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A semantic model for enterprise application integration in the era of data explosion and globalisation

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ABSTRACT
This paper presents a model for Enterprise Application Integration (EAI) in the modern era of data explosion and globalisation. Application here refers to software, which is in essence data system, and data refers to both information and knowledge (data serves as a vehicle for information as well as knowledge). The salient features of the model are: (1) separation of business functions from applications and enterprises, (2) three-layer architecture of the model (conceptual or semantic level, external or application level, internal or realisation level), and (3) integration of structured, semi-structured and non-structured data. To our best knowledge, the existing model or solution to EAI does not hold all the three features. A case study is presented to illustrate how the model works. The model can be used by an individual enterprise or a group of enterprises that form a network, e.g., a holistic supply chain network.

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1. Introduction

Demands on today's manufacturing can be characterised by (1) rapid response, (2) mass customisation, (3) mass personalisation (Baranauskas 2019; Zhao et al. 2017, 2017), (4) integrated life-cycle support (Adeyemi, Ogbeyemi, and Zhang 2021; Bi et al. 2020; Zhang, Wang, and Lin 2019; 2011), (5) resilience and sustainability (Bi et al. 2020; Wang et al. 2020). These demands result in the concept of virtual enterprise (VE) organisation along with global manufacturing (Chu et al. 2002; Zhang, Liu, and Van Luttervelt 1997). The VE concept means that a company should keep its core competences while outsourcing others (Zhang, Liu, and Van Luttervelt 1997). Consequently, manufacturing firms have been evolving into several small ones; each of them has its own competence but is connected to each other, forming network structures of manufacturing-service systems (Wang et al. 2018; Wang et al., 2014a, 2013). A business arises when one firm discovers an opportunity of a new product, a set of 'small' firms then form into an alliance to provide their

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manufacturing facilities to one or more facets of the total product development (Zhang, Liu, and Van Luttervelt 1997). The global manufacturing extends the VE such that collaborative firms in a VE system can be distributed over different countries and regions.

The main advantage of such a global VE system is the agility of manufacturing with the VE concept (Zhang, Liu, and Van Luttervelt 1997). However, the main disadvantage with the VE concept is its poor reliability, robustness, and resilience (Zhang and Luttervelt 2011; Zhang and Lin 2010), as each entity in a network has its own managerial power and may take care of more its own interest, and therefore is difficult to form a reliable network (Pego-Guerra, Zhang, and Ip 2010; Pego Guerra and Zhang 2001). To overcome this shortcoming, some regulations and protocols have been developed internationally, which are imposed on a VE network, e.g., the concept of the world trade organisation. There are also other constraints on a global VE resulting from the differences in culture, religion, ideology, and political system among a group of firms in a VE. In other words, a VE toady may need to run yet subjected to an ever-increasing number of constraints, which may be called constrained globalisation. In fact, the VE is a generic concept behind any global network manufacturing system, including various types of supply chain systems (Wang et al. 2018).

With the advancement of digital technology, information technology has been widely employed to the life cycle management of VE enterprises (Zhang, Wang, and Lin 2019), making the data management as an important tool for the VE management. In this connection, many software systems (i.e., enterprise applications) are developed to facilitate data management. Examples of these software systems are Enterprise Resource Planning (ERP) (Katuu 2020; Zach, Munkvold, and Olsen 2014), Supply Chain Management (SCM) (Daneshvar Kakhki and Gargeya 2019) and big data analytics (Hopkins and Hawking 2018; Rajaraman 2016; Salama, Kader, and Abdelwahab 2021). Each of these software systems may have several producers. For example, there are at least more than five ERP software systems in the technical software business market, and there are about dozens of tools for big data modelling (Khanra, Dhir, and Mäntymäki 2020; Guru99, n.d.). The advanced digital technology also leads to several situations, namely (1) big data, (2) cloud computing (Chen 2017; Lenzerini, Salaria, and Roma 2014; Aceto, Persico, and Pescapé 2020), and (3) deep machine learning (Zhang et al. 2018).

On one hand, digital technology has brought benefits to the global VE, but on the other hand, it creates some challenges to a VE system. One of the most important challenges is the integration of data, which could be structured data, semi-structured data, and unstructured data (Zhao, Xie, and Zhang 2002; Liu et al. 2008). In the manufacturing business world, this integration is also called enterprise application integration (EAI) (Liu et al. 2008), where the term 'application' in EAI is meant for the information and knowledge system or data system (or software system). The features of data exploration and constrained globalisation call for a new solution for EAI.

This paper presents a new approach to EAI in the era of data explosion and globalisation, a new model for EAI in this case. The salient features with this model are: (1) separation of business functions from enterprises and applications or data systems, (2) three-layer architecture of the model (conceptual or semantic level, external or application level, internal or realisation level), and (3) integration of structured, semi-structured and unstructured data. To our best knowledge, the existing model or solution for EAI does not hold all the three features.

In the remaining part of the paper, Section 2 will present a literature review to justify the need of developing a new model for EAI. Section 3 presents the new model. In Section 4, a case study is presented to demonstrate how the new model works. Section 5 is a conclusion along with a further discussion of the benefits with the new model for EAI.

2. Related work

The modern era of data explosion and globalisation has several important features on manufacturing as well as service systems and their combination, see the definition of these systems in (Wang et al., 2014a). The **first feature** is that the data representation has a mixture of formats, including structured, semi-structured and unstructured ones. A structured data or data represented in a structured format that the semantic of data can be understood by computers. The format of data expression by humans in their natural way is unstructured with respect to computers, that is, computers cannot understand the unstructured data if no 'translator' is available. Any format between the structured and unstructured data is semi-structured data in a format, e.g., XML, HTML,[1] etc. The **second feature** is that the amount of data is huge, uncertain,[2] and volatile, and data creation rate is high, which refers to the so-called big data (Singh 2019; Wigan and Clarke 2013). It is noted that big data usually takes an unstructured data format. The **third feature** is the emerging of the concept of cloud computing (Langmead and Nellore 2018; Rajaraman 2014). The **fourth feature** is that not only data of manufacturing and service systems but also data of politic and economic policies play a role in decision making with manufacturers or service providers. This is the reason that globalisation is today highly constrained.

To integrate unstructured data from manufacturing and service systems, Kassner and Mitschang (2015) developed a decision support system architecture that enables data integration in real-time. The architecture takes factory factors and human factors into consideration and identifies exceptions from unstructured data. The authors also pointed out that the integration of structured and unstructured data is more difficult than unstructured data alone due to extra pre-processing required. To address this issue, Kassner et al. (2015) proposed a product life cycle analytics approach for the holistic integration and analysis of unstructured and structured data from multiple data sources around the product life cycle. Through their own benchmarking, they claimed that the approach is a dichotomy between case-based implementations with more advanced analytics and general frameworks with limited or no analytics. As a step forwards data correctness, Blum and Schuh (2017) proposed a real-time reference system architecture for production order processing. This architecture integrates structured and unstructured data and apply countermeasures to improve data quality, for example, to reschedule operations. The architecture also contains a visualisation layer to reduce data complexity and support the user in the decision process.

In a complex manufacturing environment, data volume is growing exponentially. A conceptual framework of big-data integration was proposed by Tao et al. (2018) for smart manufacturing. The authors also pointed out a few implementation limitations that include data collection, data transmission bandwidth, and cyber data integration. Considering cleaner production, Zhang et al. (2017) developed a big-data-based analytics system architecture for product life cycle management. The architecture can be used to percept and collect real-time and multi-source big-data, and then process and exchange them in real-time between heterogeneous enterprise information systems. Cloud computing is often studied together with big data. For example, an integration process was proposed by Xiang et al. (2018), which starts from an internal equipment-cell-shop-plant-enterprise system to an external cloud. The process considers different product life cycle scenarios, from physical centralisation one to logic centralisation one. It uses different data integration methods to facilitate the interconnection and interoperability between cyberspace and physical space. Wang et al. (2019) developed a fog-computing based big data integration approach to achieve high raw data security and low network traffic loads. The approach moves the integration task from the cloud to the edge of networks and splits the task into several sub-tasks run by multiple data generators.

Although technologies such as big data and cloud computing enable global manufacturing and distributed manufacturing sites, system efficiency can be affected by policies and regulations. Ferracane et al. (2020) provided a robust and significant explanation of how the costs of data regulation affect downstream industries in an economy. The paper was claimed to be the first work that attempts to analyse this connection econometrically by setting up a proxy index to measure how restrictive a data regulation is. The same group of researchers (Ferracane, Kren, and van der Marel 2020) also analysed econometrically the extent to which these data regulations over time impact the productivity performance of downstream manufacturing and service systems. They found that stricter data policies have a negative and significant impact on the performance of downstream systems reliant on data. This adverse effect is stronger for countries with stronger technology networks, especially for service-based systems. These studies help to propose the *constrained globalisation concept*, which is first coined in the present paper.

It may be clear from the above discussion that the current literature has not addressed the enterprise integration issue in the new era with the feature of data explosion and constrained globalisation. Yet, the issue of the integration of structured and non-structured data has been addressed without any connection to the semantics of enterprises and enterprise applications. To close these knowledge gaps was the motivation of the present paper. The next section presents an approach to EAI in this new era.

