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Engineering Informatics – State of the Art and Future Trends

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13.1 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 the application of advanced computing, information, and communication technologies to a variety of engineering disciplines.

Computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM) are the terms that have appeared 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. Meanwhile, computing technology in engineering has also continuously promoted the advances in computing technology. In this evolution process, computing technology, computational methods, and a variety of engineering disciplines have increasingly intertwined as the development of the theory and practice in both disciplines (computing technology and engineering) influences each other.

Since 1990, the need for a scientific subject called engineering informatics has been recognized, although the subject has not yet been formally recognized as a scientific and engineering discipline. The following are excerpted from reports from either the National Science Foundation or the National Academies:

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

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 and 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 and Rachuri, 2008). Informatics has an engineering aspect, which addresses the engineering and operation of information processing systems that compute, store, communicate, and visualize information (Broy, 2006).

Subrahmanian and Rachuri (2008) further indicated 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 and Rachuri, 2008). Subrahmanian and Rachuri identified several strands of concepts that support the proposing of engineering informatics as a distinct discipline that interfacing engineering and informatics (Subrahmanian and Rachuri, 2008). As computer scientists or engineers cannot solve engineering informatics problems in the context of engineering systems alone, engineering informatics is an interdisciplinary and collaborative effort. In other words, the lack of required backgrounds among computer scientists in engineering and engineers in computing technology has led to develop a new interdisciplinary subject—engineering informatics.

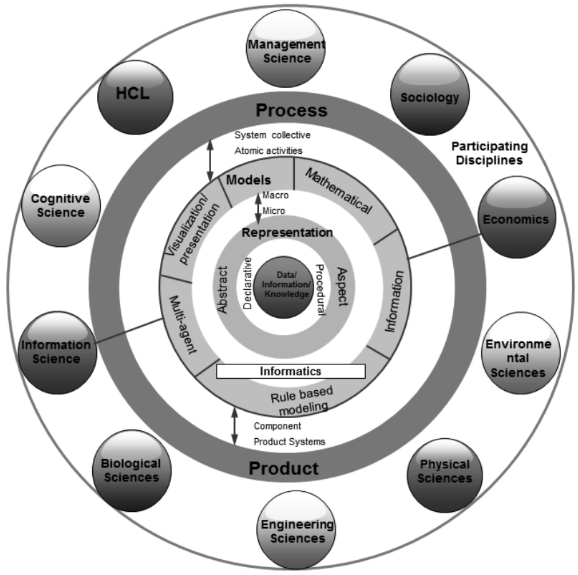
Engineering informatics is an interdisciplinary subject. For example, constructing an embedded software system for engineering purpose requires interdisciplinary efforts in mechanics, the domain, software, hardware, human-machine interfaces, and other disciplines. Engineering informatics is to use the knowledge from both informatics and engineering for forming engineering informatics knowledge framework and base.

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 (2006), "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, and structural engineering, AEC (architecture, engineering, construction) and other disciplines…" (Turk, 2006).

As informatics is applicable in multiple engineering disciplines or span multiple engineering disciplines, as such, the term "engineering informatics" was proposed, coined, and started to be used. It is natural that the informatics for a specific engineering subject start 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 and Rachuri, 2008).

Subrahmanian and Rachuri proposed their view of the field of engineering informatics (for fully represent the original contents, Figure 1 was reproduced from (Subrahmanian and Rachuri, 2008). In Figure 13.1, the inner set of circles marked as informatics covers the fundamental activities associated with informatics in general. The next circle, denoted by Product and Process, identifies the multilevel, multi-scale modeling activities of products and processes. The role that informatics plays in engineering products and processes has been becoming significant in past decades. The outer circles show the inputs to engineering informatics from a number of disciplines that provide the domain knowledge and methods and tools.

