Internet of Things and BOM-Based Life Cycle Assessment of Energy-Saving and Emission-Reduction of Products

Fei Tao, *Member*, *IEEE*, Ying Zuo, Li Da Xu, *Senior Member*, *IEEE*, Lin Lv, and Lin Zhang, *Senior Member*, *IEEE*

***Abstract*—Energy-saving and emission-reduction (ESER), carbon footprint, carbon labeling, and carbon trading have attracted much attention recently due to severe environmental challenges. One key technology for implementing the above concepts is how to realize the effective quantitative evaluation of ESER. In this paper, the existing ESER evaluation technology and systems are summarized first. It is found that the existing ESER evaluation technology and systems are almost isolated from the existing enterprise information systems, such as enterprise resource planning (ERP), product data management (PDM), and customer relationship management (CRM), which results in the expanding of the enterprise information islands. In order to address this problem, a new method for ESER life cycle assessment (LCA) based on Internet of Things (IoT) and bill of material (BOM) is proposed in this paper. A four-layered structure (i.e., perception access layer, data layer, service layer, and application layer) ESER LCA system based on IoT and BOM is designed and presented, as well as the key technologies and the functions in each layer. A prototype application system is developed to validate the proposed method. The main contributions of the proposed method are: 1) facilitate real-time intelligent perception, and the collection of energy consumption and environmental impact data generated in the entire life cycle of manufacturing by using IoT technologies; and 2) realize effective data integration between the ESER evaluation system and the existing enterprise information systems based on BOM.**

***Index Terms*—bill of material (BOM), energy-saving and emission-reduction (ESER), enterprise information system, evaluation, industrial information integration engineering (IIIE), Internet of Things (IoT), life cycle assessment (LCA).**

I. Introduction

ENERGY-SAVING and emission-reduction (ESER) means saving material resources and energy resources, and reducing the emissions of waste and environmentally harmful materials [1]. Currently, in contrast, the regulations on limiting greenhouse gas (GHG) emissions become more specific, and are more comprehensively developed. To some extent, the appearance of some new concepts such as carbon footprint, carbon labeling, and carbon trading promote the process of reducing GHG emissions. Among them, *carbon footprint* means the collection of GHG emissions caused by enterprises, activities, products, or individuals [2]. *Carbon labeling* [3] means marking the GHG emissions of the products in the production process in the product label with quantitative index to provide information of carbon of the products to consumers in the form of a label. At present, many countries and regions are piloting carbon labeling as shown in Fig. 1. *Carbon trading* [4] means GHG emission reductions trading according to international law for the promotion of reduction of global GHG emissions proposed in Kyoto Protocol. It uses market mechanism as a new solution of emission reduction problems of GHG represented by carbon dioxide.

The implementation of above-mentioned concepts relating to the limitation of GHG emissions depends on the evaluation focusing on the evaluating target. The most important prerequisite for its implementation is accurate GHG emissions evaluation. Without accurate quantitative evaluation, all index data are not credible. Reducing GHG emissions is a part of ESER. From the study of reducing GHG emissions, it can be seen that the ESER evaluation is of great significance for realizing the aim of ESER. A comprehensive implementation of ESER evaluation requires the guidance of complete ESER evaluation.

In order to effectively solve the above problems, both industry and academia have conducted research. Among them, the ESER evaluation methods are mainly life cycle assessment (LCA) [5]. ISO14040:2006 [6] and ISO14044:2006 [7] issued by International Standards Committee provide detailed provisions of terminologies, specifications, and frameworks of LCA. Based on this, LCA is combined with process selection, design and optimization [8], economic input output-LCA (EIO-LCA) [9], simplified LCA [10], eco-indicator 95, eco-indicator 99, environment-dependent interatomic potential (EDIP), and environmental priority strategies (EPS) 2000 from Sweden have been proposed. In applying ESER and LCA, De Angelis *et al.* [13] pointed out that smart grid can achieve a good effect in energy saving. Assies [12] proposed a risk-based approach to life cycle impact assessment. Wang *et al.* [11] studied the impact of climate change on residential building heating and cooling energy requirement. A software energy consumption problem on online reconfiguration control software is discussed in [14]. Akimoto *et al.* [15] used integrated assessment model

Manuscript received September 29, 2013; revised January 26, 2014; accepted January 28, 2014. Date of publication February 17, 2014; date of current version May 02, 2014. This work was supported in part by the National Natural Science Foundation of China under Grant 51005012 and Grant 71132008, and in part by the U.S. National Science Foundation under Grant SES-1318470 and Grant 1044845; and in part by the Beijing Youth Talent Plan under Grant 29201411. Article no. TII-13-0693.

F. Tao, Y. Zuo, L. Lv, and L. Zhang are with the School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China (e-mail: ftao@buaa.edu.cn).

L. D. Xu is with the Institute of Computing Technology, Chinese Academy of Sciences, Beijing 100864, China; with Shanghai Jiao Tong University, Shanghai, China; University of Science and Technology of China, Hefei 200240, China; and also with Old Dominion University, Norfolk, VA 23529 USA.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TII.2014.2306771

Fig. 1. Carbon labeling of some countries and regions.

for the assessment of global warming mitigation. Ondemir *et al.* [16] used radio-frequency identification (RFID) and sensors to achieve optimal end-of-life management in closed-loop supply chains. Zhao *et al.* [17] studied maximizing reliability of real-time embedded applications under hard energy constraint. Ma *et al.* [18] introduced how to reduce electricity consumption with an intelligent control scheme in smart power systems. Tabone and Cregg [19] combined LCA and green design and conducted the environmental impact assessment of life cycle. Klemeš *et al.* [20] developed a novel energy-saving technologies evaluation tool. Ma and Zhou [21] studied gas storage in porous metal-organic frameworks for clean energy applications. Hu *et al.* [22] proposed that nonmaterial plays an important role in environmental and energy applications. Margni *et al.* [23] proposed a new life cycle impact assessment methodology, i.e., Impact 2002+. Huijbregts and Hellweg [24] proposed an ecological footprint accounting method in the LCA of products. Boyd *et al.* [25] conducted LCA of NAND flash. Besides, some new life cycle environmental assessment methods and their applications are proposed and described [26]–[33].

When it comes to the evaluation system, there are primarily three tools.

1) Gabi: It is jointly developed by IKP at the University of Stuttgart and PE from Germany. It is based on C/S software architecture, and it is a specialized tool for LCA. The main features of Gabi are: a) a latest wide-range comprehensive database; b) providing systematic evaluation method for life cycle; c) transparency and flexibility of graphical interface; and d) providing sensitivity analysis.
2) SimaPro: It is developed by University of Leiden, the Netherlands. It is also based on C/S software architecture, and it is applied to the calculation of LCA and the environmental load calculation of product life cycle [38]. It contains a powerful database comprised of eight databases include: Dutch Input Output Database95, Data Archive, BUWAL250, ETH-ESU 96 Unit process, IDEMAT2001, Eco Invent, etc. The database includes a variety of industrial data and the data regarding environmental impact, global warming, and greenhouse effect.
3) eBalance: It is a full-featured LCA software developed by IKE Environmental Technology Co. Ltd. independently. It is based on C/S software architecture, and was first released on September 19, in 2010. It is a full-featured LCA software independently developed and released in China. eBalance supports full LCA standards and provides support for data collection, ESER evaluation, and multi-program comparison.