3. The proposed approach to EAI

The proposed approach to EAI is a new data model, which is coined enterprise semantic model (**ESM**) for the convenience of the following discussions. The ESM is built upon three ideas. The **first idea** is design thinking (Zhang and Wang 2016); that is, a complete enterprise is ready for change, and its formation is the result of design – selection of partners in particular (Chu et al. 2002). As such, the model needs to capture the business function along with the enterprise, which may be called function-structure modelling in

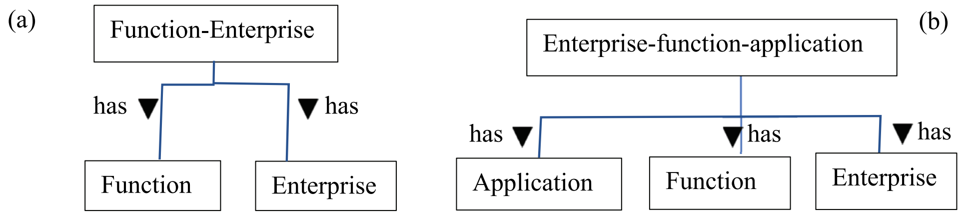

Figure 1. Data modelling of business function (or function), enterprise and enterprise application (or application). (a) the model for function and enterprise, (b) the model for function, enterprise, and application.

the field of product design (Lin and Zhang 2004; Zhang, Lin, and Shihn 2005), but now the enterprise being a product. Further, the modelling strategy goes along with three entities: (business) function, enterprise, and function-enterprise (Figure 1(a)). Here, the function-enterprise relation is a many-to-many relation. It is also worth mentioning that the earliest proposal of introducing the design thinking to the VE manufacturing or servicing may be referred to (Zhang 1996; Zhang, Liu, and Van Luttervelt 1997; Deng and Zhang 1997). The function-structure (function-enterprise in the case here) modelling can be viewed as the first level of integration of different enterprise applications or applications for short, at which different enterprises along with applications are integrated based on their functions. Separating the (business) function and enterprise will allow for ease with changes of a VE system, e.g., reconfiguration of a VE system to create functions to replace lost functions (i.e., enhancing resilience) (Zhang and Luttervelt 2011; Zhang and Lin 2010; Wang et al. 2020).

The **second idea** is that the application is separately modelled from the enterprise. As such, the application, enterprise, and function form a ternary relation (Figure 1(b)). This ternary relation means that dependency among the three entities cannot be replaced by three pair relations (i.e., function-application, function-enterprise, and enterprise-application) (Ma et al. 2001; Ma, Zhang, and Mili 2002; Ma, Zhang, and Ma 2003). The model based on this idea will allow for ease with

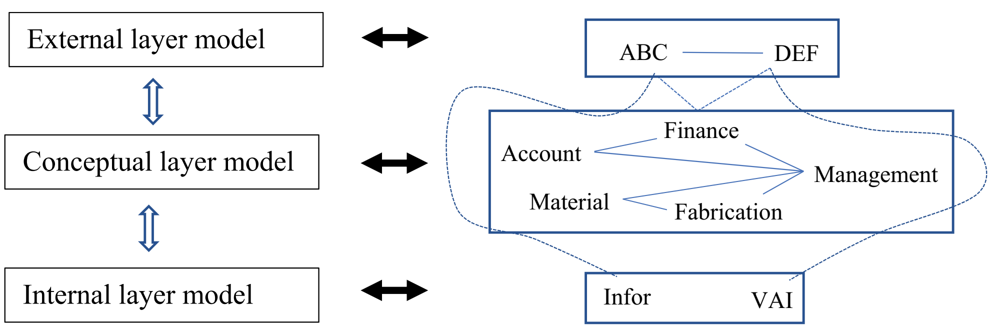

Figure 2. The three-layer architecture of the enterprise semantic model (ESM). The middle layer is the conceptual layer model which captures a particular domain of a VE system; the top layer is the external layer concerning specific enterprises (ABC, DEF, etc.); the internal layer refers to the representation of applications (Infor, VAI, etc.).

changes of a VE system, i.e., changes in enterprise applications and/or business functions and/or enterprises, to improve its performance as well as its resilience (Zhang and Lin 2010).

The ***third* idea** is a three-layer architecture of data models for a VE system, that is, a conceptual layer, an external layer, and an internal layer (Figure 2), which is inspired from the SPARC database architecture (Date 1986). The *conceptual layer* model for a VE system represents basic concepts and their relationships, which is also called a domain model or ontology model (Wang et al. 2013). The *external layer* model represents a specific enterprise in a VE system. The *internal layer* model represents specific (enterprise) applications along with their data models. To a given VE system, e.g., a holistic supply chain network system (Wang et al. 2016; Wang et al. 2018), or one specific member system in a VE, the conceptual layer model captures the ontology of the system, which mainly contains generic business functions and generic enterprises, along with (enterprise) applications. The external layer model represents a specific business function, enterprise, and application, and it can be viewed as a specialisation and a specific facet of the conceptual layer model. The internal layer model represents a specific application data model[3] (e.g., an application relational data model for structured data, an application graph-based data model for semi-structured data).

Remark 1: In developing a conceptual model for a modern enterprise, a hierarchical structure is used for the model. For example, for a steel product enterprise, a conceptual model is further divided into three layers, namely enterprise layer (bottom layer), process enterprise (middle layer), and steel enterprise (top layer).

Remark 2: There are three types of substances to any manufacturing system, namely (i) material, (ii) energy, and (iii) signal or data (Zhang, Wang, and Lin 2019). In the era of data explosion and constrained globalisation, location or region or country needs to be specified for each of these substances, as constraints may be applied on them in a global manufacturing.

Remark 3: To understand data, the computer needs a language, just as the human does. Such a language is called **data model**, e.g., relational data model (Codd 1983), object-oriented data model (Kim 1990), etc. Data models consist of key words or concepts and rules or grammars imposed on key words. In the following, 'key words' and 'concepts' are interchangeable. For instance, in the relational data model, examples of the key word are 'Table', 'Primary Key', etc., and in the object-oriented data model, examples of the word are 'Class', 'Attribute', etc. A rule is applied onto these key words or concepts. An example of the rule in the relational data model is: 'the domain of a primary key in Table A must cover the domain of a primary key in Table B.' In this paper, an object-oriented data model is used, and further a particular system called **UML** (Universal Modelling Language) is used for data modelling. In UML, there are two basic rules: 'has-a' and 'is-a', and their graphical representation is shown in (Figure 3(a)). Further, there are two kinds of key words or concepts: one that belongs to a data model, e.g., 'Table' in the relational model, and the other that belongs to application problems, e.g., 'Enterprise' in manufacturing systems. Applying a particular data model to a particular application produces an **application data model**. For instance, 'Table: Enterprise' means that 'enterprise is defined as the table type of data', where 'Table: X' is a rule or grammar available in a particular application data model. Data modelling is in its very nature is to use a data model to represent the meaning of real-world objects (Zhang and Werff Van Der 1993b; Zhang 1994).

Remark 4: In the computer language, there are three basic tools for the semantics of data in the human world, namely type, class, and instance. A **type** defines the structure of many different classes that but share the same structure, and a **class** has many different instances that but have the same set of attributes. In other words, a type can produce many classes and a class can produce many instances (Figure 3(b)). An interesting analogy can be made as this: Type corresponds to Domain in mathematics, Class corresponds to Variable in mathematics, and Instance corresponds to Value in mathematics. The format of data in the human world, expressed with the type-class-instance method, is called structured data (Figure 3(d-e)). Clearly, it is not natural for humans to express the meaning of data (Figure 3(c)) with this type-class-instance method. Instead, humans prefer to express the meaning of data with words and grammars on words in a particular language along with its grammar. The data management system for unstructured data is a set of algorithms or methods for extracting information and knowledge from unstructured data (Zhao et al. 2018) and further for representing them into structured data.

Remark 5: Due to the presence of big data, to each piece of data, one needs to specify its storage (cloud, local device) and format (structured based on a particular data model, semi-structured based on a particular data model, e.g., XML, and unstructured data managed with a particular data processor or analytics). It is noted that a cloud has a location according to Remark 2 and the location of data is important in the era of the constrained globalisation (as discussed before).

4. Case study

In this paper we take a company called ABC as an example to illustrate the above methodology and concept. It is noted that under the concept of VE, the proposed approach (or ESM) to enterprise application integration is applicable to both a single

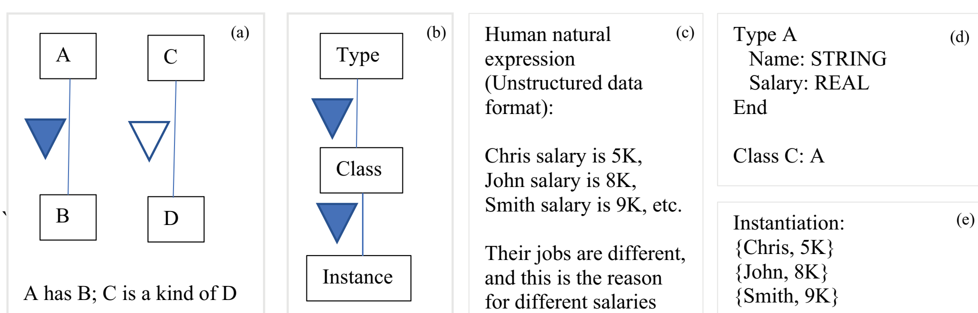

Figure 3. Several basic concepts of data modelling. (a) definition of 'has a' and 'is a'; (b) mechanism of type-class-instance; (c) unstructured data; (d) definition of an application data model; (e) writing or instantiation of real-world data with the application data model.

company and a group of companies, because a department of a company say A may be replaced by another company say B. In the latter case, the companies work together under different managerial frameworks and even different political regimes, societies in a global manufacturing era (Zhang 1996; Zhang, Liu, and Van Luttervelt 1997).

