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ENGINEERING MANAGEMENT THEORIES AND METHODOLOGIES

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Engineering Informatics: State of the Art and Future Trends

Abstract Engineering informatics is an emerging engineering discipline integrating information technology or informatics with a variety of engineering disciplines. It is an interdisciplinary scientific subject focusing on applying advanced information and communications technology (ICT) to a variety of engineering disciplines. Rapid advances in industrial information integration methods have spurred the growth of new techniques that can be used for probing industrial information integration including engineering informatics. These techniques include business process management (BPM), enterprise architecture (EA), enterprise application integration (EAI), service-oriented architecture (SOA), and others. Practical applications may require a combination of these techniques that have originated from different disciplines. These techniques have the potential to contribute to engineering informatics. For integrating complex engineering systems, both formal methods and systems methods are crucial. In this paper, we briefly review the state of the art of engineering informatics as it interfacing with industrial information integration.

Keywords: engineering informatics, industrial integration, industrial information integration engineering (IIIE), engineering management

1 Introduction

Engineering informatics is an emerging engineering discipline combining information technology or informatics with a variety of engineering disciplines. It is an interdisciplinary scientific subject focusing on applying advanced information and communications technology (ICT) to a variety of engineering disciplines.

Computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM) are the terms that have been coined over the last four decades in the area of computing technology in engineering. Computing technology has had significant impacts on a variety of engineering disciplines; vice versa, computing technology in engineering has also continuously promoted the advances in computing technology. In this coevolution process, computing technology and a variety of engineering disciplines have increasingly intertwined as the development of the theory and practice in both disciplines, computing technology and engineering, influencing each other.

Since 1990, it has been recognizing the need for a scientific subject called engineering informatics, although the subject has not yet been formally recognized as a scientific and engineering discipline. The following are excerpted from reports from the US National Research Council, US National Science Foundation, and US National Academy of Engineering: "The structuring of design information and data integration are critical requirements for data sharing between designers separated physically and in time, as well as between companies, vendors and customers. Standards do not yet exist for modeling many engineering and organizational parameters that are essential for design specification and analysis, nor are there standards for structuring rational for decisions and design procedures used" (National Research Council, 1991, p.55). "Data communication in a heterogeneous system, validation, and consistency of data, representation of textual and geometrical data… , analytical models of manufacturing processes are all risky areas of research, requiring multiyear, cooperative efforts. Solutions to these problems are needed…" (National Research Council, 1995, p.81) "Interdisciplinary collaborations will be especially important for implementing comprehensive processes that can integrate the design of mechanical systems with the design of electrical systems and software. Successful collaborations, however, will first require overcoming incompatibilities between emerging technologies and the existing technological infrastructure and organizational cultures" (National Science Foundation, 2004, p.10). "For many organizations, a fundamental change in the engineering culture will be necessary to take advantage of breakthroughs in advanced computing, human-machine interactions, virtual reality, computational

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intelligence, and knowledge-based engineering…" (National Academy of Engineering, 2005, p.10).

In 2008, Subrahmanian and Rachuri first proposed to use the term "engineering informatics" to cover the theory and practice in which computing technology and engineering are interfacing (Subrahmanian & Rachuri, 2008). "Informatics, with origins in the German word Informatik referring to automated information processing, has evolved to its current broad definition. The rise of the term informatics can be attributed to the breadth of disciplines that are now accepted and envisioned as contributing to the field of computing and information sciences. A common definition of informatics adopted by many departments/schools of informatics comes from the University of Edinburgh: 'the study of the structure, behavior, and interactions of natural and artificial computational systems that store, process and communicate information'. Informatics includes the science of information, the practice of information processing, and the engineering of information systems" (Subrahmanian & Rachuri, 2008). Informatics has an engineering aspect also, which addresses the engineering and operation of information processing systems that compute, store, communicate, and visualize information (Broy, 2006).

Meanwhile, Subrahmanian and Rachuri (Subrahmanian & Rachuri, 2008) also indicate that the history of computing technology and engineering shows a trend of increasing sophistication in the type of engineering problems being solved. Early CAD was primarily based on computational algorithms and models. Then came the engineering use of artificial intelligence (AI), driven by theories of cognitive science and computational models of cognition. More recently, models of collaboration, and the acquisition and representation of collective knowledge have been introduced. Following this trend, engineering informatics can be defined as "the study of use of information and the design of information structures that facilitate the practice of engineering and of designed artifacts that embody and embed information technology and science to achieve social, economic and environmental goals" (Subrahmanian & Rachuri, 2008).

Subrahmanian and Rachuri identified several strands of facts that support the proposing of engineering informatics as an interdisciplinary discipline that interfacing engineering and informatics (Subrahmanian & Rachuri, 2008). Developing an embedded software system for engineering purpose requires interdisciplinary efforts in mechanics, domains, software, hardware, and human-machine interfaces. Engineering informatics is to use the knowledge from both informatics and engineering for forming engineering informatics knowledge framework and basic methods. The knowledge framework of engineering informatics is unique. Computer scientists or engineers cannot solve engineering informatics problems in the context of engineering systems alone, as engineering informatics is an interdisciplinary effort. The lack of required backgrounds among computer scientists in engineering and engineers in computing technology has lend to develop a new interdisciplinary subject—engineering informatics.

Similar movements have been seen in individual engineering disciplines. In the construction engineering discipline, initially, several names have been used for the interdisciplinary field related to both construction engineering and computing technology such as "computer integrated construction", "computing in civil engineering", and "information technology in construction". The most commonly used terms are "information technology in construction" or "construction IT". They were coined in the middle 1990s (Turk, 2006). According to Turk, "years later more sober voices claim that many of the problems in the construction industry, that could have been solved by information technology, are not solved, however not only due to technical issues. It seems appropriate, therefore, to remove the word technology and leave just 'construction informatics' (CI), construction taken in the broadest sense of the word to include building, civil engineering, structural engineering, AEC (architecture, engineering, construction) and other disciplines…" (Turk, 2006).