From the above, it can be concluded that current study on ESER evaluation methods and tools faces the following issues.

Issue 1: The data required in the existing assessment methods and systems are primarily manually collected, and the assessment process primarily relying on the existing data in the database of the system. The real-time and dynamic requirements were not satisfied. Therefore, how to realize real-time, intelligent, and dynamic perception, and the collection of energy consumption and environmental impact data generated in the evaluation process is a bottleneck for the development and pervasive application of ESER technology and systems.

Issue 2: Current study on ESER primarily focuses on the environmental and process industries (e.g., cement industry), and the evaluation process treats the enterprise or region as a unit. But at the product level, such as the ESER evaluation methods and tools for the levels of products (e.g., product level, component level, and part level) and the stages of production (e.g., design, manufacturing, assembly, etc.) is still blank. Enterprises are still unable to grasp the energy consumption/environmental impact data in the entire life cycle of the products. Therefore the product design, research and development cannot be optimized. Thus, the enterprise-level and product-level ESER target cannot be met. Furthermore, the national emission reduction targets currently only remain at the policy level.

Issue 3: These ESER assessment tools or systems are independent from the existing enterprise information systems (such as PDM, CAPP, ERP, SCM, etc) which have been widely used in almost all enterprises. As a result, it is very difficult to realize the integration between the above mentioned ESER assessment tools and these existing enterprise information systems. It results in the expansion of the information islands and the increasing of enterprise information costs.

Issue 4: The architecture of the existing assessment tools (e.g., Gabi, SimaPro, and eBalance) is traditional C/S architecture, which is not good for the upgrade and maintenance, and cannot meet the requirements of networked users and trends.

At the same time, with the development of information technology, the emergence of the Internet of Things (IoT) has provided a promising opportunity to build powerful industrial systems and applications by leveraging the growing ubiquity of RFID, wireless, mobile and sensor devices, embedded object logic, object ad-hoc networking, and internet-based information infrastructure. A wide range of industrial IoT applications have been studied and deployed [34, 35]. For example, the IoT technologies have been widely used for people with disabilities [36], in global supply chain [37, 38], snowmelt flood forecasting for water resource management [39], in-home health care [40], enterprise information systems [41], and cloud computing [42]. Recently, Xu *et al.* [34], [43], [44] reviewed the advances of IoT in enterprise systems and industries, Bi *et al.* [45] studied the application of IoT in modern enterprise systems, Fan *et al.* [46] studied IoT-based smart rehabilitation system, and He *et al.* [47] applied IoT in developing vehicular data cloud service. In addition to employ IoT to identify physical and virtual objects, IoT has also been studied and used for the connection, identification, and communication of such objects in an Internet-like structure, such as requirement-oriented participation decision and compliance checking in service workflows, service composition [48]–[50], data management [51], and so on.

With the support and application of IoT technology, the potential intelligent and real-time operators of 4C (i.e., perception and *C*onnection, *C*ommunication, *C*omputing, and *C*ontrol) to both physical and virtual objects can be realized, including the energy consumption and environmental impact data generated in the entire life cycle of a product.

Furthermore, with the fast development and pervasive application of information technology in manufacturing, enterprise information systems such as product data management (PDM), enterprise resource planning (ERP), computer aided design (CAD), computer aided process planning (CAPP), customer relationship management (CRM), and supply chain management (SCM) have been widely accepted and applied by manufacturing enterprises. As one of the core data sets of product data, bill of materials (BOMs) have been involved and used in all these enterprise information systems for different aims, and it has been widely used as the bridge to realize the integration of different enterprise information systems.

Therefore, in order to address the above problems faced by current ESER evaluation technologies and tools, this paper proposed a new ESER assessment method which is based on IoT technologies and BOM. The main innovations and motivations of the proposal method are as follows.

1) For addressing **Issue 1**, the IoT technologies are employed to realize the real-time, intelligent perception and collection of energy consumption and environmental impact data generated in the entire life cycle of a product.
2) For addressing **Issue 2**, this paper carries out studies on BOM-based ESER evaluation theories and methods, which can realize the multi-structure (e.g., from parts and components to product) and multi-level (e.g., from design, manufacture, transportation, sales, use, and recycling to scrap of a product) ESER evaluation to the entire life cycle of a product.
3) For addressing **Issue 3**, the concept of big BOM is proposed, which primarily consists of 1) the available BOM information from the existing enterprise information systems; and 2) the energy consumption and environmental impact data generated in the entire life cycle of a product. With the big BOM, the effective data integration and exchange between the ESER evaluation system and the existing enterprise information system can be realized.
4) For addressing **Issue 4**, an IoT and BOM-based ESER evaluation system with B/S architecture is designed and developed, and a prototype system is developed to illustrate the practical application of the proposed method.

The remainder of the paper is organized as follows. Section II presents the architecture of the proposed new method. In Section III, the key technologies of product ESER LCA based on IoT and BOM is described. A prototype system is developed to test the validity and practicability of the proposed methods in Section IV. The conclusion and future work are presented in Section V.

II. Architecture of IoT and BOM-Based LCA of Product ESER

The architecture of the proposed IoT and BOM-based LCA of product ESER is shown in Fig. 2, which primarily consists of four layers.

1) *Perception Access Layer (P-Layer)*: It is responsible for the real-time, intelligent perception and collection of energy consumption and environmental impact data generated in the entire life cycle of a product by using IoT technologies such as RFID, wireless, mobile and sensor devices, embedded object logic, object ad-hoc networking, and internet-based information infrastructure. It consists of the following three sub-layers.
   a) *Manufacturing activity layer*, which is the substance unit produced in the evaluation of energy consumption data in entire product life cycle. For example, it can be a physical device similar to the computing devices in the design stage, the machine tools in the manufacturing stage, and the automobiles in the transporting stage.
   b) *Perception layer* is mainly used to perceive and collect the energy, emission, and environmental impact data generated in entire product life cycle.
   c) *Communication layer* mainly provides a good communication network for the entire product life cycle ESER evaluation system.
2) *Data Layer (D-Layer)*: It provides data support for running the entire product life cycle ESER evaluation system. In this study, it primarily consists of BOM data, enterprise basic data, and evaluation index data.
3) *Service Layer (S-Layer)*: It provides evaluation services for the application layer. It primarily includes the basic system service (such as user management, role management, and data entry and update service, etc.), the middle computational services (e.g., environmental impact material calculation, the characteristic and the normalized calculation, etc.), and evaluation analysis services (e.g., ESER evaluation service for component, parts, product, respectively, evaluation results visualization analysis, energy-saving potential analysis, product structure analysis, etc.).
4) *Application Layer (A-Layer)*: Application layer is primarily responsible for providing evaluation data for different users, such as enterprise users, government users, personal users, and third-party users.