4.1 Overview of the case company (ABC)

ABC's sole line of business is steel making and fabricating, and its core business includes tubular products and flat-rolled alloy steels. The main facility of ABC is the electric arc furnace. The major raw material used in ABC is ferrous scrap, which is purchased from a network of scrap dealers. ABC is one the largest consumers of electricity in the province. In addition, ABC consumes up to 46 million imperial gallons of water daily, chiefly as a process coolant. The water is constantly re-treated, purified, and then recycled. At the time this study was performed, ABC had the following enterprise applications or information systems: SAPTM ERP and DLGLTM systems for accounting and human resources management; SDCTM system for maintenance scheduling; PreactorTM for production scheduling; AutoCADTM R12 for engineering; OutboundTM for shipping; KinectricsTM for quality management; and SimensTM and UniversalTM for process control.

4.2 Overview of the ESM for ABC

The enterprise semantic model (**ESM)** as defined above is applied to ABC. Figure 4 is the ESM for the production process of ABC. The information surrounding each process is sent to various departments in the order from charging, melting, casting, transportation, and finishing (Figure 4). Figure 5 presents the ESM for the manufacturing equipment. It is noted that the models of Figure 4 and Figure 5 correspond to the external layer model of Figure 2.

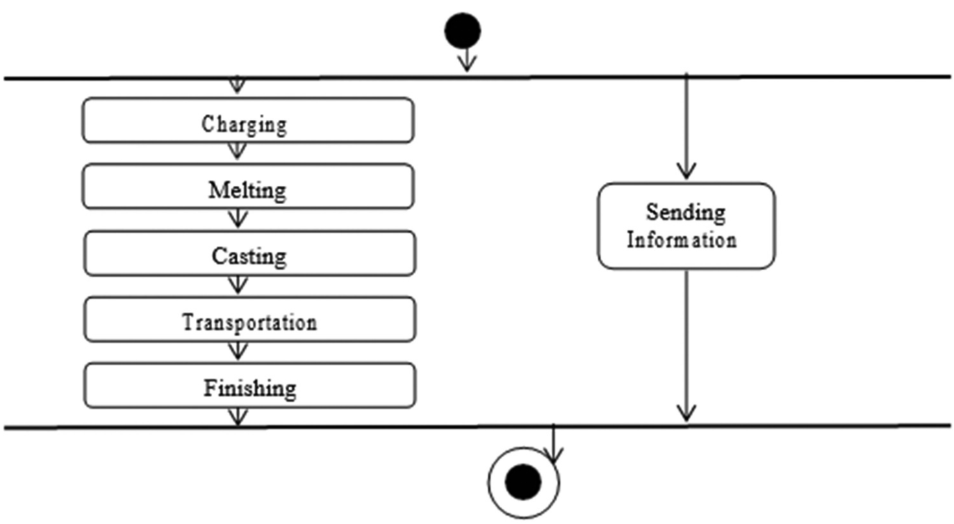

Figure 4. ESM for manufacturing.

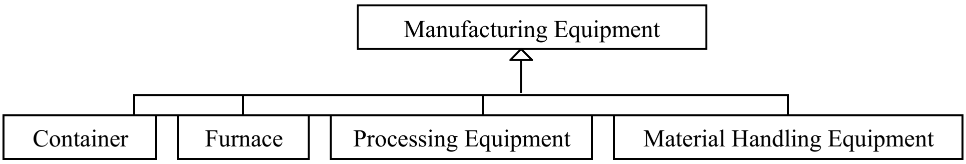

Figure 5. ESM for manufacturing equipment.

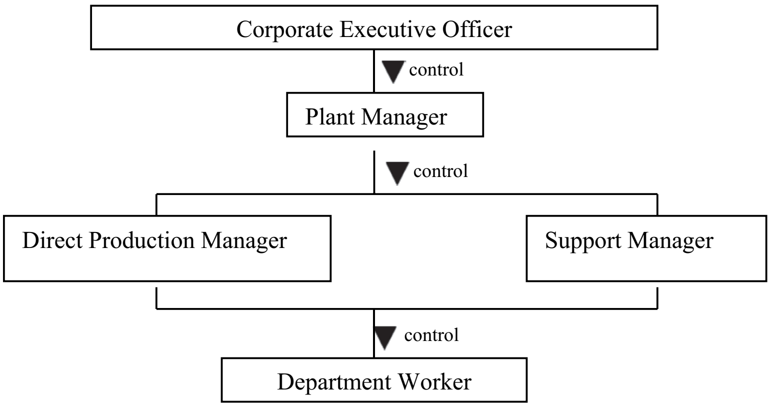

Figure 6. ESM for the organisation structure.

In Figure 6, the ESM for the organisation structure of ABC is presented, which depicts that the corporate executive officer controls the plant manager, who in turn controls the direct production manager and support manager, and these managers control their respective department workers. The ESM of a particular supplier's information, the quality information of raw materials is modelled in Figure 7. It is noted that various types of quality information are to be considered when buying raw materials from supplier, which include the property of raw materials and

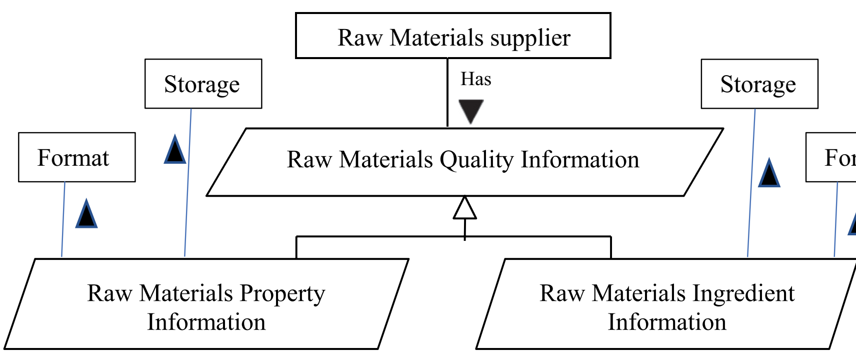

Figure 7. ESM for supplier's information. The storage and format are referred to remark 4 in Section 2 before. The parallelogram diagram refers to the information that is either semi-structured data or unstructured data.

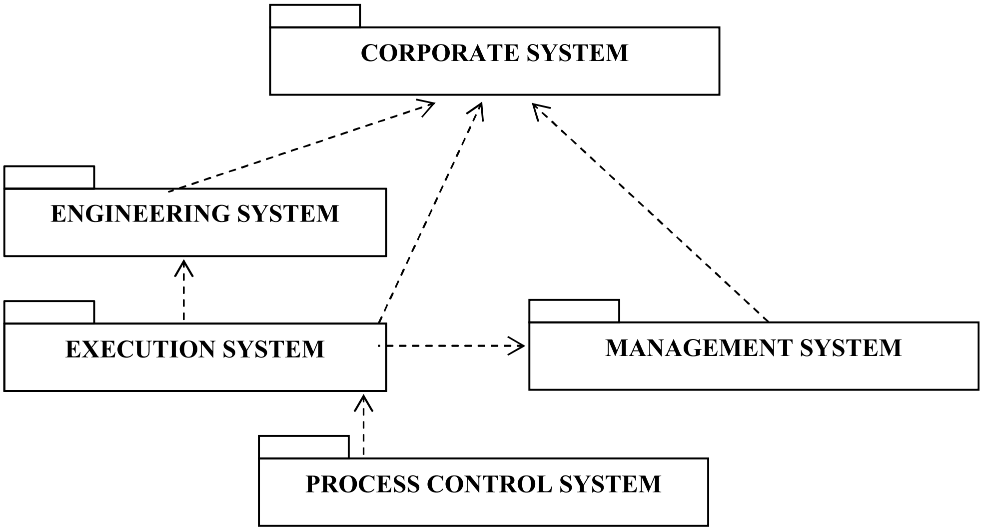

Figure 8. ESM for applications or information systems- functional view.

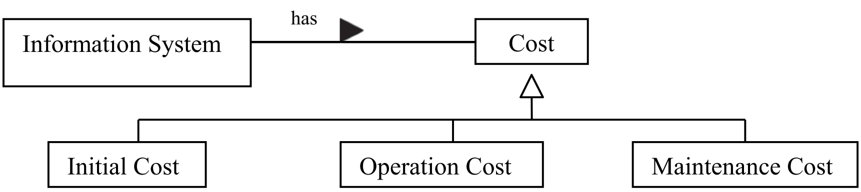

Figure 9. ESM for the information systems – cost.

ingredient of raw materials. Finally, the ESM for the functional view of information systems of ABC is modelled in Figure 8. It is noted that the models of Figure 6 to Figure 8 correspond to the conceptual layer model of Figure 2.