As informatics is applicable in multiple engineering disciplines or spanning multiple engineering disciplines, the term "engineering informatics" was proposed, coined, and started to be used. It is natural that the informatics for a specific engineering subject starts expanding to cover a variety of engineering disciplines, and eventually, a more general term called engineering informatics was proposed and coined. Engineering informatics is considered as a distinct discipline, at the interface between engineering and informatics, in the same vein as bioinformatics and medical informatics (Subrahmanian & Rachuri, 2008).

Subrahmanian and Rachuri proposed their view on the subject of engineering informatics (for fully representing the original contents, *Figure 1* was reproduced from Subrahmanian & Rachuri, 2008). In *Figure 1*, the inner set of circles marked as informatics covers the fundamental activities associated with informatics in general. The role that informatics plays in engineering processes and products has been becoming significant in past decades. The next circle, denoted by process and product, identifies the multilevel and multi-scale modeling activities of processes and products. The outer circles show the inputs to engineering informatics from a number of disciplines that provide the knowledge, methods, and tools.

Although Subrahmanian and Rachuri have proposed their view on the subject of engineering informatics, the scope of engineering informatics, can be further refined. As indicated by Broy, software and systems engineering is the key for constructing information processing systems. In particular, software and systems engineering addresses issues such as requirements engineering and reliability engineering (Broy, 2006).

Before the need for engineering informatics was formally presented in 2007 and the term "engineering informatics" was coined in 2007 and 2008 (Regli, 2007; Subrahmanian & Rachuri, 2008), a scientific and engineering discipline called

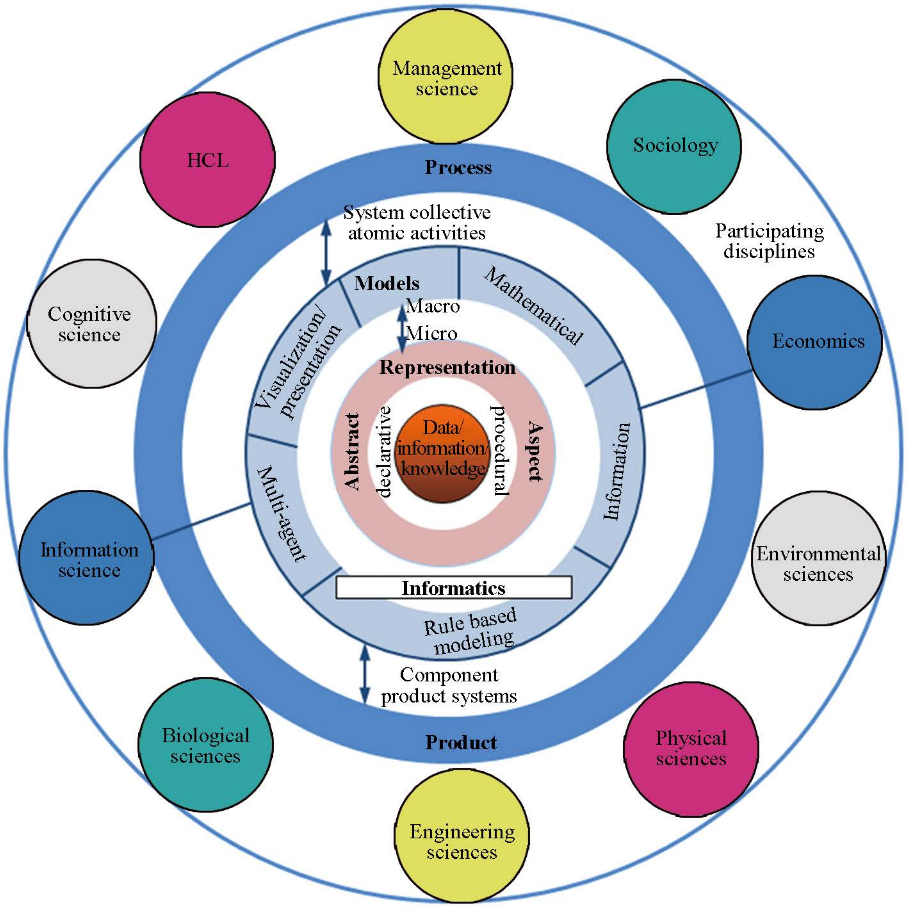

Figure 1. The scope of engineering informatics proposed in 2008 (Subrahmanian & Rachuri, 2008).

industrial information integration engineering (IIIE) was formerly proposed and recognized by international organizations such as International Federation for Information Processing (IFIP) and the Institute of Electrical and Electronics Engineers (IEEE) in 2005.

In June 2005, at a meeting of the IFIP Technical Committee for Information Systems (TC8) held at Guimarães, Portugal, the committee members intensively discussed and formally recognized the important role played by industrial information integration and the innovative and unique characteristics of IIIE as a scientific sub-discipline (Raffai, 2007; Roode, 2005). IIIE is a set of foundational concepts and techniques that facilitate the industrial information integration process; specifically speaking, IIIE comprises methods for solving complex problems when developing ICT infrastructure for industrial integration, especially in the aspect of information integration. It was decided at this meeting that the IFIP First International Conference on Research and Practical Issues of Enterprise Information Systems would be held in 2006 in Vienna, Austria. In August 2006, at the IFIP 2006 World Computer Congress held in Santiago, Chile, the IFIP TC8 WG8.9 Enterprise Information Systems was established. In 2007, the Enterprise Information Systems Technical Committee was established within the IEEE Systems, Man and Cybernetics Society. To further respond to the needs of both academicians and practitioners for communicating and publishing their research outcomes, the science and engineering journal entitled *Enterprise Information Systems*, exclusively devoting itself to the topics of industrial information integration, was launched in 2007 (*Figure 2*).

IIIE emphasizes multiple aspects, including one of the major aspects which completely overlapping with the scope of engineering informatics: engineering information integration. Information integration is one of the key research issues in engineering informatics. In 2007, Regli indicated that, in the information technology in engineering, although there have been great strides made by academic and commercial entities in the past decades, the fundamental problems of information integration remain the same (Regli, 2007). In 2008, Subrahmanian and Rachuri indicated the numerous incompatibilities in engineering information exchange and coordination. The delays that occurred in Airbus 380 and Boeing 787 are examples of the problems of this nature (Subrahmanian & Rachuri, 2008). Regli and other researchers have indicated the key technological issue of engineering informatics is “the apparent lack of fundamental progress in areas of information integration” (Regli, 2007).