III. Key Technologies for implementing IoT and BOM-Based LCA of Product ESER

A. P-Layer: Perception and Access of ESER Data Based on IoT

The IoT-based P-Layer primarily performs real-time data collection of the energy consumption and environmental impact (ECEI) for different substance unit and manufacturing process in the entire life cycle of the products, by using the powerful perception ability of IoT. According to the five stages (i.e., design, substance obtaining, manufacturing, use/maintenance, disposal/recycling) of the life cycle of a product, the perception

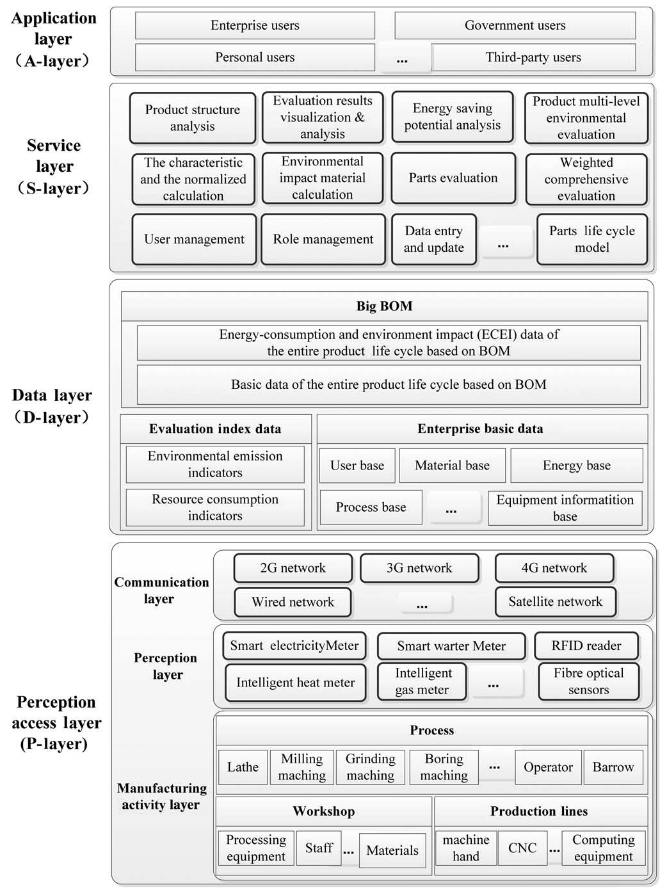

Fig. 2. Architecture of IoT and BOM-based LCA of product ESER.

and access of ECEI data for a product is divided into five parts too as shown in Fig. 3.

At the product design stage, the enterprise mainly designs the components of products, constructs three-dimensional (3-D) model, and tests and analyzes the structure using computer. There is no direct ECEI data generated by product in design stage. But the product design scheme has strong influences on next stages such as substance obtaining and manufacturing, as well as related ECEI data. In this study, the design tools such as computer and other electronic equipment are considered as the main ECEI source in this stage. The basic properties and unit emission information of these tools can be obtained from the label on them, and the exact electricity consumption of unit substance can be measured by the ammeter. Combining the above obtained ECEI data and the related design BOM in design stage, a related ECEI BOM can be established.

The substance obtaining of a product consists of raw material obtaining, semi-product obtaining, and part or product obtaining, which is provided by other company. Therefore, the ECEI data in substance obtaining stage of a product are primarily the sum of all the energy consumption and environmental impact data generated by producing all the obtained and used raw materials, semi-products, and part or products by other companies or enterprises, as well as their transportation. It can be collected from related database (such as material database), or by reading the barcode, carbon labeling, RFID, and so on, which are attached on the semi-product or parts.

At the manufacturing stage, the ECEI data is primarily generated when using different kinds of manufacturing equipment such as various machine tools in each manufacturing process (e.g., lathing, milling, grinder, and planning). Therefore, the main generated ECEI data in this stage is collected using RFID, smart meters, embedded system, and other intelligent sensor, instruments, and apparatuses, which are installed on these manufacturing equipment.

At the use/maintenance stage, the ECEI data consist of use ECEI data and maintenance ECEI data. The use ECEI data is the multiplication of the rated ECEI data of product unit time and its life expectancy, while maintenance ECEI data is primarily generated when using different kinds of repairing tools or replacement parts, as well as their transportation. It can be collected from the related database (such as product data base of PDM), or by reading the barcode, carbon labeling, RFID, and so on.

At the disposal/recycling stage, the ECEI data are primarily generated in the product's decomposition or disassembling, dissolution or combustion, remanufacturing and recycling process, as well as their transportation. In these processes, many special equipment and tools are employed, as well as some energy such as coal, oil, and so on. Therefore, the ECEI data generated using equipment and tools can be collected using the same method in the above-mentioned manufacturing stage, and the ECEI data generated using energy can be collected from the related database such as energy base and material base.

B. D-Layer: Data Management for the Proposed ESER Evaluation System

The proposed product ESER evaluation method based on BOM is an LCA method of multi-level of product. There are two advantages based on BOM.

1) The structure information of products is included in BOM, which clarifies the structure relationship between products and components, and among components, including the multi-layer assessment and summary of the parts, components, and products, and thus greatly improve the accuracy of the assessment.
2) BOM is the core data foundation of enterprise products. The ESER evaluation based on BOM can significantly improve the availability and real-time characteristics of the evaluation, and reduce the error rate of evaluation data collection. Furthermore, with the application of BOM, the evaluation system designed with this method can realize effective integration with enterprise information system more conveniently.

How to achieve the effective integration between ESER evaluation system and enterprise information system is a difficult issue. To solve this problem effectively, this paper calls all collected data as big data, which is required for the running of ESER evaluation system. According to its features, it can be divided into several parts as shown in Fig. 4: 1) *big BOM data*; 2) *enterprise basic data*; and 3) *evaluation index data*.

1) Big BOM: Big BOM is the combination of the existing data in each stage of the product life cycle, and the related - ECEI data

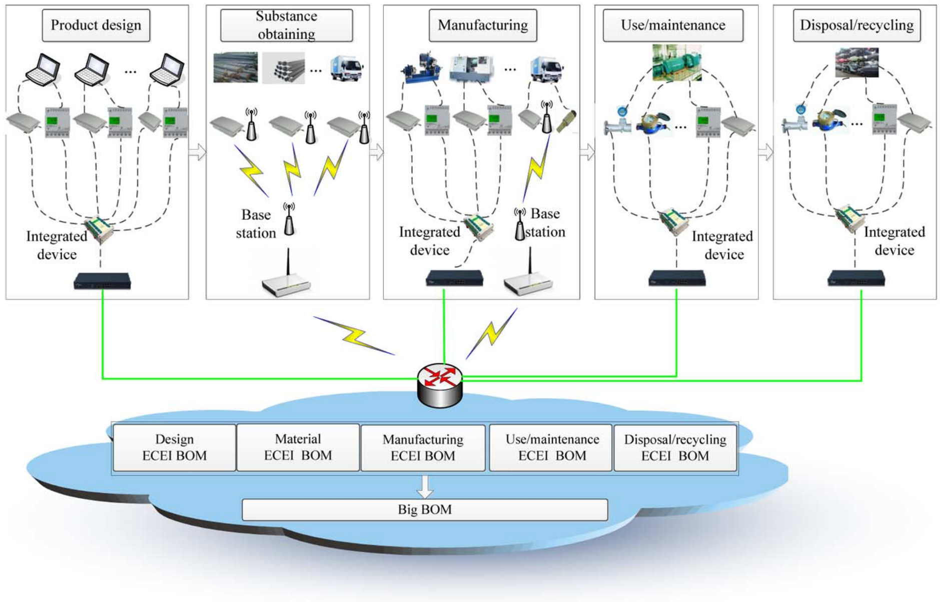

Fig. 3. Perception and access of ESER data based on IoT.