Figure 13.1. The Scope of Engineering Informatics Proposed



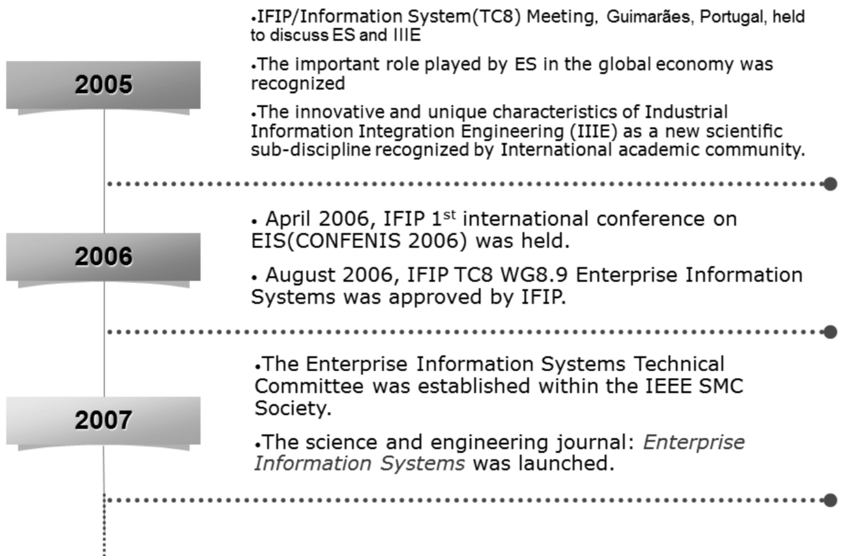
Although Subrahmanian and Rachuri proposed their view of the field of engineering informatics, the scope of engineering informatics, can be further refined. As indicated by Broy (2006), software and systems engineering is the key for constructing information processing systems. In particular, software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

Regli (2007) 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. In 2008, Subrahmanian and Rachuri indicate the numerous incompatibilities in information exchange and coordination. The delays that occurred in Airbus 380 and Boeing 787 are examples of the problems of this nature (Subrahmanian and Rachuri, 2008). The information integration within or across industrial sectors is still a dream. 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).

Before the need for engineering informatics was formally presented in 2007 and term "engineering informatics" was coined in 2007 and 2008 (Subrahmanian and Rachuri, 2008; Regli, 2007), a scientific and engineering discipline called Industrial Information Integration Engineering was formerly proposed and recognized by international organizations International Federation for Information Processing (IFIP) and the Industrial Information Integration Engineering (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 (Roode, 2005; Raffai, 2007). 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 IT infrastructure for industrial sectors, 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 (CONFENIS, 2006) would be held 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 SMC 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,* was launched in 2007 (Figure 13.2). In 2016, the science and engineering journal entitled *Journal of Industrial Information Integration,* exclusively devoting itself to the topics of IIIE, will be launched (Elsevier, 2016).

Figure 13.2. IIIE Discipline History



The concept of IIIE emphasizes multiple aspects, including one of the major aspects that completely overlaps with the scope of engineering informatics: engineering information integration.

This chapter is focused on one of the major aspects of IIIE that completely overlaps with the scope of engineering informatics: engineering information integration. The objective of this article 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 the relationship between engineering integration and engineering information integration. Section III describes major techniques or technologies in engineering information integration applicable to engineering informatics, while Section IV concludes this paper.

13.2 Overview of Engineering Information Integration

13.2.1 IIIE-A New Discipline of Industrial Information Integration

Broadly speaking, IIIE 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 information technology infrastructure for industrial sectors, especially in the aspect of information integration (Xu, 2015). 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) And, at each level of IIIE (i.e., frameworks, theories, and models/techniques), how can real-world problem solving support be provided? IIIE is an interdisciplinary discipline with the typical characteristics of giant and complex system. According to the subsystems that make up a system, the number of subsystems 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 a 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.

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 National Academy of Engineering in the U.S. The National Academy of Engineering is organized into 12 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 for the workflows that are commonly modeled and represented include managerial perspective. Based on the definition of management defined (Xu and Xu, 2011), in a broad sense, management is the most comprehensive science that covers all the disciplines. Judging from these, IIIE is defined as a complex giant system that can advance and integrate the concepts, theory, and methods in each relevant discipline and opens up a new discipline for the industry information integration purposes, which is characterized by its interdisciplinary nature. Figure 13.3 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 13.3. Discipline Structure of IIIE