This paper focuses on one of the major aspects of IIIE

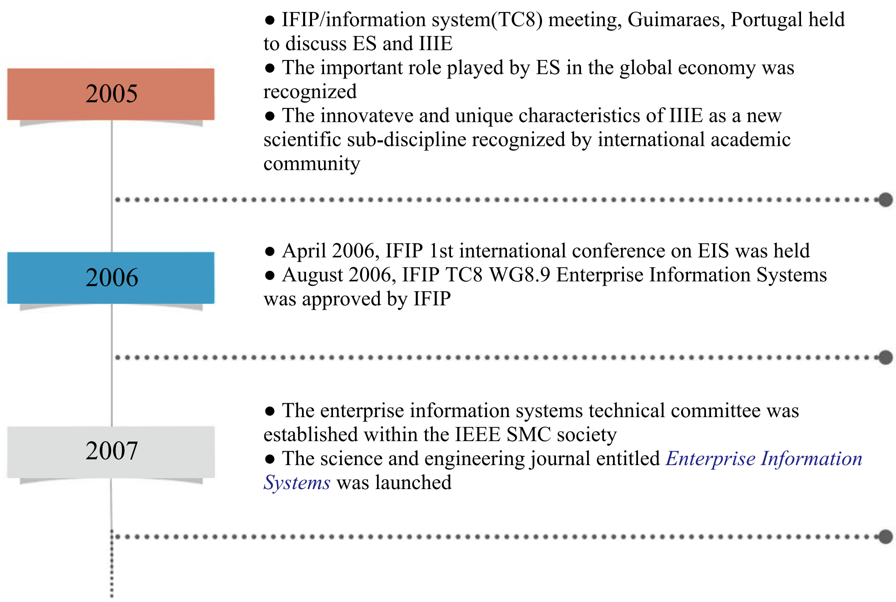

Figure 2. IIIE discipline history.

which completely overlapping with the scope of engineering informatics: engineering information integration. The objective of this paper is to introduce to the communities of engineering and engineering informatics the current development and future opportunities that exist in engineering information integration, but it is by no means meant to be exhaustive. In Section II, we briefly discuss industrial information integration and engineering information integration. Section III describes major techniques or technologies in information integration applicable to engineering informatics, while Section IV concludes this paper.

2 Engineering information integration

2.1 IIIE-A new discipline for industrial integration and industrial information integration

The significance of industrial integration has been fully recognized in recent years (Siemens, 2014). Siemens refers industrial integration as integrating entire product development and production process, from product design and production planning to production engineering, production execution and services (Siemens, 2014). IIIE is a discipline specifically developed for industrial integration in both broad and narrow senses (Xu, 2012). It is a set of foundation concepts and techniques that facilitate the industrial information integration process. Specifically speaking, IIIE comprises methods for solving complex problems in developing ICT infrastructure for industrial sectors, especially in the aspect of information integration. IIIE has been proposed and studied through identifying its theoretical foundation, body of knowledge, frameworks, theories, and models at multiple levels. The key research questions addressed include: ① what is the scientific foundation that will provide IIIE with the disciplinary support at the levels of frameworks, theories, and models? ② at each level of IIIE (i.e. frameworks, theories, and models/techniques), how can real-world problem solving support be provided?

According to the subsystems that make up a system, the number of sub-systems involved, and the degree of complexity involved with the subsystems, the overall system can be categorized either as a simple system or as a giant system. If a system is made up of a huge number of subsystems, the system is referred to as a giant system. In addition, if a system has numerous subsystems and layers and if the relationships among the subsystems and layers are complicated, the system is referred to as a complex giant system. IIIE is an interdisciplinary discipline with the typical characteristics of giant and complex system.

As an interdisciplinary discipline, IIIE interacts with scientific disciplines such as mathematics, computer science, and almost every engineering discipline among the twelve engineering disciplines defined by the US National Academy of Engineering. The US National Academy of Engineering is organized into twelve sections, each representing a broad engineering category. IIIE interacts with almost every one of them in separate layers. In terms of scientific and engineering methods, at the methodological layer, IIIE interacts with computer science and engineering, industrial systems engineering, information systems engineering, and interdisciplinary engineering. In terms of developing and implementing enterprise systems in different industrial sectors, at the application layer, IIIE interacts with aerospace engineering, bioengineering, civil engineering, energy engineering, communication engineering, material engineering, and earth resources engineering. In addition to the scientific and engineering disciplines, IIIE also interacts with management and social sciences. For example, any effective engineering process relies on effective management. As a result, the perspectives on the workflows that are commonly modeled and represented include managerial perspective. Based on the definition of management defined (Xu & Xu, 2011), in a broad sense, management is the most comprehensive science which covers all the disciplines. Judging from these, IIIE is defined as a complex giant system which can advance and integrate the concepts, theory, and methods in each relevant discipline and open up a new discipline for the industry information integration purposes which is characterized by its interdisciplinary nature. *Figure 3* shows IIIE at the top level; relevant scientific, engineering, management, and social science disciplines at the second level; and application engineering fields at the third level. At the fourth level and the levels below, many relevant frameworks, theories, and models can be listed.

Figure 3 can be huge in size, in order to cover all of the details involved. For example, enterprise interoperability is involved with frameworks such as the advanced technologies for interoperability of heterogeneous enterprise networks and their applications (ATHENA) interoperability framework, business interoperability parameters, the CEN/ISSS eBusiness roadmap, C4 interoperability framework (C4IF), the interoperability development for enterprise application and software (IDEAS) interoperability framework, the European interoperability framework, levels of conceptual interoperability, levels of information system interoperability (LISI) C4ISR, NATO C3 technical architecture (NC3TA), and the organizational interoperability maturity model.