It is noted that there is no model for the enterprise-function relationship (see Figure 1), because this case study only concerns one firm in a VE rather than a VE. In the following, the model for (enterprise) applications is presented.[4] An enterprise application has cost, e.g., the cost for initial installation and the cost for operation and maintenance, the ESM of which is shown in Figure 9. Figure 10 is the ESM for the software interface of enterprise information systems, such as graphical user interface and non-graphical user interface. The models of Figure 9 to Figure 10 correspond to the conceptual layer model of Figure 2. The ESM for the enterprise information system or enterprise application is directed to Supplemental Material of the paper.

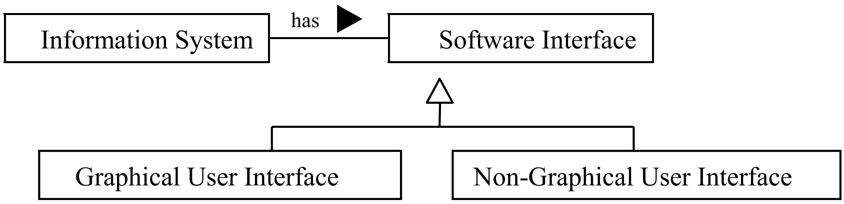

Figure 10. ESM for the information systems – software interface.

4.3 Instantiation of the enterprise semantic model for ABC

The ESM for both the functions and information systems of ABC is developed by instantiating the ESM developed in Section 4.2. In this section, the ESM for the functional aspects of ABC, such as the manufacturing business process, equipment resources, organisation structure and supplier information, is modelled. **First**, the ESM for the manufacturing business process of ABC is modelled in Figure 11 by instantiating the ESM of Figure 4. The charging includes the bucket makeup and furnace charging. The melting includes melting in the electric arc furnace, refining, tapping into ladle, adding alloy and de-sulphurizing agents, and slag removal. The casting includes casting in the continuous slab caster and the transportation includes the slab transportation by over-head crane. The finishing includes re-heating, rolling in 2-hi slabbing mill, shearing in shearing mill, finishing in 4-hi rolling mill, and cooling in cooling bed. The class 'sending information' in Figure 4 is instantiated by the information including information to engineering, HRD, R&D, finance, and maintenance departments. By modelling all the activities shown in Figure 11 as classes, and then they are instantiated, based on the concept of 'instance-as-type' (Li, Zhang, and Tso 2000). For example, 'slag removal', which is an instance in Figure 11, can be viewed as a class, and 'exact slag removal' is an instance of the class 'slag removal.

Second, the ESM for the manufacturing equipment of ABC is modelled in Figure 12 by instantiating the ESM of Figure 5. Container includes ladle and bucket; furnace includes electric arc furnace, walking beam furnace, slab re-heat furnace, and ladle metallurgy furnace; processing equipment includes rolling mill, shearing mill, leveller, continuous slab caster, cooling bed, up-coiler, slabbing mill, and finishing mill; and the material handling system includes transfer cars and over- head cranes. The classes shown in Figure 12 can be further instantiated. For example, the class electric arc furnace can be instantiated to an object, **Fuchs**TM, the exact electric arc type of furnace used in ABC.

Third, the ESM for the organisation structure of ABC is modelled in Figure 13 by instantiating the ESM of Figure 6. Direct production manager has the managers for purchasing, design, sales, manufacturing, inventory, and workflow; support manager has managers for finance, HRD, CRM, R&D, information systems, maintenance, quality control, safety control, shareholder relations, and environmental affairs; and department worker includes department supervisors and department laymen. The 'sales manager' in Figure 13 can be a class on its own sake with the attributes like 'name' of the sales manager.

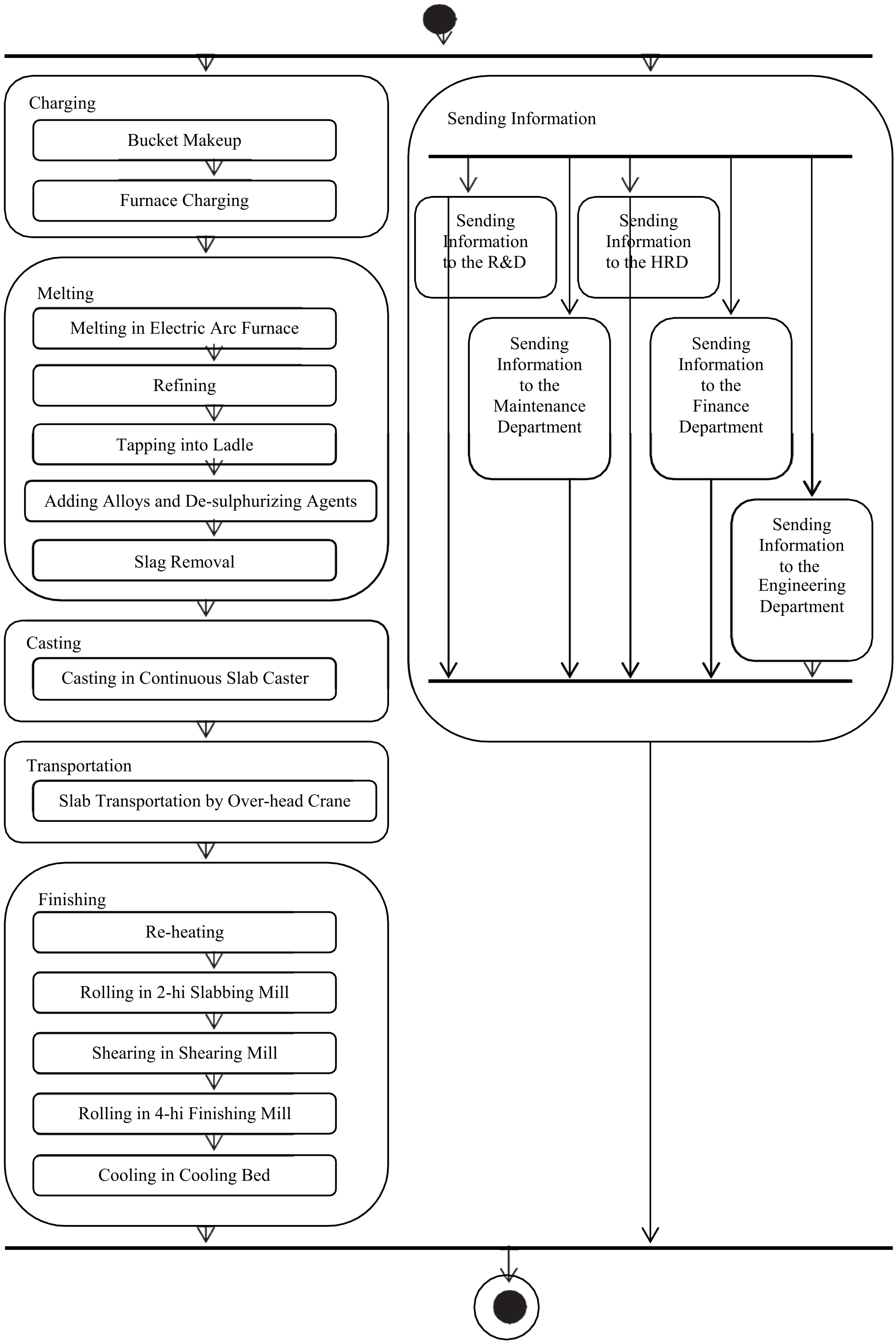

Figure 11. ESM for the ABC's business process- manufacturing.

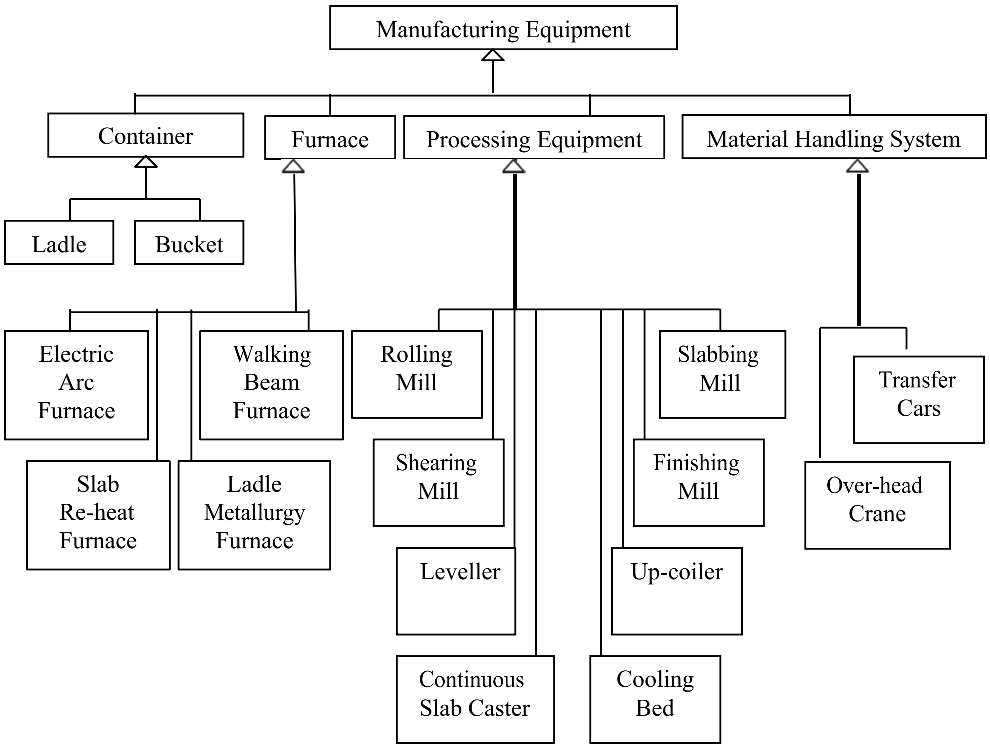

Figure 12. ESM for the ABC resource – manufacturing equipment.