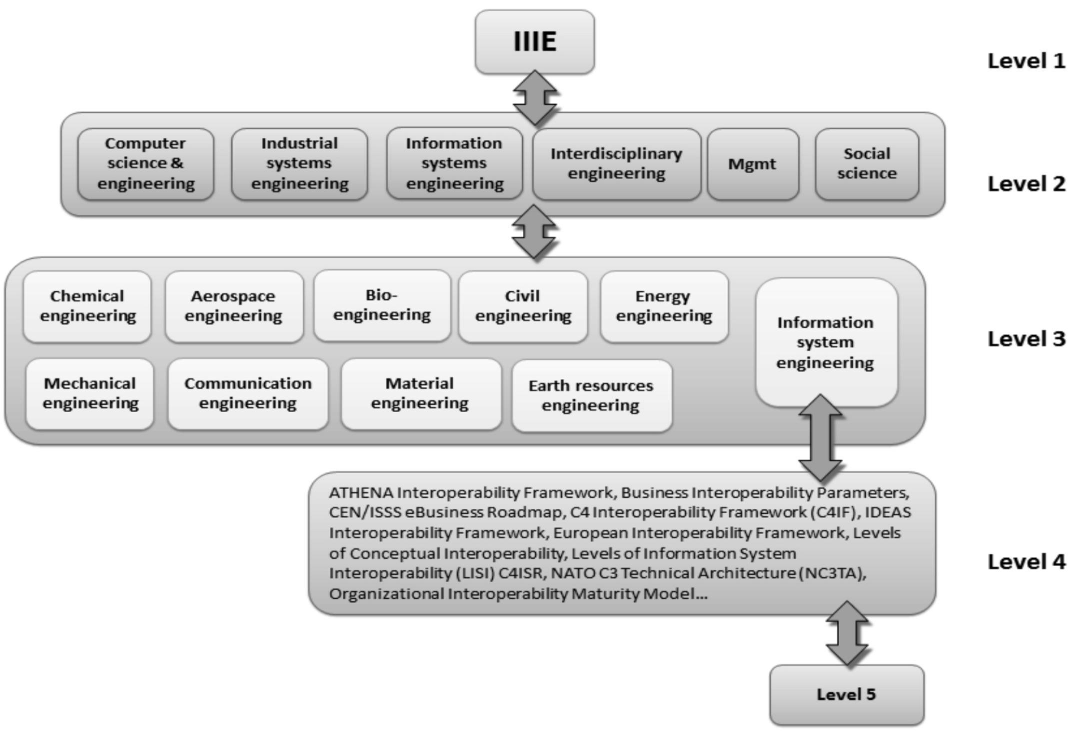
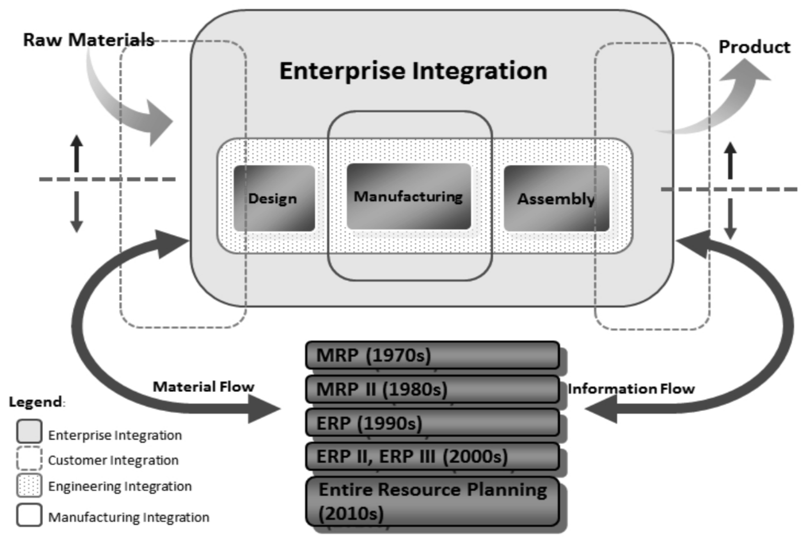


Figure 13.3 can be huge in size in order to cover all of the details involved. For example, enterprise interoperability is involved with frameworks such as the ATHENA Interoperability Framework, Business Interoperability Parameters, the CEN/ISSS eBusiness Roadmap, C4 Interoperability Framework (C4IF), the 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.

13.2.2 Engineering Integration

In today's global competition atmosphere, industrial systems including engineering systems need to be constantly and smoothly reengineered in order to allow them to respond to the fluctuating market and to technological evolution. In 1980s, traditionally, MRP II systems interface with engineering design systems to receive BOM and routing information. However, the interface is not always advanced, as it is unable to pass critical information back to the engineering design system. In 2000, engineering integration became one of the main components of enterprise systems (Langenwalter, 2000). Figure 13.4 shows the relationship between engineering integration, manufacturing integration, customer integration, and enterprise integration.

