Figure 4 to generate the results (Figure 6(h)), which are returned to the end user. The other phases are similar for estimating and obtaining energy consumption data in the use stage, disassembly stage, and recycling stage. For example, the energy estimation methods in the use stage, disassembly stage, and recycling stage have been reported by Qi (2006), and all the calculation models can be obtained in the form of cloud service.

5. Case study

A Bearing bracket in a toy aircraft is selected as a case study to illustrate the working of the proposed system. As illustrated at the top of Figure 7, the Bearing bracket consists of three parts, denoted as P1 (Retaining washer), P2 (bushing), and P3 (internal bracket). Two types of materials (steel and aluminium alloy) can be selected for the three parts in the design phase. Three steps are required when manufacturing P2, and each step has two different manufacturing processes for selection in the manufacturing phase. If the component does not consume energy in the post-production stage, product design and manufacturing optimisation will follow the same procedure as in the case study in this paper.

5.1. *ECEA cloud-based product design optimisation*

There are eight types of material combination solutions (MCSs) in the design phase. In order to reduce energy consumption, after the designer has completed the structure design, he needs to select an energy-efficient MCS with minimal energy consumption, while satisfying certain functional quality (safety, reliability, life cycle, performance) requirements within a budget (below USD30) constraint. The cost of each MCS is calculated as the multiplication of the price of the selected material and the required weight. The functional quality of each MCS is evaluated using method proposed by Tao (2013), and the energy consumption of each MCS is calculated using the proposed method.

The cost, functional quality, and energy consumption for the eight MCSs are shown in Figure 7. It can be seen from Figure 7 that the cost of MCS1 is over the budget and MCS8 is below the basic line of function quality requirement, so they are not qualified candidate solutions. The other six MCSs are within the function quality and budget constraints, and they are feasible solutions. The comparison results of the energy consumption of the six MCSs are MCS5<MCS2<MCS6<MCS3<MCS7<MCS4. Therefore, for the material combinations solution, MCS5 is first recommended to the designer by the ECEA Cloud system, followed by MCS2, MCS6, MCS3, MCS7, and MCS4 in turn.

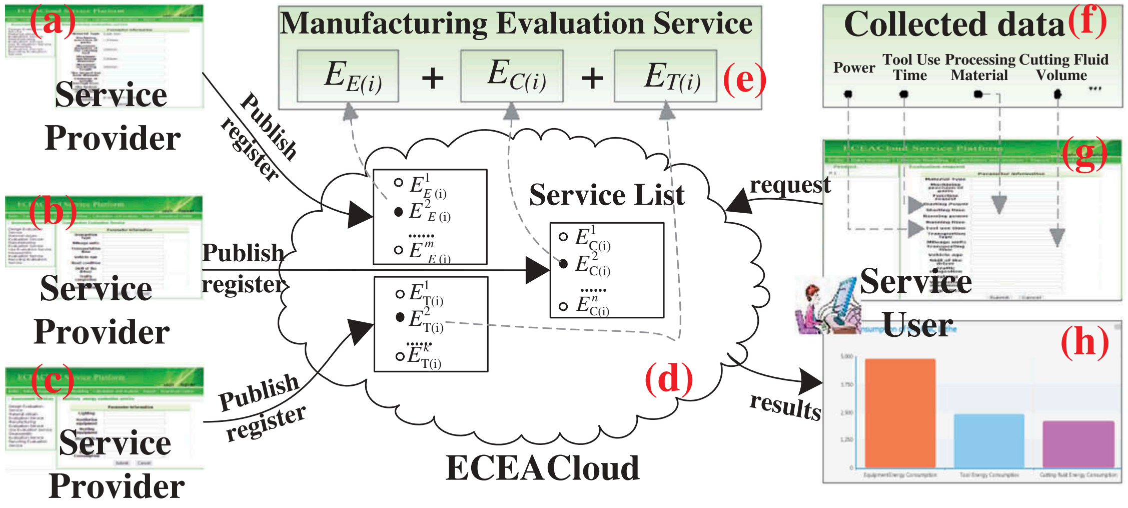

Figure 6. Service publication and invoking in the ECEA Cloud system.