Fourth, the ESM for the supplier information of ABC is modelled in Figure 14 by instantiating the ESM of Figure 7. Raw materials property information includes heat property, specific gravity, reactivity, and solubility information; and raw materials ingredient information includes mineralogical, chemical content, and hazardous ingredients information. The specific gravity information can be further instantiated to the instance 'exact specific gravity' of the raw material used in ABC.

4.4 The ESM for the ABC's information system

The ESM for the information system of ABC represents the functional view, cost, software interface, hardware interface, operating system, database management system, and producer's information of an application. The ESM for the functional view of ABC information systems is shown in Figure 15 by instantiating the ESM of Figure 8. The corporate system includes the finance and accounting systems and human resource systems. The engineering system includes CAD systems. The management system includes the order entry and shipping systems. The execution system includes maintenance scheduling, production scheduling, raw materials and finished products tracking, and quality management systems. The process control system includes supervision, packaging/handling, powerhouse, warehouse, and data acquisition systems also PLCs (Programmable

Logic Controllers) and other controllers. The instance 'CAD' in the model of Figure 15 can be further instantiated to an object '**AutoCAD**TM **R12'**, which is a particular CAD system used in the ABC.

The ESM for the cost of ABC information systems is modelled in Figure 16, by instantiating the ESM template shown in Figure 9. Initial cost includes process control information system, ERP, CRM, logistics, e-commerce, engineering, quality management, production scheduling systems and database cost; operation cost includes technical support and processing cost; and maintenance cost includes perfective cost, corrective cost, and adaptive cost. The instance 'ERP' (Enterprise Resource Planning) cost can be further instantiated to an object, the exact cost of SAPTM, the ERP system used in ABC.

The ESM for the software interface of ABC information systems is modelled in Figure 17 by instantiating the ESM of Figure 10. ERP system interface includes graphical and non-graphical user interface. Graphical user interface includes user interface; and non-graphical interface includes application program interface (API). The instance 'application program interface' (API) can be further instantiated to an

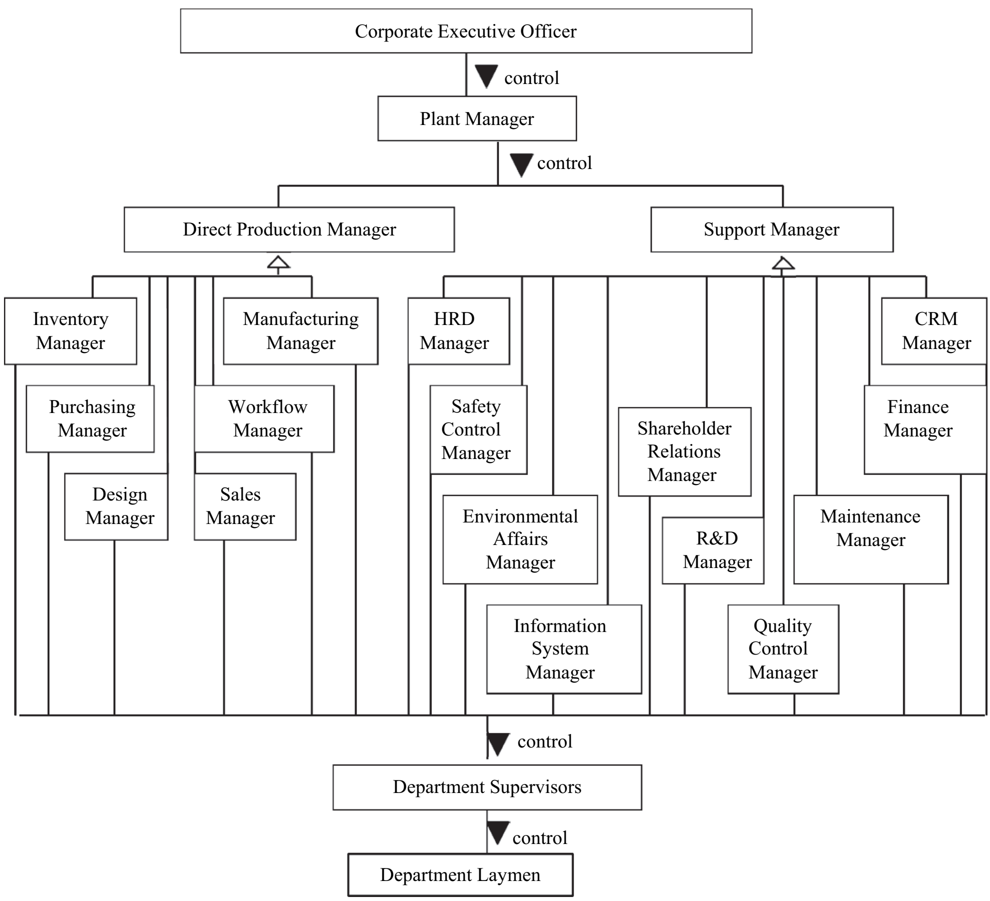

Figure 13. ESM for the organisation structure of ABC.

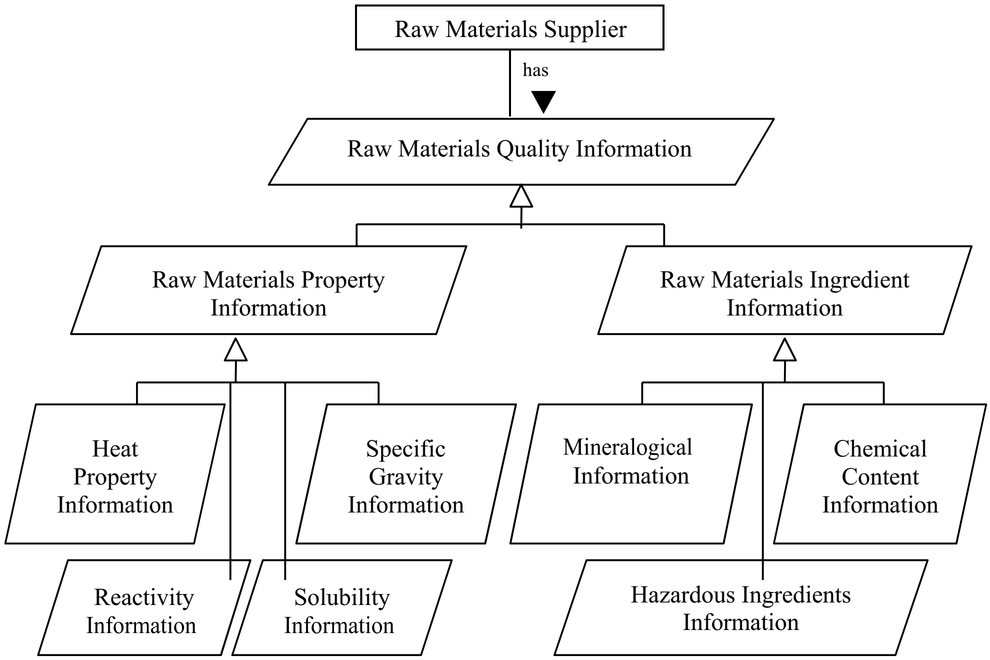

Figure 14. ESM for the supplier information of ABC.

object, SAPTM Netweaver API, the exact API used by the SAPTM- ERP system in ABC. The specific ESM for the enterprise information systems, e.g., hardware interface, etc. for the ABC company is directed to the supplemental material.

4.5 Applications of the ESM for ABC

An example will be discussed in the following to illustrate the usefulness of the ESM. In a situation where ABC wants to purchase a new CAD (Computer Aided Design) system, e.g., SolidWorks. To make this decision, the decision maker needs to know if a new CAD system will cause a communication problem with the existing information systems in ABC. Also, if there is a correlation between the functions performed by this new CAD system and the existing system in ABC. Also, if ABC has the required resources and organisation structure to operate this new CAD system to its full functionality and finally if it is wise to invest on this new CAD system.

It is assumed that the following types of information are available in the ESM of ABC: (1) Business processes, (2) Resources, (3) Organization structure, (4) Functional view of information systems, (5) Software interface of information systems, (6) Operating systems of information systems, and (7) Database management systems of information systems. Further, assume that a knowledge system, which is essentially a decision-making system (Chunli, Lu, and Zhang 2020, 2021), for EAI is available with ABC.

From the ESM of ABC, it can be found that SAP ERP, the ERP system used in ABC, needs to communicate with the SolidWorks CAD system. It can also be found from the ESM of ABC that the SAP ERP system uses SAP NetWeaver Application Program Interface (API). Further, suppose it is known that SolidWorks uses Microsoft .NET API. As such, to integrate SAP and SolidWorks, the compatibility issue between SAP NetWeaver API and Microsoft .Net API will be examined. Suppose it is known that SAP NetWeaver API and Microsoft .Net API are found to be compatible and hence, SAP and SolidWorks can readily be integrated from the viewpoint of API.