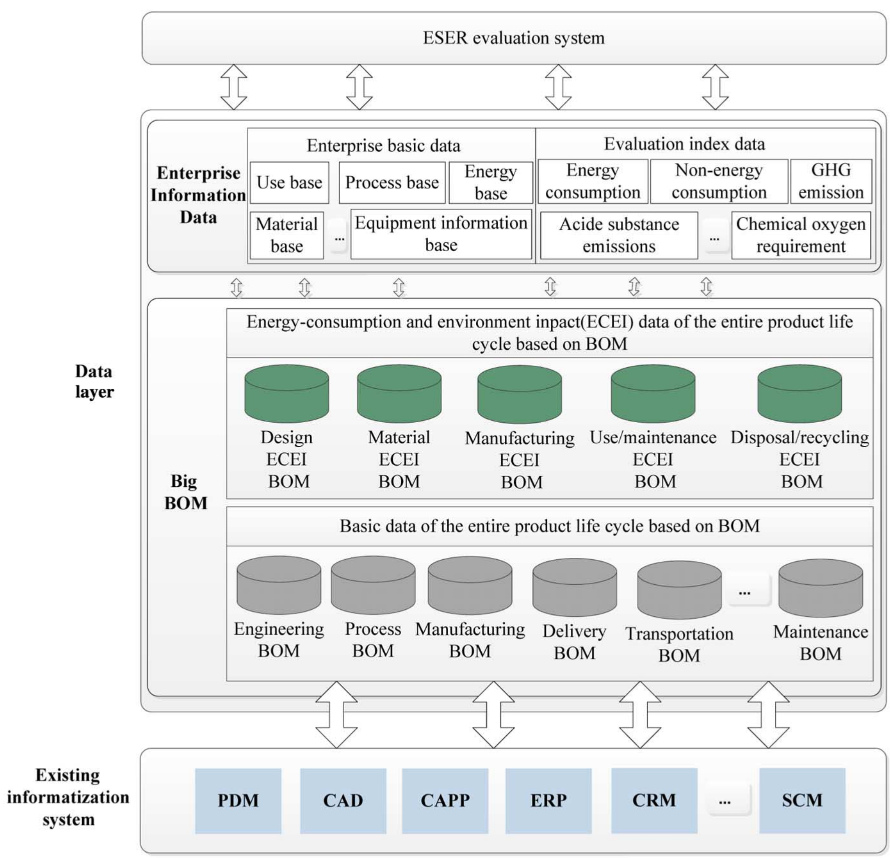

Fig. 4. Structure of the data in ESER system.

generated in the process of each stage. It primarily consist of the following two parts.

1) The ECEI data of the entire product life cycle based on BOM: it is the reflects the environmental impact data generated in each unit process in product life cycle, which is mainly perceived and collected by using IoT. It includes design ECEI BOM, material ECEI BOM, manufacturing ECEI BOM, use/maintenance ECEI BOM, disposal/recycling ECEI BOM, and so on.

2) The basic data of the entire product life cycle based on BOM: It refers to the basic data of product produced in the entire product life cycle, and these data are stored or used

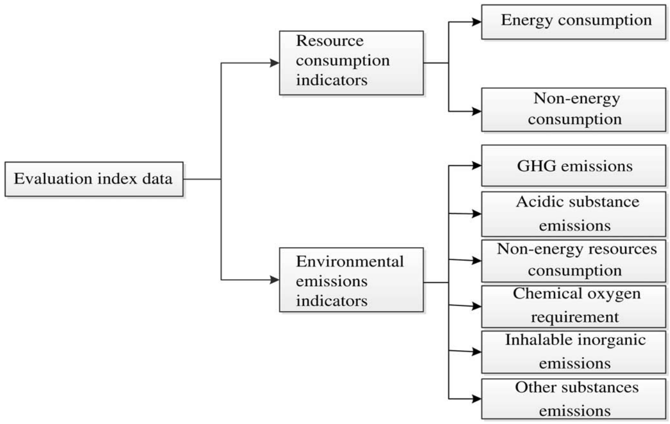

Fig. 5. ESER LCA index.

by different enterprise information systems, such as PDM and ERP. It includes engineering BOM, process BOM, manufacturing BOM, delivery BOM, transportation BOM, maintenance BOM, and so on.

2) Enterprise Basic Data: The enterprise basic data primarily stores the basic data required in the entire product life cycle management process. It is the source of big BOM basic data. It mainly includes the following aspects.

1) *User base* stores the system users' information such as username, password, department, authority, etc.
2) *Material base* stores the information of materials required in the entire product life cycle such as the name, inventory, types, cost of material, energy-consumption and emission information of material production or purchase, etc.
3) *Process base* stores the process information related to manufacturing. It contains the tools and manufacturing equipment required by the specific process, energy consumption and emissions information of the process in unit time, etc.
4) *Energy base* stores the information of all energy in the entire product life cycle. It contains the name of energy, the source of energy, the cost of energy, the emission information of energy consumption and the conversion coefficient from energy to standard coal.
5) *Equipment information base* stores related properties of all equipments in the enterprise.

3) Evaluation Index Data: The evaluation index data primarily stores the evaluation index type, the conversion factors between different types of index, the ESER standard data in related industries or areas, etc. The purpose is to quantitatively evaluate the environmental impact of the product life cycle. First of all, one should be clear about what kind of environmental impact is in the scope of evaluation. It is the prerequisite of all work of LCA, and will guide the conduction of all the following work. Generally the environmental impact evaluation index can be divided into two parts: 1) resources consumption; and 2) environmental emissions. The resources consumption includes energy consumption and non-energy consumption. The environmental emissions includes GHG emissions data, acidic substance emissions data, sewage emissions data, non-energy resources consumption data, chemical oxygen requirement data, inhalable inorganic emissions data, and other substances emissions data, as shown in Fig. 5.

C. S-Layer: ESER LCA Technology of Product

The substance flow between the product life cycle and its environment is the root of impact of product life cycle on the environment: the first one is the substance flow (including energy, metal, nonmetal materials, etc.) from the environment to the product life cycle; the second one is the substance flow (including GHG, sewage, solid waste, etc.) from the product life cycle to the environment. It is also the mainline of the environmental impact evaluation calculation method. Fig. 6 shows the substance flow model of product system.

The following is the introduction of the evaluation algorithm for multi-level structure and multi-stage of the product.