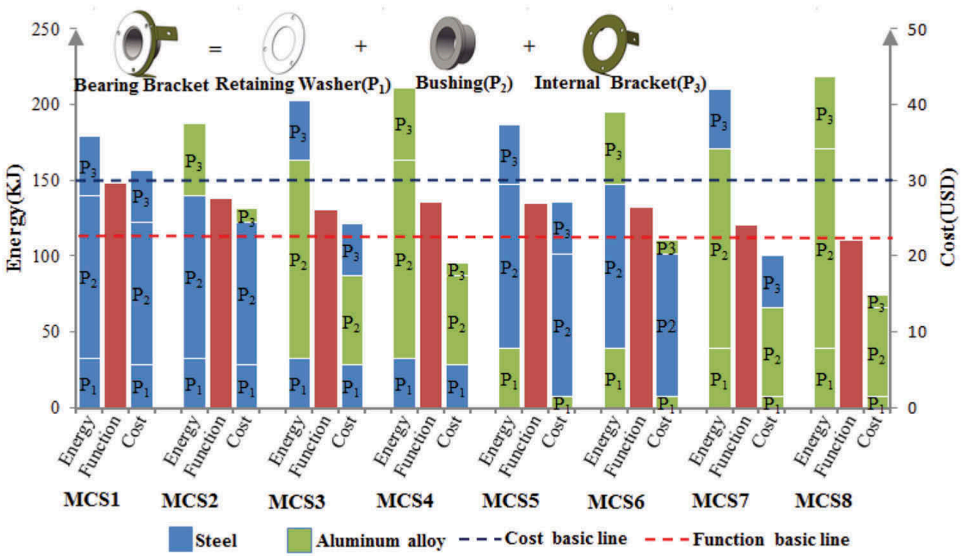

Figure 7. ECEA results of material combination solutions of case-study product.

5.2. *ECEA cloud-based product manufacturing optimisation*

Product manufacturing optimisation is usually a NP-hard problem, many intelligent optimisation methods have been used to address this issue, such as novel hybrid immune algorithm (Yildiz 2009), cooperative co-evolving particle swarm optimisation (Li et al. 2012), scalable optimisation algorithm (Gibney, Klepal, and Pesch 2011). In this paper, these algorithms can be selected and used in the form of cloud services. Since the scale addressed in this paper is relatively small, an exhaustive optimisation method can be achieved. Therefore, there are eight kinds of candidate manufacturing process combination paths (PCPs) for selection in the manufacturing stage of P2. In order to reduce the energy consumption of the entire product life cycle, the manufacturing process designer can also select the energy-efficient PCP from the eight PCPs based on the ECEA results (Figure 8) by using the developed experimental bench and ECEA Cloud system as shown in Figures 4 and 6.

In Figure 8, $A_iB_jC_k$ (i, j, k = 1 or 2) represents the manufacturing PCP of $A_i \rightarrow B_j \rightarrow C_k$. The height of the rectangle with the symbol of a process name (e.g. A_1) represents the energy consumption generated by using the process. AE_i (i = 1, 2, 3,…) denotes the auxiliary energy consumption required by the supporting activities and auxiliary equipment for the selected process in each PCP and it can be calculated using the method in Reference 1. The entire energy consumption of a PCP is the sum of the energy consumption of its selected processes and auxiliary energy consumption. Obviously, the entire energy consumption of $A_1B_2C_1$ in Figure 8 is the lowest. Therefore, $A_2B_2C_1$ is first recommended by the ECEA Cloud system, followed by $A_1B_2C_2$, $A_1B_1C_1$, $A_1B_1C_2$, $A_2B_2C_1$, $A_2B_2C_2$, $A_2B_1C_1$, and $A_2B_1C_2$ in turn.