Further, from the ESM of ABC it can be found that the SAP ERP system supports the Windows 98 operating system (OS) and ORACLE database management system (DBMS). Suppose it is known that SolidWorks supports Windows XP OS. To integrate

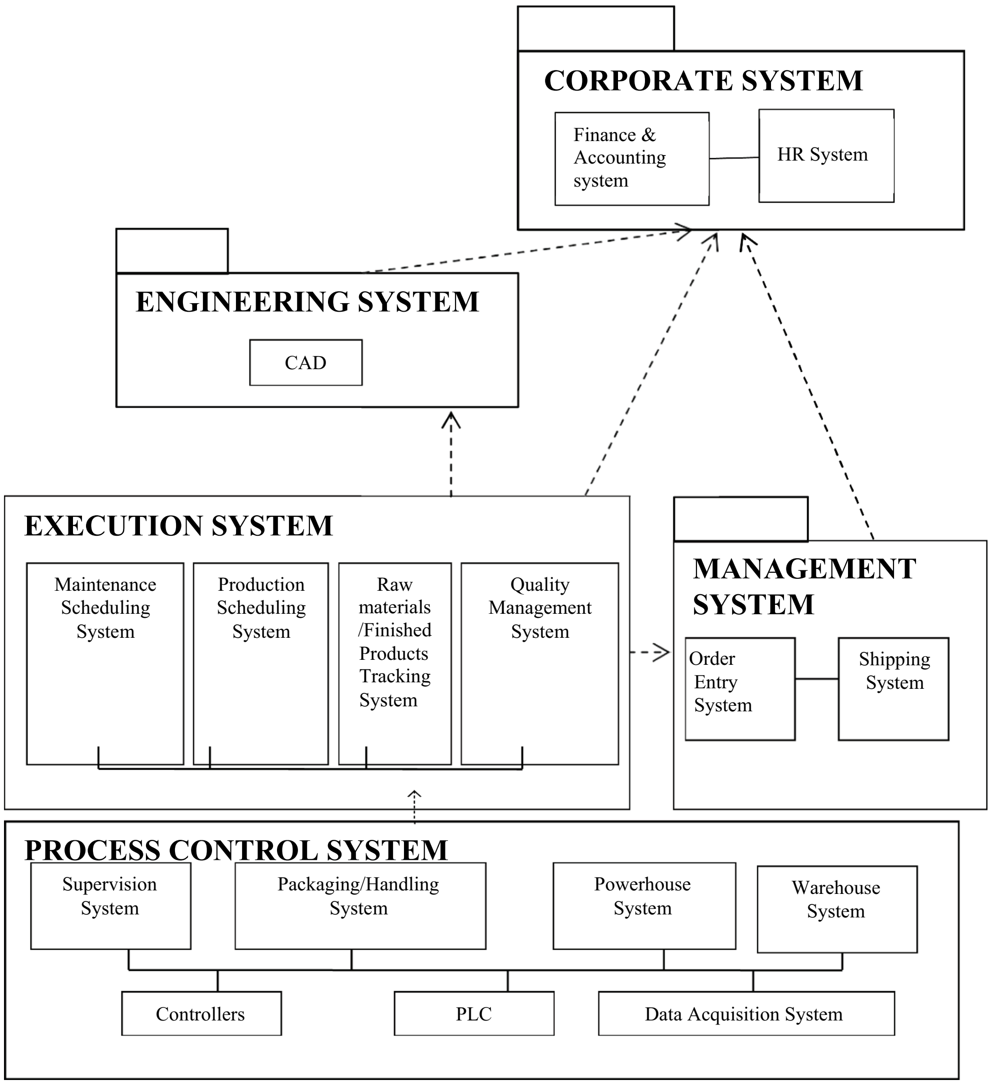

Figure 15. ESM for the ABC information systems- functional view.

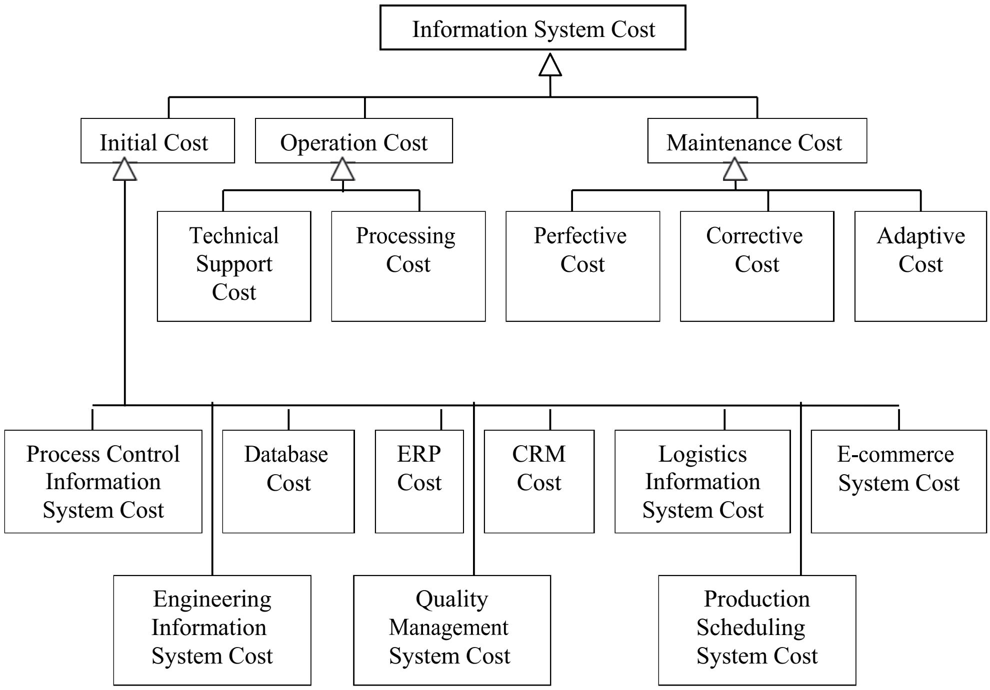

Figure 16. ESM for the ABC information system- cost.

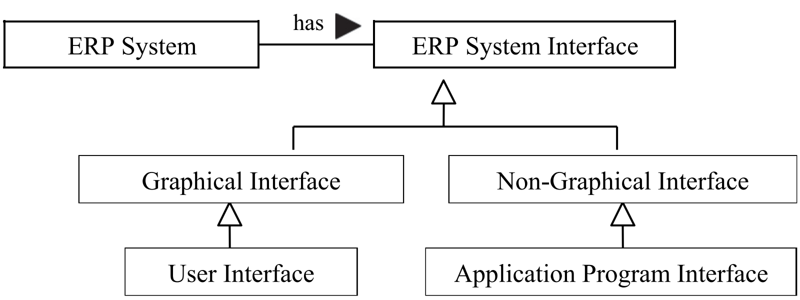

Figure 17. ESM for the ABC information system- software interface.

SAP and SolidWorks from the viewpoint of OS, the compatibility issue between Windows 98 and Windows XP is reviewed. Suppose Windows 98 and Windows XP are found to be compatible, and hence, ORACLE-DBMS, SAP ERP and SolidWorks can be readily integrated from the viewpoint of OS.

Finally, from the ESM of ABC, it can be found that $5000 US is available for purchasing a new CAD system. Suppose it is known that the cost of SolidWorksTM is $6000 US. Hence, there is a conflict in the **cost**. Also, suppose it is known that the price of SolidWorksTM will be reduced to $4500 US in later years. Hence, if the ABC purchases SolidWorksTM by that year, there will not be any financial conflict. As such, to the ABC information system, SolidWorksTM has no compatibility problems with the existing software in the ABC. In addition, there is a functional redundancy with the ABC, namely both AutoCAD R12TM and SolidWorksTM can perform the 2D modelling task.

It is worth mentioning that the aforementioned decision-making process can be computer-performed or automated with the availability of the ESM model. This is an important merit with the ESM as well as the important motivation to develop the ESM for the EAI problem in the era of data explosion and constrained globalisation.

5. Conclusion with further discussions

Today, the environment where manufacturing systems stay can be characterised by data explosion and globalisation. The characteristics have led to agile and flexible manufacturing in the past decades, but they have created some challenges today. The first challenge is the difficulty in integration of data, which have three formats (structured, semi-structured, and unstructured). Data integration is imperative as various companies work together in the today's manufacturing system. The second challenge is to improve the resilience of a global manufacturing system. It is more apparent today than ever before that global manufacturing systems are strongly affected by social and politic systems, and this had made a global manufacturing system more vulnerable. One of the bottle-neck measures to these challenges is to develop an effective solution to the problem of enterprise application integration (EAI), where enterprise application refers to software (information and knowledge) system.

It is well known that an effective idea for the solution to the EAI problem is comprehensive data modelling, where data includes both information and knowledge (Zhang et al. 1994). In this paper, we proposed an approach to enterprise data modelling aimed at providing a solution to the EAI problem for today's manufacturing systems. This approach is called Enterprise Semantic Model (ESM) owing to a feature with the approach, i.e., focusing on enterprise semantics. The SEM is based on three ideas, namely (in short) design thinking, application-enterprise-function ternary relation, and three-layer architecture of an enterprise system. A comprehensive case study was conducted to illustrate how ESM works. Both theoretical deliberation and case study can conclude that the proposed approach provides a general solution to the EAI problem for manufacturing enterprises today. In future, we will consider human factors in EAI, as it is often the case that human workers are reluctant to use digital tools (Ogbeyemi et al. 2020; Trunzer, Wullenweber, and Vogel-Heuser 2020). Another future work is to study information integration for service system for emergency management (Yin, Zhang, and Dong 2020). Finally, EAI with consideration of privacy and security and resilience (Bouloiz 2020; Lin et al. 2021; Tsai and Lasminar 2021) is a worthy future work.