2.2 Engineering integration

In today's global competition atmosphere, industrial systems including engineering systems need to be constantly re-engineered in order to respond to the fluctuating market and the technological evolution, in which ICT infrastructure is always important. *Figure 4* shows the relationship between engineering integration, manufacturing integration, customer integration, and enterprise integration, as well as their IT infrastructures including earlier systems such as material requirements planning (MRP), manufacturing resource planning (MRP II), enterprise resource planning (ERP), and new systems such as ERP. In particular, *Figure 4* shows that engineering integration plays an important role in industrial integration and industrial information integration. Numerous efforts have been made on engineering integration. In 1980s, MRP II systems were developed to integrate with engineering design systems to receive bill of materials (BOM) and routing information. Due to technical limitations, MRP II

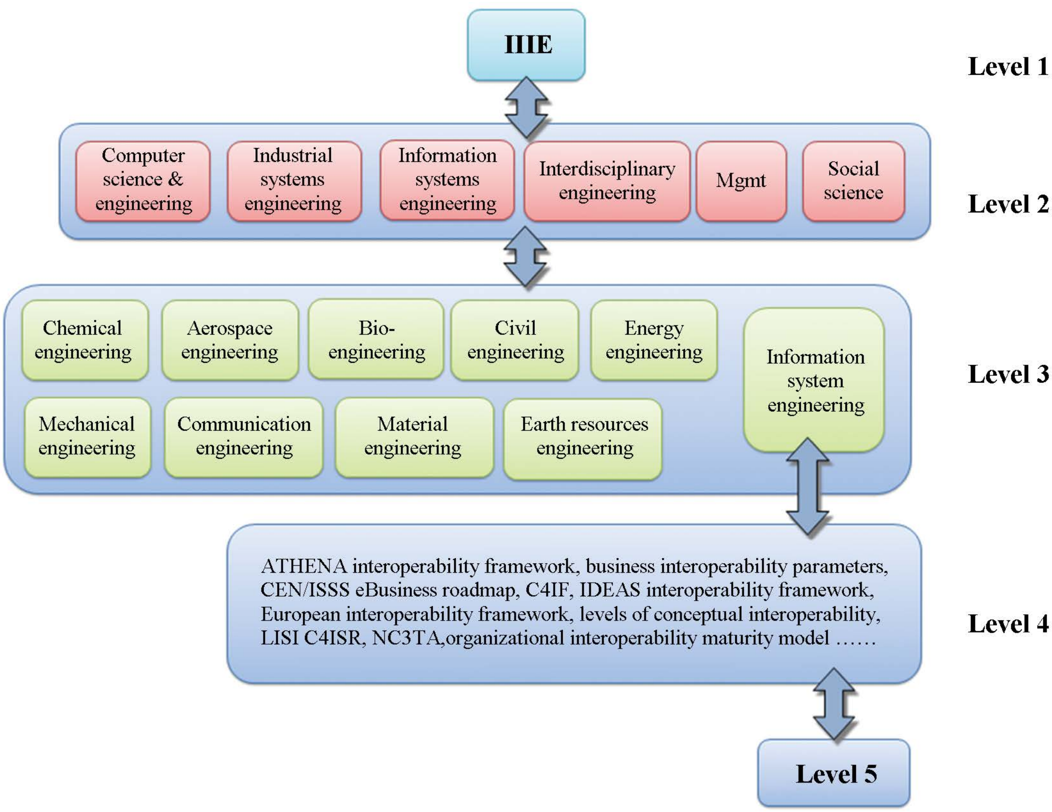

Figure 3. Discipline structure of IIIE.

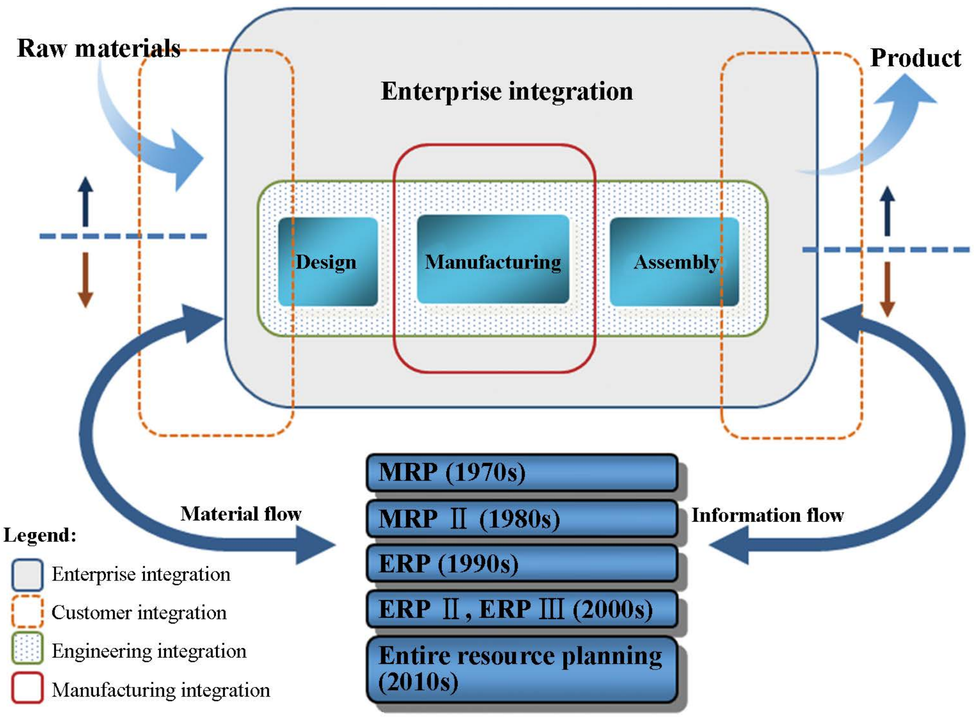

Figure 4. The relationship between engineering integration, manufacturing integration, customer integration, and enterprise integration.

systems were unable to pass critical information back to the engineering design systems. In 2000, in new generation enterprise systems, engineering integration first time became one of the main components of industrial enterprise systems (Langenwalter, 2000).

Engineering integration has been classified by researchers as (Kulvatunyou & Wysk, 2000).

(1) Data-oriented integration in CAD, computer-aided process planning or computer-aided production planning (CAPP), CAM, and computer-integrated manufacturing (CIM).

(2) Cooperative team-oriented integration such as the organizing of a concurrent engineering team or an integrated process and product development team.

(3) Procedure-oriented integration, such as quality function deployment (QFD), Taguchi method, axiomatic design, and automated assembly planning.