1) The Environmental Impact Calculation Method for Parts: Parts are in the leaf node of product structure tree and have simple structure. The environmental impact of single substance can be expressed as follows:

$$I_{i,x} = I_{i,x}^D + I_{i,x}^A + I_{i,x}^M + I_{i,x}^U + I_{i,x}^R$$

where $I_{i,x}$ indicates the generation of environmental impact substance x in the life cycle of part i, and $I_{(i,x)}^D$, $I_{(i,x)}^A$, $I_{(i,x)}^M$, $I_{(i,x)}^U$, $I_{(i,x)}^R$ indicates the generation of substance x in the stage of design, substance obtaining, manufacturing, use/maintenance, and disposal/recycling, respectively. Substance only exists in parts form at the manufacturing stage, while other stage is product or other forms. Therefore the single substance environmental impact evaluation of parts generally only consider manufacturing and substance obtaining stage, which can be expressed as follows:

$$I_{i,x} \approx I_{i,x}^A + I_{i,x}^M.$$

2) The Environmental Impact Calculation Method for Components: The components also exist alone in the manufacturing stage. But different from parts, components are composed by more than one part. Its environmental impact consists of three parts: 1) environmental impact in the obtaining process of substance required for the assembling of components; 2) environmental impact from the parts directly consist of the component; and 3) environmental impact from related equipment in the assembling process. The signal substance of environmental impact can be expressed as follows:

$$I_{j,x} \approx \sum_i I_{i,x} + I_{i,x}^A + I_{j,x}^M$$

where $I_{j,x}$ indicates the generation of environmental impact substance x in the life cycle of component j; $\sum_i I_{i,x}$ indicates the generation of substance x in the life cycle of all the parts consist component j; $I_{i,x}^A$ indicates the generation of substance x in the substance obtaining stage for component j; $I_{j,x}^M$ indicates the generation of substance x in the manufacturing stage of component j.

3) The Environmental Impact Calculation Method for Product: The product environmental impact evaluation is the core of ESER. Compared with parts and components, the life cycle of product is more complicated. The environmental impact of unit product primarily includes the environmental impact in

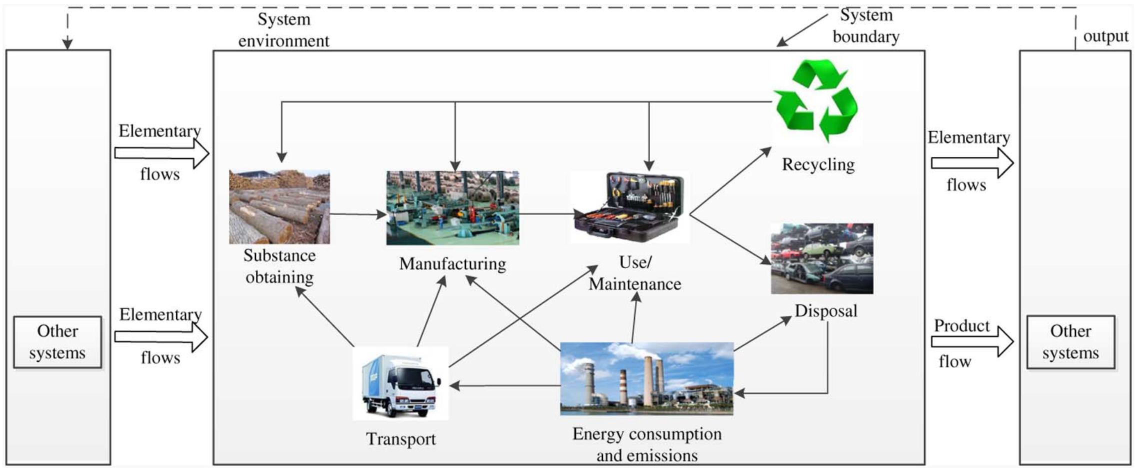

Fig. 6. Substance flow model of product system.

the five stages of life cycle and the environmental impact of parts and components directly consist of the product.

Product design stage: The environmental impact of the product is obtained by using statistical method. $I_{p,x}^{D}$ is used to express the generation of substance x in this stage.

Substance obtaining stage: The substance obtaining can be divided into two kinds: 1) obtain basic materials and basic energy; and 2) obtain finished products and semi-finished products. The former one are often conducted according to the batches. If the generation of substance x in this stage is I_{x}^{A}, and can be used in producing n products, then the generation of substance x of product can be expressed as I_{x}^{A}/n; in the latter one, the generation of substance x generated by finished products and semi-finished products can be expressed by $I_{p,x}^{A}$.

Manufacturing stage: The environmental impact from the product in the manufacturing stage mostly comes from the equipment. It can be collected in the production workshop. The term $I_{p,x}^{M}$ is used to express the generation of environmental impact substance x in this stage.

Use/Maintenance stage: The environment impact of product in the use/maintenance stage is primarily calculated according to the related rated data of the product, and the data gathered in the maintenance of product. $I_{p,x}^{U}$ is used to express the generation of substance x in this stage.

Disposal/recycling stage: The main task of product disposal/recycling stage is dismantling scrapped products, which requires related equipment and tools. The environmental impact in this stage to a large extent is determined by using such tools and equipment. Generally the rated data of equipment and tools are used in estimating the environmental impact of the product at this stage. The generation of substance x is expressed as $I_{p,x}^{R}$.

In summary, it can be summarized that the generation of environmental impact substance x in the product life cycle, $I_{p,x}$ can be expressed as follows:

$$I_{p,x} = I_{p,x}^{D} + I_{p,x}^{A} + I_{p,x}^{M} + I_{p,x}^{U} + I_{p,x}^{R} + \sum_{i} I_{i,x} + \sum_{j} I_{j,x}$$

where, $\sum_i I_{i,x}$ refers to the sum of generation of substance x in the life cycle of all the parts; and $\sum_j I_{j,x}$ refers to the sum of generation of substance x in the life cycle of all the components.

D. A-Layer

The ESER evaluation has a wide range of applications, and the related users primarily includes the following classfications.

Personal users: The application can be divided according to the different stages which different employees are in. For example, the product designers can conduct energy consumption analysis to the components and materials with the resulting data of ESER, and select the material and components with low energy consumption. Technicians can conduct manufacturing process energy consumption analysis by using the process energy consumption data which will allow technicians to schedule process sequences with low ECEI data; manufacturing staff can conduct manufacturing energy consumption analysis with manufacturing energy consuming data to choose better manufacturing model; the equipment staff analyze the unit energy consumption of the equipment.

Enterprise users: Enterprise executives can conduct effective analysis on the energy-saving potential of the company, which can be divided into several kinds of application: department potential analysis, product potential analysis, enterprise standard analysis, process optimization analysis, and so on.

Government users: With the energy consumption data uploaded by enterprises, the government staff can conduct energy consumption analysis on both enterprises and areas, which help the government staff to set good ESER policies, optimize the structure of industry, improve the corresponding evaluation mechanism, and eliminate enterprises with high energy consumption.

The third-partusers: Divide the enterprise energy consumption quotas through the regional energy consumption analysis, and set the trading price of the quotas according to the regional energy consumption data.

IV. Prototype System

To conduct the effective ESER evaluation on the entire product life cycle, an ESER evaluation system is developed. In this system, the main research object is a turbine cylinder. Through the division of authority of persons using this system, person with different authority can manage different perception data.