It is worth mentioning that EAI is part of the much broader problem called Enterprise Architecture (EA) (Saint-Louis, Morency, and Lapalme 2019; Saint-Louis and Lapalme 2018). The EA problem concerns business activities to make an enterprise more resilient and sustainable by primary means of EAI. As such, the ESM developed in this paper for EAI will be applicable to the EA problem as well.

Notes

1. Such a language has a tag and a content tied to the tag, and the presentation of the content is further defined by attributes, e.g., colour of the content. Each content can be further associated with an entity which could be an image or word document.
2. Definition of uncertainty refers to the paper (Cai et al. 2017).
3. Details will be discussed later.
4. In the following, applications, enterprise applications, information systems, enterprise information systems are used interchangeable.

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References

Aceto, G., V. Persico, and A. Pescapé. 2020. "Industry 4.0 And Health: Internet of Things, Big Data, and Cloud Computing for Healthcare 4.0." *Journal of Industrial Information Integration* 18 (February): 100129. doi:10.1016/j.jii.2020.100129.

Adeyemi, B., A. Ogbeyemi, and W. Zhang. 2021. "Combining Simple Motion Measurement, Lean Analysis Technique and Historical Data Review for Countering Negative Labor Cost Variance: A Case Study." *International Journal of Engineering Business Management* 13: 184797902110236. doi:10.1177/18479790211023617.

Baranauskas, G. 2019. "Mass Personalization Vs. Mass Customization: Finding Variance in Semantical Meaning and Practical Implementation between Sectors." *Social Transformations in Contemporary Society* 2019 (7): 6–15.

Bi, Z. M., M. Luo, Z. Miao, B. Zhang, W. J. Zhang, and L. Wang. 2020. "Safety Assurance Mechanisms of Collaborative Robotic Systems in Manufacturing." *Robotics and Computer-Integrated Manufacturing* 67 (April): 2020. doi:10.1016/j.rcim.2020.102022.

Bouloiz, H. 2020. "Sustainable Performance Management Using Resilience Engineering." *International Journal of Engineering Business Management* 12: 184797902097620. doi:10.1177/1847979020976205.

Cai, M. Y., Y. Lin, B. Han, C. J. Liu, and W. J. Zhang 2017. ""On A Simple and Efficient Approach to Probability Distribution Function Aggregation," IEEE Trans. On System, Man and Cybernetics, Part A." Published on April. 27, 2016. 10.1109/TSMC.2016.2531647.

Chen, Y. 2017. "Integrated and Intelligent Manufacturing : Perspectives and Enablers." *Engineering* 3 (5): 588–595. doi:10.1016/J.ENG.2017.04.009.

Chu, X., S. Tso, W. Zhang, Q. Li, *et al*. 2002. "Partnership Synthesis for Virtual Enterprises." *The International Journal, Advanced Manufacturing Technology* 19 (5): 384–391. doi:10.1007/s001700200028.

Chunli, J., X. W. Lu, and W. J. Zhang. 2020. "A Bi-Objective Optimization Model for Expert Opinions Aggregation and Its Application in Group Decision Making." *IEEE System Journal*. doi:10.1109/JSYST.2020.3027716.

Chunli, J., X. W. Lu, and W. J. Zhang. 2021. "Development of New Operators for Expert Opinions Aggregation: Average-Induced Ordered Weighted Averaging Operators." *International Journal of Intelligent Systems*. doi:10.1002/int.22328.

Codd, E. F. 1983. "A Relational Model of Data for Large Shared Data Banks." *Communications of the ACM* 26 (1): 64–69. doi:10.1145/357980.358007.

Daneshvar Kakhki, M., and V. B. Gargeya. 2019. "Information Systems for Supply Chain Management: A Systematic Literature Analysis." *International Journal of Production Research* 57 (15–16): 5318–5339. doi:10.1080/00207543.2019.1570376.

Data Modeling Tools and Design. (n.d.). https://www.guru99.com/data-modeling-tools-design-database.html

Date, C. 1986. *An Introduction to Database. Systems*, 1986. Addison-Wesley, Reading, Mass.

Deng, G. S., and W. J. Zhang, 1997. "On Reformation of Manufacturing Planning & Scheduling Model for Virtual Factory in Global Manufacturing Era." Proceedings of Int. Conf. of World Manufacturing Congress'97, New Zealand, 243–246. (ISBN: 3-906454-08-8).

Ferracane, M. F., J. Kren, and E. van der Marel. 2020. "Do Data Policy Restrictions Impact the Productivity Performance of Firms and Industries?." *Review of International Economics* 28 (3): 676–722. doi:10.1111/roie.12467.

Hopkins, J., and P. Hawking. 2018. "Big Data Analytics and IoT in Logistics: A Case Study." *International Journal of Logistics Management* 29 (2): 575–591. doi:10.1108/IJLM-05-2017-0109.

Kassner, L., C. Gröger, B. Mitschang, and E. Westkämper. 2015. "Product Life Cycle Analytics Next Generation Data Analytics on Structured and Unstructured Data." *Procedia CIRP* 33: 35–40. doi:10.1016/j.procir.2015.06.008.

Kassner, L. B., and B. Mitschang 2015. "MaXCept–Decision Support in Exception Handling through Unstructured Data Integration in the Production Context: An Integral Part of the Smart Factory." In 2015 48th Hawaii International Conference on System Sciences, (pp. 1007–1016). IEEE.

Katuu, S. 2020. "Enterprise Resource Planning: Past, Present, and Future." *New Review of Information Networking* 25 (1): 37–46. doi:10.1080/13614576.2020.1742770.

Khanra, S., A. Dhir, and M. Mäntymäki. 2020. "Big Data Analytics and Enterprises: A Bibliometric Synthesis of the Literature." *Enterprise Information Systems* 14 (6): 737–768. doi:10.1080/17517575.2020.1734241.

Kim, W. 1990. "Object-Oriented Databases: Definition and Research Directions." *IEEE Transactions on Knowledge and Data Engineering* 2 (3): 327–341. doi:10.1109/69.60796.

Langmead, B., and A. Nellore. 2018. "Cloud Computing for Genomic Data Analysis and Collaboration." *Nature Reviews Genetics* 19 (4): 208–219. doi:10.1038/nrg.2017.113.

Lenzerini, M., V. Salaria, and I. Roma 2014. "Data Integration: A Theoretical Perspective Data Integration: A Theoretical Perspective." 10.1145/543613.543644.

Li, Q., W. J. Zhang, and S. K. Tso., January 2000. "Generalization of Strategies for Product Data Modeling with Special Reference to Instance-As-Type Problem." *Computers in Industry* 41 (1): 25–34. doi:10.1016/S0166-3615(99)00041-X.

Lin, W., X. Ming, H. Jingyi, and W. Zhang 2021. "Privacy, Security and Resilience in Mobile Healthcare Applications." Enterprise Information Systems. DOI: 10.1080/17517575.2021.1939896

Lin, Y., and W. J. Zhang. 2004. "Towards a Novel Interface Design Framework : Function – Behavior – State Paradigm." 61: 259–297. doi:10.1016/j.ijhcs.2003.11.008.

Liu, X., W. J. Zhang, R. Radhakrishnan, and Y. L. Tu. 2008. "Manufacturing Perspective of Enterprise Application Integration: The State of the Art Review." *International Journal of Production Research* 46 (16): 4567–4596. doi:10.1080/00207540701263325.

Ma, Z. M., W. J. Zhang, and F. Mili. February 2002. "Fuzzy Data Compression Based No Data Dependencies." *Nternational Journal of Intelligent Systems* 17 (4): 407–424.

Ma, Z. M., W. J. Zhang, and W. Y. Ma. 2003. "Extending Object-Oriented Database for Fuzzy Information Modeling." *Journal of Information Systems* 29 (5): 421–435. 2004.

Ma, Z. M., W. J. Zhang, W. Y. Ma, and C. Chen. 2001. "Conceptual Design of Fuzzy Object-oriented Databases Using Extended Entity-relationship Model." *International Journal of Intelligent Systems* 16 (6, May): 697–711. doi:10.1002/int.1031.

Miao, Z., Z. M. Bi, W. J. Bing Zhang, and L. W. Zhang. 2020. "Overview of Safety Assurance Mechanisms of Collaborative Robotic Systems in Manufacturing." *Robotics and Computer-Integrated Manufacturing* 67 February 2021 102022.

Ogbeyemi, A., W. Lin, F. Zhang, and W. Zhang. 2020. "Human Factors among Workers in a Small Manufacturing Enterprise: A Case Study." In *Enterprise Information System. Accepted in September*, 2020.

Pego Guerra, M. A., and W. J. Zhang. 2001. "Computer Application in Agile Manufacturing." In *Agile Manufacturing: The 21st Century Competitive Strategy By* A. Gunasekaran, 135–155. Elsevier Publisher. https://doi.org/10.1016/B978-0-08-043567-1.X5000-1

Pego-Guerra, M., W. J. Zhang, and W. H. Ip, 2010. "Robust Management of Virtual Enterprise." ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Montreal, Canada, August 22–26.