In a typical product development process, the design data/information flow may not be well supported by the existing systems. If associative relations among engineering features were not available through the system, data consistency and design changes would be difficult to manage. At different stages of a product's life cycle, from its requirement specifications to its conceptual design to its more detailed structure design and finally to its production, engineering data, information, and knowledge must be integrated. The ways in which the engineering division integrates with the rest of divisions in an enterprise have been intensively researched. A complete integration includes the design process, product data management, integration with customers, integration with suppliers, integration with the rest of the organization, and integration inter-organizationally.

In concurrent engineering, all of the engineering processes should be supported by integrated computer-aided tools, and should be based on a consistent set of data with different application views. Such applications include conceptual design, structural design, detailed design, design analysis for certain specific engineering aspects, CAPP, and CAM. However, this desirable scenario has not been fully realized yet due to the interoperability limitations of software packages.

Concurrent design has become increasingly important in designing complex products. A concurrent design process consists of many design activities that are interrelated with each other. It is likely to generate better design. Numerous concurrent design techniques have been developed, in which information integration plays an important role.

As one of the concurrent design techniques, integrating unified modeling language (UML) with polychromatic sets provides a powerful tool for modeling and analyzing concurrent design processes. UML is a graphical and visual modeling language. UML has been applied to concurrent design in which UML model of concurrent design process has been developed and mapped into a polychromatic sets contour matrix model. Using this novel modeling and analysis method for a concurrent design process based on UML and polychromatic sets, a concurrent design process can be modeled formally and analyzed quantitatively, and the major factors which affect the concurrent design process can be considered.

Polychromatic sets theory is a mathematical theory which is regarded as a promising approach for many applications. Due to the idea and the theory that were developed, namely to use a standardized mathematical model to simulate different objects, the techniques of polychromatic sets have been widely applied to areas such as product conceptual design, product modeling, process modeling, process optimization, product life cycle simulation, and concurrent engineering. The polychromatic sets theory has been applied to computer-aided tolerancing (CAT). In CAD/CAM, the comprehensive design of dimensional and geometric tolerances for mechanical products using computers is called CAT. This is a focal point of research in CAD/CAM. In the process of product design and manufacturing, the tolerance values of a mechanical part are closely related to its manufacturing process, which not only influences the quality of product but also affects the manufacturing cost. So far, considerable research has been conducted on CAT analysis and synthesis, tolerance information modeling and representation, concurrent tolerance design, dynamic tolerance control, and tolerance information verification. Based on the variational geometric constraint (VGC) theory and technologically related surfaces (TTRS) theory, a hierarchical reasoning model of tolerance information is developed which applies the polychromatic sets theory to optimize computer-aided generation of tolerance types.

A concurrent design process, as introduced above, usually requires that data and information are exchanged efficiently. If information sharing and integration issues are not addressed properly, concurrent design may not work effectively. In the above-mentioned concurrent design efforts, the role played by information integration is always important.

In recent years, engineering design has required more and more multidisciplinary design efforts. Engineering designers from a number of different disciplinary areas may interact and exchange in the design process. Therefore, efficient processing and integration of engineering data among numerous heterogeneous data sources plays an important role in engineering design. Engineering information integration thus is assumed to play a major role in supporting multidisciplinary engineering design activities throughout product development cycles. The characteristics of data diversity, irregularity, and heterogeneity differentiate engineering information integration from information integration in other domains. This poses a challenge to effective engineering integration. There has been much ongoing research in this area. The topics include: ① approaches for engineering software integration and product data exchange to support interoperability among different engineering phases; ② web services-based multidisciplinary design optimization frameworks which provide data exchange services and integration; ③the methodology for developing a virtualization-based platform in support of multidisciplinary design of complex products. The research on engineering integration is becoming more prevalent now. Research has recently been conducted on the methods and models for large-scale engineering projects.

3 Enabling technologies

Rapid advances in industrial information integration methods have spurred tremendous growth of a variety of techniques. Many applications require a combination of these techniques. At present, we are at a new break point in the evolution of selected enabling technologies. In the following, we will introduce the main enabling technologies for IIIE as well as for engineering informatics, which include BPM, information integration and interoperability, enterprise architecture (EA), enterprise application integration (EAI), and service-oriented architecture (SOA).

3.1 Business process management

Engineering design process modeling can inherit methods and approaches developed in business process management. Theiben, Hai and Marquardt (Theiben, Hai &, Marquardt, 2008) introduced a method for modeling, improving, and implementing design processes in chemical engineering. The method inherits some methods developed in the domain of business process reengineering and workflow management (Theiben, Hai &, Marquardt, 2008). Thus BPM becomes an interesting topic in engineering informatics.

BPM is an approach that is focused on aligning all of the aspects of an industrial organization in order to promote process effectiveness and efficiency with the help of information technology. Through business process modeling, BPM can help industries standardize and optimize business processes, increasing their agility in responding to the changing environment for competitive advantage, accomplishing business process reengineering, and realizing cost reduction.

The modeling, monitoring, and controlling of industrial processes is important, as it enables us to understand and optimize such processes. Process modeling results can be applied to process automation and factory automation. Manufacturing process modeling is a typical example. Modeling manufacturing processes is important as it enables manufacturers to understand the process and to optimize the process operation. All process details in a manufacturing process which relate to the desired outputs of the process need to be understood. Modeling industrial control is another example. Such modeling draws the domain expertise of multiple disciplines/subjects including information technology, process technology, and factory automation, and industrial communication systems. The control and predictive capability of process modeling may offer useful insights into quite a few engineering fields covered in *Figure 3*. Industrial process modeling can be listed somewhere in *Figure 3* at a level below Level 3; as such, the industrial process control itself is complex and interdisciplinary.

To track the status of each instance of the process as it moves through an organization, the concept of workflow becomes important. In a process, a workflow consists of a number of tasks that need to be carried out and a set of conditions that determine the order of the tasks. The objective of workflow management is to manage workflows in different types of processes, eventually facilitating process automation, and providing predictive capabilities. It enables organizations to maintain control over their processes.