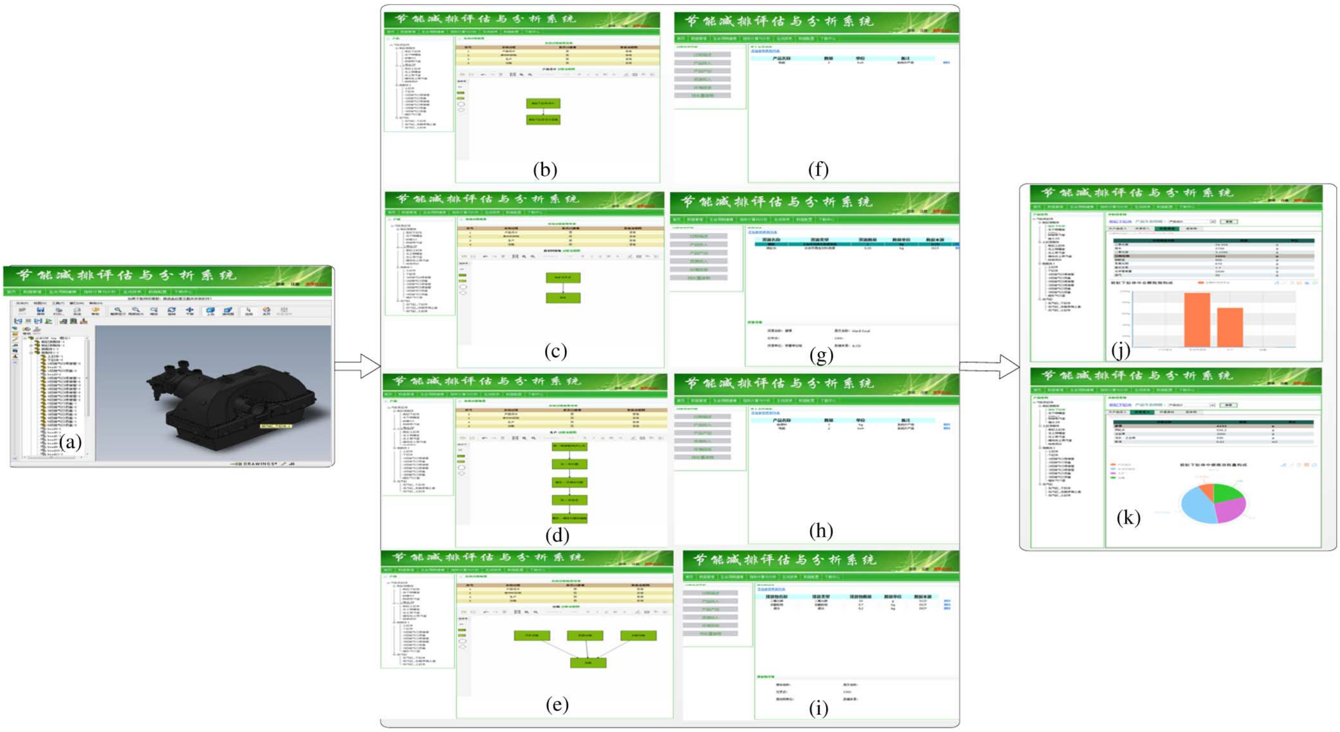

Fig. 7. ESER LCA of products based on IoT and BOM.

The detailed steps of ESER evaluation by using this system are illustrated as follows as shown in Fig. 7.

1) According to the product that requires evaluation, the enterprise fills in the corresponding product BOM data, then the 3-D product BOM structure can form as shown in Fig. 7(a).
2) According to the product design process of the LCA, the designers conduct design unit process modeling , as shown in Fig. 7(b).
3) After the unit process modeling in the design stage, the designers associate the related perception equipment used in this stage, and add some properties manually. The interface is shown in Fig. 7(c).
4) According to the substance obtain of the LCA, the procurement staffs pursue the material acquisition unit process modeling. The interface is as shown in Fig. 7(d).
5) After the material acquisition unit process modeling, the procurement staff associates the related perception equipment and manually add some properties, as shown in Fig. 7(e).
6) According to the manufacturing stage of the LCA, technicians pursue manufacturing unit process modeling as shown in Fig. 7(f).
7) After the manufacturing unit process modeling, technicians associate the related perception equipment used at all stages, and manually add some properties, as shown in Fig. 7(g).
8) According to the transportation process of the LCA, vehicle scheduling staffs pursue transportation unit process modeling. The interface is shown in Fig. 7(h).
9) After the transportation unit process modeling, the vehicle scheduling staffs associate the related perception equipment used at all stages, and manually add some properties. The interface is shown in Fig. 7(i).
10) Calculate the data of energy consumption and emissions at all stages in product life cycle, and achieve visual analysis of the evaluation results through the data visualization technology. The interface is as shown in Fig. 7(j) and (k).

TABLE I
Comparison Between the Proposed Method and Existing Methods and Tools

Feature / Name	Architecture	Data sources	Real time	Model	Multi level and multi-phase ESER Evaluation of product	Integration with existing enterprise information system
Gabi	C/S	Manual collection	N	LCA	N	Low
Simapro	C/S	Manual collection	N	LCA	N	Low
eBalance	C/S	Manual collection	N	LCA	N	Medium
The proposed method	B/S	Automatic collection	Y	LCA	Y	High

From the above case analysis, the proposed method, compared with the existing evaluation methods, has advantages as shown in Table I.

V. Conclusion and Future Work

How to manage and reduce the energy consumption and GHG emission in the entire process (including design, manufacture, transportation, sales, use, recycling) of a product is a big challenging problem faced by modern manufacturing industry. This study proposed a new method for ESER evaluation based on the BOM of a product and the new technology of IoT. In order to implement the proposed method, a four-layered structure (i.e., perception access layer, data layer, service layer, and application layer) ESER LCA system based on IoT and BOM is proposed, a prototype application system is developed to validate the proposed method.

The two contributions of the proposed method are as follows.

1) The IoT technologies are first used to realize the real-time, intelligent perception and collection of energy consumption and environmental impact data generated in the entire life cycle of a product, which is a very new application direction of IoT.
2) The concept of big BOM is proposed, which can facilitate the effective data integration and exchange between the ESER evaluation system and the existing enterprise information system, e.g., PDM, ERP, SCM, based on big BOM.

The proposed method can be further improved and used in many applications, such as enterprise information systems [52]–[54], data management and processing system [55], energy management and monitoring for public infrastructures and systems [56]–[58], IT devices and softwares [59]–[62], cloud manufacturing system [63]–[66], and so on.

However, the research of IoT and BOM-based ESER LCA of products is just beginning, and the relevant theories, technologies, and application are immature and require further research. In future, the following work will be emphasized: 1) IoT-based real-time and dynamic data collection and acquisition, and processing of energy consumption and environmental impact data; 2) establishment and management of multi-levels and multi-phases evaluation index; 3) BOM-based data modeling of the entire life cycle of product; 4) real-time processing, dynamic analysis and optimization, visualization of the evaluation results; 5) integration of the ESER system with the existing enterprise information systems; and 6) design, developing, and application of ESER comprehensive cloud service platform which can provide various required ESER services such as modeling service, evaluation service, simulation service, analysis service, optimization services, and others.

REFERENCES

[1] M. Z. Ma and X. Zhang, "Study on the benefit of energy conservation and emission reduction on life cycle assessment," *Environ. Eng.*, vol. 26, no. 1, pp. 88–89, 2008.

[2] T. Wiedmann, "Carbon footprint and input-output analysis-an introduction," *Econ. Syst. Res.*, vol. 21, no. 3, pp. 175–186, 2010.

[3] M. A. Cohena and M. P. Vandenbergh, "The potential role of carbon labeling in a green economy," *Energy Econ.*, vol. 34, no. 1, pp. S53–S63, 2012.