Rajaraman, V. 2014. "Cloud Computing." *Resonance* 19 (3): 242–258. doi:10.1007/s12045-014-0030-1.

Rajaraman, V. August 2016. "Big Data Analytics (Articulo En Ingles)." 695–716.

Saint-Louis, P., and J. Lapalme. 2018. "An Exploration of the Many Ways to Approach the Discipline of Enterprise Architecture." *International Journal of Engineering Business Management* 10: 184797901880738. doi:10.1177/1847979018807383.

Saint-Louis, P., M. C. Morency, and J. Lapalme. 2019. "Examination of Explicit Definitions of Enterprise Architecture." *International Journal of Engineering Business Management* 11: 184797901986633. doi:10.1177/1847979019866337.

Salama, M., H. A. Kader, and A. Abdelwahab. 2021. "An Analytic Framework for Enhancing the Performance of Big Heterogeneous Data Analysis." *International Journal of Engineering Business Management* 13: 184797902199052. doi:10.1177/1847979021990523.

Singh, N. 2019. "Big Data Technology: Developments in Current Research and Emerging Landscape." *Enterprise Information Systems* 13 (6): 801 831. doi:10.1080/17517575.2019.1612098.

Tao, F., Q. Qi, A. Liu, and A. Kusiak. 2018. "Data-driven Smart Manufacturing." *Journal of Manufacturing Systems* 48: 157–169. doi:10.1016/j.jmsy.2018.01.006.

Trunzer, E., A. Wullenweber, and B. Vogel-Heuser. 2020. "Graphical Modeling Notation for Data Collection and Analysis Architectures in Cyber-physical Systems of Systems." *Journal of Industrial Information Integration* 19: 100155. doi: 10.1016/j.jii.2020.100155. May 2019.

Tsai, Y.-T., and R. G. Lasminar. 2021. "Proactive and Reactive Flexibility: How Does Flexibility Mediate the Link between Supply Chain Information Integration and Performance?." *International Journal of Engineering Business Management* 13: 184797902110076. doi:10.1177/18479790211007624.

Wang, F., Z. Qian, Z. Yan, C. Yuan, and W. Zhang. 2020. "A Novel Resilient Robot: Kinematic Analysis and Experimentation." *IEEE Access* 8: 2885–2892. doi:10.1109/ACCESS.2019.2962058.

Wang, J., P. Zheng, Y. Lv, J. Bao, and J. Zhang. 2019. "Fog-IBDIS: Industrial Big Data Integration and Sharing with Fog Computing for Manufacturing Systems." *Engineering* 5 (4): 662–670. doi:10.1016/j.eng.2018.12.013.

Wang, J. W., H. F. Wang, J. L. Ding, K. Furuta, T. Kanno, W. H. Ip, and W. J. Zhang, 2016. "On Domain Modelling of the Service System with Its Application to Enterprise Information Systems." Enterprise Information Systems. DOI: 10.1080/17517575.2013.810784.

Wang, J. W., H. F. Wang, W. J. Zhang, W. H. Ip, and K. Furuta. 2014a. "On a Unified Definition of the Service System: What Is Its Identity?." *IEEE Systems Journal* 8 (3): 821–826. doi:10.1109/JSYST.2013.2260623.

Wang, J. W., R. L. Dou, R. R. Muddada, J. L. Ding, H. F. Wang, and W. J. Zhang. 2018. "Management of a Holistic Supply Chain Network for Proactive Resilience: Theory and Case Study." *Computers & Industrial Engineering* 125 (November): 668–677. doi:10.1016/j.cie.2017.12.021.

Wang, J. W., R. R. Muddada, H. F. Wang, J. L. Ding, Y. Lin, C. L. Liu, and W. J. Zhang. 2014b. "Towards a Resilient Holistic Supply Chain Network System: Concept, Review and Future Direction." *IEEE Systems Journal*. doi:10.1109/JSYST.2014.2363161.

Wang, J. W., W. H. Ip, R. Muddada, J. L. Huang, and W. J. Zhang. 2013. "On Petri Net Implementation of Proactive Resilient Holistic Supply Chain Networks." *International Journal of Advanced Manufacturing Technology* 69 (1–4): 427–437. doi:10.1007/s00170-013-5022-x.

Wigan, M. R., and R. Clarke. 2013. "Big Data's Big Unintended Consequences." *Computer* 46 (6): 46–53. doi:10.1109/MC.2013.195.

Xiang, F., Q. Yin, Z. Wang, and G. Z. Jiang. 2018. "Systematic Method for Big Manufacturing Data Integration and Sharing." *The International Journal of Advanced Manufacturing Technology* 94 (9–12): 3345–3358. doi:10.1007/s00170-017-0575-8.

Yin, S., N. Zhang, and H. Dong. 2020. "Preventing COVID-19 from the Perspective of Industrial Information Integration: Evaluation and Continuous Improvement of Information Networks for Sustainable Epidemic Prevention." *Journal of Industrial Information Integration* 19 (June): 100157. doi:10.1016/j.jii.2020.100157.

Zach, O., B. E. Munkvold, and D. H. Olsen. 2014. "ERP System Implementation in SMEs: Exploring the Influences of the SME Context." *Enterprise Information Systems* 8 (2): 309–335. doi:10.1080/17517575.2012.702358.

Zhang, W. J., 1994. "An Integrated Environment for CADCAM of Mechanical Systems." Ph.D. thesis, printed by Delft University of Technology, The Netherlands. pp. 1–263. ISBN 90-370-0113-0.

Zhang, W. J., 1996. "Methodology for Designing a Conceptual Database System to Support Partner Synthesis in Virtual Enterprises." The Proceedings of the 3rd CIRP Workshop on Design and Implementation of Intelligent Manufacturing System (IMS), Tokyo, Japan, June 19-21, pp.137–144.

Zhang, W. J., and C.A. van Luttervelt. 2011. Toward a resilient manufacturing system. *CIRP Annals* 60 (1): 469–472. doi:10.1016/j.cirp.2011.03.041

Zhang, W. J., G. Yang, Y. Lin, C. Ji, and M. M. Gupta, 2018. "On Definition of Deep Learning." Stevenson, WA: 2018 World Automation Congress (WAC). pp. 1–5, doi: 10.23919/WAC.2018.8430387.

Zhang, W. J., and J. W. Wang. 2016. "Design Theory and Methodology for Enterprise Systems (Editorial)." *Enterprise Information Systems* 10 (3): 245–248. doi:10.1080/17517575.2015.1080860.

Zhang, W. J., J. W. Wang, and Y. Lin. 2019. "Integrated Design and Operation Management for Enterprise Systems." *Enterprise Information Systems* 13 (4): 424–429. doi:10.1080/17517575.2019.1597169.

Zhang, W. J., and K. Werff Van Der. 1993b. "Guidelines for Product Data Model Formulation Using Database Technology." Proc. of Int. Conf. on Engineering Design (ICED'93), Vol.3, The Hague, 1618–1626.

Zhang, W. J., K. Werff, and Van Der, 1994. "A Critique of Conceptual Data Modeling Notions Relative to the Machine Design Domain." Proc. of 1994 ASME Engineering Database Symposium'94, Minneapolis, USA, Sept 11-14, 59–66.

Zhang, W. J., X. Liu, and C. A. Van Luttervelt, 1997. "On the Proposal of a New Theory, Methodology and Computer Aid for Virtual Enterprises Manufacturing Systems Design – In Relation to Partner Factories Selection." Proceedings of International Conference of World Manufacturing Congress' New Zealand, 97 61–66. (ISBN: 3-906454-08-8)

Zhang, W. J., and Y. Lin. 2010. "Principles of Design of Resilient Systems and Its Application to Enterprise Information Systems." *Enterprise Information Systems* 4 (2): 99–110. doi:10.1080/17517571003763380.

Zhang, W. J., Y. Lin, and N. Shihn 2005. "On the Function-Behavior-Structure Model for Design." *Canadian Design Engineering Network Conference* 2005, Proceedings of the Canadian Design Engineering Network (CDEN) Conference, Kaninaskis, Alberta, July 18-20, 2005.

Zhang, Y., S. Ren, Y. Liu, and S. Si. 2017. "A Big Data Analytics Architecture for Cleaner Manufacturing and Maintenance Processes of Complex Products." *Journal of Cleaner Production* 142: 626–641. doi:10.1016/j.jclepro.2016.07.123.

Zhao, X., J. Xie, and W. J. Zhang. 2002. "The Impact of Information Sharing and Ordering Co-ordination on Supply Chain Performance." *Supply Chain Management* 7 (1): 24–40. doi:10.1108/13598540210414364.

Zhao, Y., J. Song, A. Montazeri, M. M. Gupta, Y. Lin, C. Wang, and W. J. Zhang. 2018. "Mining Affective Words to Capture Customer's Affective Response to Apparel Products." *Textile Research Journal* 88 (12): 1426–1436. doi:10.1177/0040517517712092.

Zhao, Y., J. Sun, M. M. Gupta, W. Moody, W. H. Laverty, and W. Zhang. 2017. "Developing a Mapping from Affective Words to Design Parameters for Affective Design of Apparel Products." *Textile Research Journal* 87 (18): 2224–2232. doi:10.1177/0040517516669072.