Workflow management is expected to provide increased process efficiency through improved information availability, task assignment on an automatic basis, process monitoring, and process standardization. Although workflow monitoring and management spans a broad continuum, the key idea of workflow management is to track process-related information. When the first prototype of a workflow management system (WfMS) was developed, the early idea of business process automation was initiated. The research on business processes and related workflows have gained greater interest since the early 1990s. Research about business processes and workflows has become a prominent area that attracts attention both from academia and from industry. Workflow management systems have been considered as efficient tools that enable the business process management, the business process reengineering, and eventually the automation of organizational business processes. Workflow management has been considered as an efficient way of monitoring, controlling, and optimizing business processes through information technology support and is playing an important role in improving an organization's performance through the automation of its business processes.

The workflow management coalition (WMC) defines a workflow as a computerized facilitation for the automation of a business process, in whole or in part. Three types of workflows are generally recognized in literature. A production workflow is associated with routine processes, and is characterized by a fixed definition of tasks and an order of execution. An ad hoc workflow is associated with non-routine processes, which could result in a novel situation. In an administrative workflow, cases follow a well-defined procedure, but alternative routing of a case is possible. Compared with the other two types, production workflows correspond to critical business processes and possess high potential to add value to the organization.

It is important to study both intra- and inter-organizational business processes. A scientific approach is needed for addressing complex business processes taking place within and beyond the enterprise. Not only does the intra-organizational business process need to be addressed, but so does the inter-organizational process.

Inter-organizational workflows are comprised of intra- and inter-organization workflows. Wolfert et al. define intra- and inter-organizational integration, process integration, and application integration in this way: Intra-organizational integration overcomes fragmentation between organizational units; inter-organizational integration integrates enterprises in the supply chain; process integration aligns tasks through coordination; and application integration aligns software systems to reach cross-system interoperability (Wolfert, Verdouw, Verloop &, Beulens, 2010).

Process integration is one of main types of industrial integration and can be either intra- or inter-organizational. Process modeling is not only expected to help automate business processes within the organization, but also to automate inter-organizational business processes. As such, more efforts have been focused on the integration of inter-organizational systems to form inter-organizational architecture. Due to the closed connections between process management and workflow management, an intra- and inter-organizational workflow management capability is expected to enhance the performance of intra- and inter-organizational integration. Inter-enterprise workflow architecture supports the inter-operations between independent enterprises. An intra- and inter-organizational workflow management capability can enhance information sharing at both the intra- and inter-organizational levels, eventually enabling all of the partners in the extended supply chain system to better collaborate, to optimize operations, and to gain competitive advantage.

Today, a changing business environment requires an organization to dynamically and frequently adjust and integrate both its intra- and inter-organizational processes and workflows. Workflow management systems are increasingly applied to cooperative business domains including cooperative engineering design, and they are inter-organizational. Inter-organizational business process and workflow management provides enterprises the opportunity to reshape their business processes beyond their organizational boundaries. Benefits of interconnecting business processes and workflows across systems and organizations include higher degrees of integration and the facilitation of the material and information flows.

WfMS defines, manages, and executes workflows through the execution of software. WfMS has become a standard solution for managing complicated processes in many organizations since its appearance in the early nineties. Despite a few failures associated with the introduction of WfMS, workflow technology has managed to become an indispensable part of enterprise systems. Workflow technology can be used to improve the business process and to increase performance, since the improvement can be quantified with respect to lead time, wait time, service time, utilization of resources, etc. WfMS can be employed as a repository of valuable process knowledge and can act as a vehicle for collecting and distributing knowledge across the supply chain. WfMS can also be used as a platform for knowledge sharing and learning inter-organizationally, and allows the knowledge workers in each organization to perform creative intellectual activities.

Practicing inter-organizational workflow management requires coping with technical challenges. The complex nature of business processes, particularly processes spread across multiple organizations, presents technical challenges. Most traditional workflow management systems assume one centralized enactment service, are only able to support workflows within one organization, and have problems in dealing with workflows crossing organizational boundaries. It is critical to ensure that technical problems such as inconsistency do not arise due to the lack of transparency across different organizations.

Workflow research can be viewed in terms of three layers. The first layer pertains to issues about intra-organizational workflows, which link activities between the different units within one organization. The second layer corresponds to inter-organizational workflows, which cover distributed processes between different organizations. The third layer concerns the workflows in e-business settings. Effective management of business processes relies on sophisticated workflow modeling and analysis.

The existing workflow modeling techniques have advantages as well as disadvantages. Among the workflow modeling techniques, most of them have shown the capability in graphical representation and formal semantics in modeling workflows in an intra-organizational context. Currently, there is an urgent demand for translation between various models so that different workflow management systems can interoperate with each other. This could lead to methods that will enable the integration of heterogeneous models within a unified framework. Efforts regarding inter-organizational workflow modeling are exploring the better approaches in order to combine different organizational workflows while continuing to reconcile the differences. Some approaches have been specifically proposed for modeling inter-organizational workflows, such as the routing approach and the interaction model. Some cognitive approaches have been proposed for the dynamic routing of information; meanwhile, new languages have been proposed to handle the routing of information among organizations. At present, in the area of workflow management, there has been great interest in service workflow modeling and security management. SwSpec is a service workflow specification language which allows arbitrary services in a workflow to formally and uniformly impose requirements. System flexibility has been considered to be a major functionality of workflow systems. More research is needed for such functionality in order to provide sufficient flexibility for coping with complex business processes. Other topics for research include the communication among multi-workflows in complicated business process, simplifying the workflow modeling process, and automating workflows, among other topics.

In process modeling, existing techniques still have limitations as they attempt to address only some of the modeling aspects. For example, business process models may contain numerous elements with complex intricate interrelationships. Efforts are needed to address how to properly capture such complexities.

3.2 Information integration and interoperability

Regli and other researchers have indicated the key technological issue of engineering informatics is “the apparent lack of fundamental progress in areas of information integration” (Regli, 2007). Subrahmanian and Rachuri indicate the numerous incompatibilities in engineering information exchange and coordination. The delays that occurred in Airbus 380 and Boeing 787 are examples of the problems of this nature (Subrahmanian & Rachuri, 2008). Although there has been different explorations, there is still much progress to be made that can provide effective methods for information integration (Broy, 2006), and the information integration within or across industrial sectors.

Today’s businesses of all sizes need to share data with suppliers and customers. Information integration is not only significant for large scale enterprises or for supply chain integration, but also at the microscopic level. Compressed product development cycles and just-in-time (JIT) imply that intra- and inter-organizational systems must be inter-connected, and the applications composing the information systems of enterprises increasingly need to work together. Meanwhile, the demand for engineering integration has also been increasing.