[4] J. Bebbington and C. Larrinaga-González, "Carbon trading: Accounting and reporting issues," *Eur. Accounting Rev.*, vol. 17, no. 4, pp. 697–717, Nov. 2008.

[5] G. Finnveden, M. Z. Hauschild, T. Ekvall *et al.*, "Recent developments in life cycle assessment," *J. Environ. Manage.*, vol. 91, no. 4, pp. 1–21, Aug. 2009.

[6] International Organization for Standardization, "Environmental management-life cycle assessment-principles and framework (ISO14040: 2006)," *European Committee for Standardization*, 2006.

[7] International Organization for Standardization, "Environmental management-life cycle assessment-requirements and guidelines (ISO14044:2006)," *European Committee for Standardization*, 2006.

[8] A. Azapagic, "Life cycle assessment and its application to process selection, design and optimisation," *Chem. Eng. J.*, vol. 73, no. 1, pp. 1–21, 1999.

[9] S. Joshi, "Product environmental life-cycle assessment using input-output techniques," *J. Ind. Ecol.*, vol. 3, no. 2, pp. 95–120, 1999.

[10] T. Hur, J. Lee, J. Ryu *et al.*, "Simplified LCA and matrix methods in identifying the environmental aspects of a product system," *J. Environ. Manage.*, vol. 75, no. 3, pp. 229–237, May 2005.

[11] X. Wang, D. Chen, and Z. Ren, "Assessment of climate change impact on residential building heating and cooling energy requirement in Australia," *Building Environ.*, vol. 45, no. 7, pp. 1663–1682, 2010.

[12] J. A. Assies, "A risk-based approach to life-cycle impact assessment," *J. Hazardous Mater.*, vol. 61, no. 1, pp. 23–29, Aug. 1998.

[13] F. De Angelis, M. Boaro, D. Fuselli *et al.*, "Optimal home energy management under dynamic electrical and thermal constraints," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 719–728, Aug. 2012.

[14] T. Strasser, F. Andrén, F. Lehfuss *et al.*, "Online reconfigurable control software for IEDs," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1455–1465, Aug. 2013.

[15] K. Akimoto, T. Tomoda, F. Yasumasa *et al.*, "Assessment of global warming mitigation options with integrated assessment model Dne21," *Energy Econ.*, vol. 26, no. 4, pp. 635–653, Jul. 2004.

[16] O. Ondemir, M. A. Ilgin, and S. M. Gupta, "Optimal end-of-life management in closed-loop supply chains using RFID and sensors," *IEEE Trans. Ind. Informat.*, vol. 8, no. 3, pp. 1518–1527, Aug. 2012.

[17] B. Zhao, H. Aydin, and D. Zhu, "On maximizing reliability of real-time embedded applications under hard energy constraint," *IEEE Trans. Ind. Informat.*, vol. 6, no. 3, pp. 316–328, Aug. 2010.

[18] H. Ma, K. W. Chan, and M. Liu, "An intelligent control scheme to support voltage of smart power systems," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1405–1414, Aug. 2013.

[19] M. D. Tabone and J. Cregg, "Sustainability metrics: Life cycle assessment and green design in polymers," *Environ. Sci. Technol.*, vol. 44, no. 21, pp. 8264–8269, 2010.

[20] J. Klemeš, I. Bulatov, and J. Koppejan, "Novel energy saving technologies evaluation tool," *Comput. Chem. Eng.*, vol. 33, no. 3, pp. 751–758, 2009.

[21] S. Ma and H.-C. Zhou, "Gas storage in porous metal–organic frameworks for clean energy applications," *Chem. Commun.*, vol. 46, no. 1, pp. 44–53, 2010.

[22] X. Hu, G. Li, and J. C. Yu, "Design, fabrication, and modification of nanostructured semiconductor materials for environmental and energy applications," *Langmuir*, vol. 26, no. 5, pp. 3031–3039, 2009.

[23] M. Margni, R. Charles, S. Humbert *et al.*, "Impact 2002+: A new life cycle impact assessment methodology," *Int. J. Life Cycle Assess.*, vol. 8, no. 6, pp. 324–330, 2003.

[24] M. A. Huijbregts and S. Hellweg, "Ecological footprint accounting in the life cycle assessment of products," *Ecol. Econ.*, vol. 64, no. 4, pp. 789–807, 2008.

[25] S. Boyd, A. Horvath, and D. Dornfeld, "Life-cycle assessment of NAND flash memory," *IEEE Trans. Semicond. Manuf.*, vol. 24, no. 1, pp. 117–124, Feb. 2011.

[26] F. Yao, Z. Y. Dong, K. Meng *et al.*, "Quantum-inspired particle swarm optimization for power system operations considering wind power uncertainty and carbon tax in Australia," *IEEE Trans. Ind. Informat.*, vol. 8, no. 4, pp. 880–888, Nov. 2012.

[27] F. Kennel, D. Gorges, and S. Liu, "Energy management for smart grids with electric vehicles based on hierarchical MPC," *IEEE Trans. Ind. Informat.*, vol. 9, no. 3, pp. 1528–1537, Aug. 2013.

[28] L. De Benedetto and J. Klemeš, "The environmental performance strategy map: An integrated Lca approach to support the strategic decision-making process," *J. Cleaner Prod.*, vol. 17, no. 10, pp. 900–906, 2009.

[29] G. Du and R. Karoumi, "Life cycle assessment of a railway bridge: Comparison of two superstructure designs, structure and infrastructure engineering: Maintenance, management," *Life-Cycle Des. Perform.*, vol. 9, no. 11, pp. 1149–1160, 2013.

[30] A. Rowe, K. Lakshmanan, H. Zhu, and R. Rajkumar, "Rate-harmonized scheduling and its applicability to energy management," *IEEE Trans. Ind. Informat.*, vol. 6, no. 3, pp. 265–275, Aug. 2010.

[31] R. Frischknecht, "LCI modelling approaches applied on recycling of materials in view of environmental sustainability, risk perception and eco-efficiency," *Int. J. Life Cycle Assess.*, vol. 15, no. 7, pp. 666–671, 2010.

[32] W. Su, H. Rahimi-Eichi, W. Zeng, and M. Y. Chow, "A survey on the electrification of transportation in a smart grid environment," *IEEE Trans. Ind. Informat.*, vol. 8, no. 1, pp. 1–10, Feb. 2012.

[33] F. Tao, D. Zhao, Y. Hu, and Z. Zhou, "Resource service composition and its optimal-selection based on particle swarm optimization in manufacturing grid system," *IEEE Trans. Ind. Informat.*, vol. 4, no. 4, pp. 315–327, Nov. 2008.

[34] L. Xu, W. He, and S. Li, "Internet of Things in industries: A survey," *IEEE Trans. Ind. Informat.*, doi: 10.1109/TII.2014.2300753.