6. Conclusions and future works

Green and sustainable manufacturing are the main directions of the future manufacturing industry. Enhancing the intelligence of product design and manufacturing processes, and realising intelligent manufacturing have received increasing attention in many national manufacturing strategic plans. However, the main aim of intelligent manufacturing is to improve energy efficiency and reduce pollutant emissions. Therefore, enhancing intelligent ECEA and reducing energy consumption in product life cycle is one of the key problems faced by the modern manufacturing industry. In order to address this issue, an IoT and cloud-based ECEA method is proposed in this paper. In the proposed method, energy flow and data management of the ECEA of a product is analysed, a six-layered architecture (i.e. service collection layer, ECEA Cloud layer, service manager layer, user layer, IoT layer, and physical manufacturing life cycle layer) ECEA system based on IoT and cloud is proposed. IoT-based ECEA data collection and the related experimental bench have been designed and the ECEA model for product and ECEA Cloud is established. A prototype system is developed to validate the proposed method. Finally, a case study is provided to test and validate the effectiveness of the proposed approach in the design and manufacturing processes of a product.

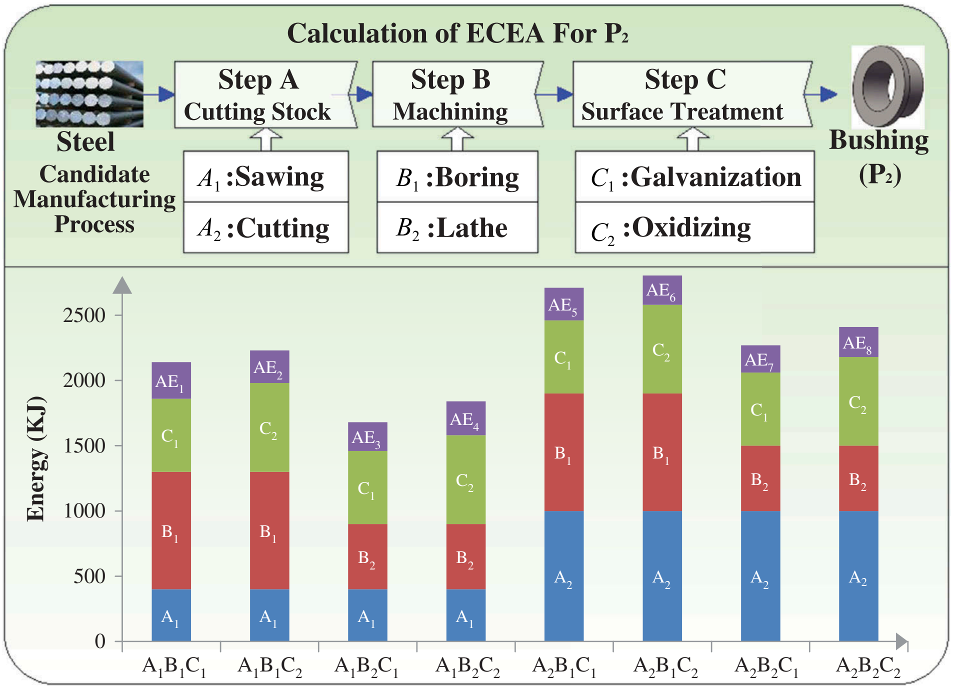

Figure 8. ECEA results of manufacturing process composition paths of case-study part.

The main contributions of this paper are as follows:

(1) The IoT technologies are employed to achieve real-time and dynamic collection of energy consumption data generated in the entire product life cycle.
(2) Various required functions and data in ECEA are encapsulated into services which are managed in a cloud server.

However, the research on IoT and cloud-based ECEA for a product life cycle is at its infancy, and the relevant theories, technologies, and applications are still evolving and would require further research. The following future work will be planned: (1) Introduce more advanced IoT and cloud technologies for the implementation of intelligent monitoring of energy consumption and the control in the product life cycle; (2) solve the computational complexity problem of the proposed approach in a complex case; (3) control the accuracy and quality of information before implementing this in the system; (4) select the most appropriate model and algorithm from social provider.

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