As a consequence of such developments, enterprise systems are increasingly moving toward inter-organizational integration as the benefits of inter-organizational information sharing become obvious. An inter-organizational system is aimed at providing a higher level system related to activities that involve the coordination of business processes (both intra-and inter-organizational) and is able to provide an integrated architecture to organizations within the supply chain. Now, more efforts have been focused on inter-organizational systems, and more and more enterprises have moved toward inter-organizational integration in order to support supply chain management. Inter-organizational systems are able to allow communication between partners in the supply chain. Integrated enterprise systems can collect valuable management information for all of the related business processes across the supply chain including engineering processes. By using integrated systems, organizations can better predict their markets, can better innovate in response to market conditions, and can better align their operations across supply chain networks.

The integration of inter-organizational systems is a complex task for most enterprises. Several frameworks have been proposed for information integration. Fox et al. indicate that at the core of the supply chain management system lays a generic enterprise model (Fox, Chionglo &, Barbuceanu, 1993). Hasselbring proposes a three-layer architecture for integrating different types of architectures (Hasselbring, 2000). In Puschmann and Alt’s framework, the data level is considered as a separate layer (Puschmann & Alt, 2004). Giachetti’s framework includes a typical characterization of the different types of integration (Giachetti, 2004). However, as indicated by Wolfert et al. (Wolfert et al., 2010), the contents of these frameworks are not comprehensive, and an overall framework of information integration has yet to be developed.

The current level of engineering integration may be limited by the lack of techniques, and the successful execution relies upon more sophisticated integration techniques than what is currently available. It is expected that IIIE as well as engineering informatics will attract more efficient and effective integration methods in which the seamless integration of industrial operations and inter-organizational systems can be realized. Among the new technologies, IoT has attracted much attention.

IoT can be considered as a global network infrastructure composed of numerous connected devices that rely on sensory, communication, networking, and information processing technologies. A foundational technology for IoT is the RFID technology, which allows microchips to transmit the identification information to a reader through wireless communication. By using RFID readers, it is possible to identify, track, and monitor any objects attached with RFID tags automatically. Another foundational technology for IoT is the wireless sensor networks (WSN), which mainly use interconnected intelligent sensors. The advances in both RFID and WSN significantly contribute to the development of IoT. In addition, many other technologies and devices such as cloud computing are being used to form an extensive network for supporting IoT (see *Figure 5*).

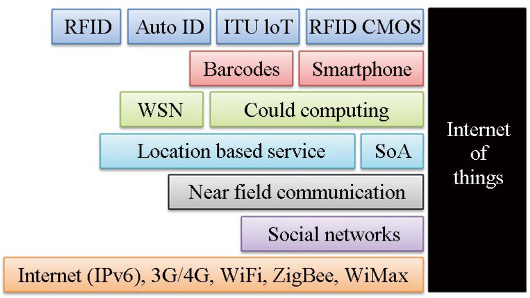

Figure 5. Technologies associated with IoT.

In industrial applications, IoT's applications include industrial monitoring. So far IoT has been gaining attraction in industry sectors such as manufacturing. With the advances in wireless communication and sensor network technologies, more and more networked things or smart objects are being involved in IoT. As a result, these IoT related technologies have been making a significant impact on new ICT, industrial integration, IIIE, as well as engineering informatics (see *Figure 6*).

IoT related technologies have made an impact on industrial sectors already. As an example, IoT has been applied to mining industry. Mine safety is a big concern for many countries due to the working condition in the underground mines. To prevent and reduce accidents in the mining, there is a need to use IoT technologies to sense mine disaster signals in order to facilitate early warning, disaster forecasting, and safety improvement of underground production.

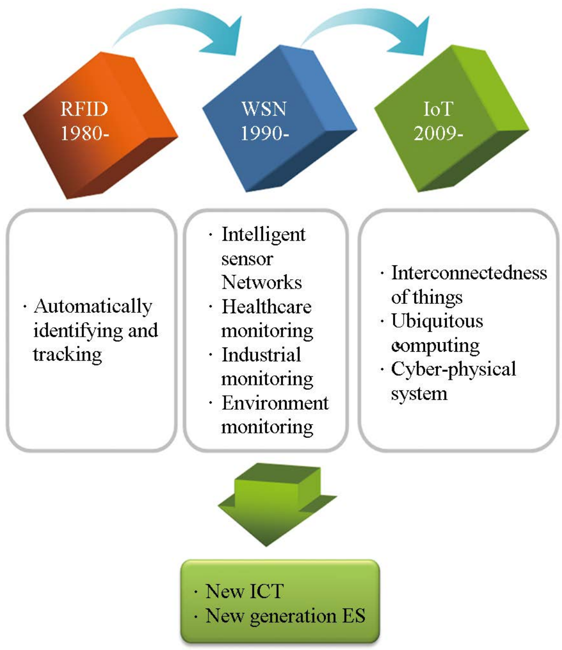

Figure 6. IoT related technology and their impact on new ICT.

By using RFID and wireless communications technology to enable effective communication between surface and underground, mining operations can track the location of underground miners and analyze critical safety data collected from sensors to enhance safety measures.

3.3 Enterprise architecture and enterprise application integration

"Interdisciplinary collaborations will be especially important for implementing comprehensive processes that can integrate the design of mechanical systems with the design of electrical systems and software. Successful collaborations, however, will first require overcoming incompatibilities between emerging technologies and the existing technological infrastructure and organizational cultures" (National Science Foundation, 2004, p.10).

To industrial organizations, an enterprise can be an organization, a part of a larger enterprise, or an extended enterprise. An EA defines the scope of the enterprise, the internal structure of the enterprise, and its relationship with the environment. As it describes the structure of an enterprise, it comprises main enterprise components such as enterprise goals, organizational structures, and business process, as well as information infrastructure including engineering information infrastructure. An EA is generally considered an important aid for understanding and designing an enterprise. Just as information infrastructure is a component of EA and the term enterprise as used in EA generally involves information systems employed by an industrial organization, EA is highly relevant to IIIE and engineering informatics, as IIIE concerns information flow within the entire industrial organization, and engineering informatics concerns information flow within the engineering domain.