[35] T. S. Lopez, D. C. Ranasinghe, and M. Harrison, “Adding sense to the internet of things: An architecture framework for smart object systems,” *Pers. Ubiquit. Comput.*, vol. 16, pp. 291–308, 2012.
[36] M. C. Domingo, “An overview of the Internet of things for people with disabilities,” *J. Netw. Comput. Appl.*, vol. 35, pp. 584–496, 2012.
[37] L. Li, “Technology designed to combat fakes in the global supply chain,” *Bus. Horiz.*, vol. 56, no. 2, pp. 167–177, 2013.
[38] L. Xu, “Information architecture for supply chain quality management,” *Int. J. Prod. Res.*, vol. 49, no. 1, pp. 183–198, 2011.
[39] S. Fang, L. Xu, H. Pei, and Y. Liu, “An integrated approach to snowmelt flood forecasting in water resource management,” *IEEE Trans. Ind. Informat.*, vol. 10, no. 1, pp. 548–558, 2014.
[40] Z. Pang, L. Zheng, J. Tian, S. Kao-Walter, E. Dubrova, and Q. Chen, “Design of a terminal solution for integration of in-home health care devices and services towards the Internet-of-Things,” *Enterp. Inf. Syst.,* 2014, doi: 10.1080/17517575.2013.776118.
[41] S. Li, L. Xu, X. Wang, and J. Wang, “Integration of hybrid wireless networks in cloud services oriented enterprise information systems,” *Enterp. Inf. Syst.*, vol. 6, no. 2, pp. 165–187, 2012.
[42] Q. Li, Z. Wang, W. Li, J. Li, C. Wang, and R. Du, “Applications integration in a hybrid cloud computing environment: Modelling and platform,” *Enterp. Inf. Syst.*, vol. 7, no. 3, pp. 237–271, 2013.
[43] L. Xu, “Enterprise systems: State-of-the-Art and future trends,” *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 630–640, Nov. 2011.
[44] L. Xu, “Introduction: Systems science in industrial sectors,” *Syst. Res. Behav. Sci.*, vol. 30, no. 3, pp. 211–213, 2013.
[45] Z. Bi, L. Xu, and C. Wang, “Internet of Things for enterprise systems of modern manufacturing,” *IEEE Trans. Ind. Informat.*, doi: 10.1109/TII.2014.2300338.
[46] Y. Fan, Y. Yin, L. Xu, Y. Zeng, and F. Wu, “IoT based smart rehabilitation system,” *IEEE Trans. Ind. Informat.*, doi: 10.1109/TII.2014.2302583.
[47] W. He, G. Yan, and L. Xu, “Developing vehicular data cloud services in the IoT environment,” *IEEE Trans. Ind. Informat.*, doi: 10.1109/TII.2014.2299233.
[48] L. Xu and W. Viriyasitavat, “A novel architecture for requirement-oriented participation decision in service workflows,” *IEEE Trans. Ind. Informat.*, doi: 10.1109/TII.2014.2301378.
[49] W. Viriyasitavat, L. Xu, and W. Viriyasitavat, “A new approach for compliance checking in service workflows,” *IEEE Trans. Ind. Informat.*, doi: 10.1109/TII.2014.2301143.
[50] W. Viriyasitavat, L. Xu, and W. Viriyasitavat, “Compliance checking for requirement-oriented service workflow interoperations,” *IEEE Trans. Ind. Informat.*, doi: 10.1109/TII.2014.2301132.
[51] J. Cooper and A. James, “Challenges for database management in the Internet of things,” *IETE Tech. Rev.*, vol. 26, no. 5, pp. 320–329, 2009.
[52] M. Kataev, L. Bulysheva, A. Emelyanenko, and V. Emelyanenko, “Enterprise systems in Russia: 1992–2012,” *Enterp. Inf. Syst.*, vol. 7, no. 2, pp. 169–186, 2013.
[53] F. Wang, B. Ge, L. Zhang, Y. Chen, Y. Xin, and X. Li, “A system framework of security management in enterprise systems,” *Syst. Res. Behav. Sci.*, vol. 30, no. 3, pp. 287–299, 2013.
[54] X. Chen and Y. Fang, “Enterprise systems in financial sector-an application in precious metal trading forecasting,” *Enterp. Inf. Syst.*, vol. 7, no. 4, pp. 558–568, 2013.
[55] X. Wang and X. Xu, “DIMP: An interoperable solution for software integration and product data exchange,” *Enterp. Inf. Syst.*, vol. 6, no. 3, pp. 291–314, 2012.
[56] B. M. Wilamowski and O. Kaynak, “Oil well diagnosis by sensing terminal characteristics of the induction motor,” *IEEE Trans. Ind. Electron.*, vol. 47, no. 5, pp. 1100–1107, Oct. 2000.
[57] C. Le, X. Gu, K. Pan, F. Dai, and G. Qi, “Public and expert collaborative evaluation model and algorithm for enterprise knowledge,” *Enterp. Inf. Syst.*, vol. 7, no. 3, pp. 375–393, 2013.
[58] X. Chen, A. Guan, X. Qiu, H. Huang, J. Liu, and H. Duan, “Data configuration in railway signaling engineering-an application of enterprise systems techniques,” *Enterp. Inf. Syst.*, vol. 7, no. 3, pp. 354–374, 2013.
[59] F. Tao, D. Zhao, and L. Zhang, “Resource service optimal-selection based on intuitionistic fuzzy set and non-functionality QoS in manufacturing grid system,” *Knowl. Inf. Syst.*, vol. 25, no. 1, pp. 185–208, 2010.
[60] W. Tan, W. Xu, F. Yang, L. Xu, and C. Jiang, “A framework for service enterprise workflow simulation with multi-agents cooperation,” *Enterp. Inf. Syst.*, vol. 7, no. 4, pp. 523–542, 2013.
[61] H. Yu, T. Xie, S. Paszczynski, and B. Wilamowski, “Advantages of radial basis function networks for dynamic system design,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 12, pp. 5438–5450, Dec. 2011.
[62] F. Tao, L. Zhang, K. Lu, and D. Zhao, “Research on manufacturing grid resource service optimal-selection and composition framework,” *Enterp. Inf. Syst.*, vol. 6, no. 2, pp. 237–264, 2012.
[63] F. Tao, L. Zhang, V. C. Venkatesh *et al.*, “Cloud manufacturing: A computing and service-oriented manufacturing model,” *J. Eng. Manuf.*, vol. 225, no. 10, pp. 1969–1976, 2011.
[64] F. Tao, Y. J. Laili, L. Xu, and L. Zhang, “FC-PACO-RM: A parallel method for service composition optimal-selection in cloud manufacturing system,” *IEEE Trans. Ind. Informat.*, vol. 9, no. 4, pp. 2023–2033, Dec. 2013.
[65] F. Tao, Y. Zuo, L. D. Xu, and L. Zhang, “IoT-based intelligent perception and access of manufacturing resource toward cloud manufacturing,” *IEEE Trans. Ind. Informat.*, 2014, doi: 10.1109/TII.2014.2306397.
[66] F. Tao, Y. Cheng, L. Xu, L. Zhang, and B. H. Li, “CCIoT-CMfg: cloud computing and Internet of things-based cloud manufacturing service system,” *IEEE Trans. Ind. Informat.*, 2014, doi: 10.1109/TII.2014.2306383.

Fei Tao (M’13), photograph and biography not available at the time of publication.

Ying Zuo, photograph and biography not available at the time of publication.

Li Da Xu (M’86–SM’11), photograph and biography not available at the time of publication.

Lin Lv, photograph and biography not available at the time of publication.

Lin Zhang (S’05–M’06–SM’13), photograph and biography not available at the time of publication.