Enterprise architects use a variety of models, methods, and tools to describe the structure and dynamics of an enterprise. Artifacts are used to describe the logical organization of business processes and business functions, as well as information architecture and information flow. A collection of these artifacts is considered to be its enterprise architecture.

An enterprise architecture's landscape is usually divided into various domains which allow enterprise architects to describe an enterprise from a number of important perspectives. One of the main domains in EA is the information domain. The important components in this domain include information architecture. Software architecture, network architecture, and database architecture are components of information architecture. The other two domains with components that are highly relevant to industrial information integration are the application domain and its component "interfaces between applications" and technology domain with its components as middleware, networking, and operating systems.

Representing the architecture of an enterprise correctly and logically will improve the performance of an organization. This includes innovations about the structure of an organization, business process re-engineering, and the quality and timeliness of the information flow that represents material flow. This also includes "overcoming incompatibilities between emerging technologies and the existing technological infrastructure and organizational cultures" as emphasized by the National Science Foundation (National Science Foundation, 2004, p.10).

Enterprise integration has become a key issue for many enterprises looking to improve business processes through integrating and streamlining processes both internally and with partners in the supply chain. It consists of plans, methods, and tools. Typically, an enterprise has existing legacy systems which are expected to continue in service while adding or migrating to a new set of applications. Legacy and newer systems are expected to be integrated to provide greater competitive advantages. Integrating data and applications is expected to be accomplished without requiring significant changes to existing applications and/or data. In general, those enterprise applications that were not designed as interoperable need to be integrated on an intra- and/or inter-organizational basis. To address this issue, a solution that can help to achieve quality integration is referred to as EAI. Originally, EAI was only focused on integrating enterprise systems with intra-organizational applications, but now it has been expanded to cover aspects of inter-organizational integration. EAI facilitates the integration of both intra- and inter-organizational systems. Solutions comprise the efficient integration of diverse business processes and data across the enterprises, the interoperation and integration of intra- and inter-organizational enterprise applications, the conversion of varied data representations among involving systems, and the connection of proprietary/legacy data sources, enterprise systems, applications, processes, and workflows inter-organizationally.

EAI entails integrating enterprise data sources and applications so that business data and processes can be easily shared. EAI is able to integrate the heterogeneous applications which are created with different methods and on different platforms. The integration of enterprise applications includes the integration of data, business processes, applications, and platforms, as well as integration standards. Through creating an integrative structure, EAI connects heterogeneous data sources, systems, and applications intra- or inter-organizationally. EAI aims to not only connect the current and new system processes, but also to provide a flexible and convenient process integration mechanism. By using EAI, intra-or inter-organizational systems can be integrated seamlessly to ensure that different divisions or even enterprises can cooperate to each other, even using different systems. A complete EAI offers functions such as business process integration and information integration. Through the coordination of the business processes of multiple enterprise applications and the combination of software, hardware, and standards together, enterprise systems can exchange and share data seamlessly in a supply chain environment.

In EAI, the constantly changing business requirements and the need for adapting to the rapid changes in the supply chain may require help from SOA. EAI provides the integration of both intra- and inter-organizational systems and is moving toward integrating both intra- and inter-organizational applications. The objective of EAI is to facilitate information exchange among business enterprises in a timely, accurate, and consistent fashion, in order to support business operations in a manner that appears to be seamless.

EA and EAI are of significance for overcoming incompatibilities between emerging technologies and the existing organizational and technological infrastructures, as indicated by US National Science Foundation (National Science Foundation, 2004, p.10).

3.4 SOA

SOA represents the latest trend in integrating heterogeneous systems which has great potential in engineering informatics. SOA has received much attention as an architecture for integrating platforms, protocols, and legacy systems, and it has been considered as a suitable paradigm that helps integration, since it is characterized by simplicity, flexibility, and adaptability. Srinivasan, Lammer and Vettermann (Srinivasan, Lammer & Vettermann, 2008) indicate the importance of SOA in engineering informatics. Their paper describes how product information sharing service has been architected and implemented using the concept and techniques of SOA.

SOA represents an emerging paradigm for engineering informatics to use in order to coordinate seamlessly in the environment of heterogeneous information systems, enabling the timely sharing of information in the cooperative systems, and developing flexible large-scale software systems for engineering applications. Some example applications related to engineering informatics include the information integration based on SOA in agri-food industry (Wolfert et al., 2010), among others.

4 Summary and challenges

Despite that engineering informatics has been formally proposed as a discipline, significant challenges still remain. Research indicates that training engineers for 21 century with the capacity of using engineering informatics presents a challenge to us (Subrahmanian & Rachuri, 2008). Lack of a single stakeholder is another challenge. As such, it is difficult to evaluate economic costs and benefits of information interoperability (Broy, 2006).

Although there has been a variety of explorations of information integration methods, there is still much progress to be made that can provide effective methods for information integration. Developing universal metrics for information integration can be challenging (Broy, 2006).The development of advanced methodologies, especially formal methods and a systems approach, have to be synched with the rapid technological developments. Solving "system of systems" problems can be challenging. Engineering informatics involves complexity which mainly stems from their high dimensionality and complexity. For engineering informatics, there exists a gap between the level of complexity and dimensionality inherent and the set of formal methods that could potentially contribute. The interdisciplinary nature of engineering informatics implies another challenge, i.e., the complexity level will rise as it involves a multiplicity of informatics and a variety of engineering subjects.

Although some technologies introduced in this paper are currently not yet fully used in industrial information integration and engineering informatics, they are expected to have great potential to play a major role in near future. Efforts focusing on blending the capabilities of existing technology and the emerging technologies are needed. With this blending, industries will be able to harness the power of current and emerging technologies to dramatically improve the performance of industrial information integration including engineering informatics by adopting new technologies. The successful engineering informatics practice relies upon sophisticated technologies than those that are available now. There are still many challenges and issues that need to be resolved in order for engineering informatics to become more applicable. However, both IIIE and engineering informatics will continue to embrace cutting-edge technology and techniques, and will open up new applications that will impact industrial sectors. IIIE and engineering informatics can and will contribute to the success of this endeavor.

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