Figure 13.4. The Relationship Between Engineering Integration, Manufacturing Integration, Customer Integration, and Enterprise Integration



In general, about 90% of a product's cost is determined during its design cycle; its quality characteristics are also determined during the product design stage. In a typical product development process (such as in plastic injection mold design), the design 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 knowledge* must be integrated. A complete integration includes the design process, product data management, integration with customers, integration with suppliers, integration with the rest of the organization, and project management. The ways in which the engineering division integrates with the rest of divisions in an enterprise have been intensively researched.

According to Kulvatunyou and Wysk (2000), integration can be classified into three types:

1. Data-oriented integration, which integrates CAD, CAPP, CAM, and CIM;
2. Structure-oriented integration, which is an implementation of team-oriented concepts, such as the use of a simultaneous engineering team, a concurrent engineering team, and an integrated product and process development team;
3. Procedure-oriented integration, which refers to concurrent engineering-enabling technologies include QFD, the Taguchi method, axiomatic design, and design for manufacturing and assembly.

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, computer-aided process planning (CAPP), and computer-aided manufacturing (CAM) tool path generation, etc. However, this desirable scenario has not been fully realized due to the interoperability limitations of different software packages.

A concurrent design process consists of many design activities that are interrelated with each other. Concurrent design has become increasingly important in designing complex products. When it is implemented in manufacturing enterprise systems along with engineering integration, it is likely to generate better design. Numerous concurrent design techniques have been developed, such as PERT (Project Evaluation and Review Technique), ISM (Interpretative Structure Modeling), DSM (Design Structure Matrix), Petri nets, and polychromatic sets. Each of these methods has some weakness. For example, PERT is useful for the design processes in which activities have a clear sequential relationship. However, it is inflexible and therefore unable to include feedback information and the iterative characteristics of the concurrent design. Using the adjacent matrix, ISM and DSM can apply partitioning algorithms and other algorithms in the concurrent design process. Although the Petri net is suitable for modeling concurrent processes, it does not have sufficient capacity to represent data flow or handle computational complexity. UML is a graphical and visual modeling language. Integrating UML with polychromatic sets provides a powerful tool for modeling and analyzing concurrent design processes. UML has been applied in concurrent design such that a 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, the concurrent design process can be modeled formally and analyzed quantitatively, and the major factors that affect the concurrent design process can be considered.

In the CAD/CAM field, the comprehensive design of dimensional and geometric tolerances for mechanical products using computers is called Computer Aided Tolerancing (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. The research covers: (1) the concept for determining the geometric shape and the dimensional and geometric tolerance of a part using a computer. Based on this, designed dimensions and tolerances of the part with a geometric shape can be described using mathematical formulae; (2) the method to control the tolerance of design and manufacturing using computerized dimension chain; (3) the theory of tolerance, which defines the concept of tolerance according to the offset values of the real entity of a part and provides a theoretical basis for its CAT design; (4) the concept of virtual boundary requirements (VBRs), which describe tolerance and conditional tolerance; (5) TTRS (Topologically and Technologically Related Surfaces) theory, which establishes the important theoretical foundation for dimensional tolerance and geometric modeling in the CAD system; (6) and the theory based on wavelet and fractal technology with application in designing the tolerance.

With the continuous development of CAT technology, a number of tolerance models have been proposed, such as attribute models, parametric models, kinematic, and DOF models. In attribute models, a tolerance can be directly stored as an attribute of either geometric entities or metric relations. Offset models can obtain the maximal and minimal object volumes by offsetting the object by corresponding amounts on either side of the nominal boundary. However, they cannot distinguish the interactions of different tolerance types. Parametric models represent tolerances as ± variations of dimensional or shape parameters. In current CAD systems, the modeling method for parametric models has been widely applied. Kinematic models use vector additions to analyze tolerances. A kinematic link is used between a tolerance zone and its datum features. TTRS models have many similarities to DOF models.

With the development of three-dimensional (3D) CAD system, it has become urgent to construct a 3D dimension chain and to comprehensively design dimensional and geometric tolerances. Researchers have put forward the Variational Geometric Constraint (VGC) theory, which can effectively handle the comprehensive design of dimensional and geometric tolerance, although with some difficulties in computation.

In CAD/CAM technology, the importance of CAT research has been emphasized by researchers. Consequently, CAT research is becoming more and more popular. The polychromatic sets theory has been applied in CAT. Based on the VGC theory and TTRS theory, a hierarchical reasoning model of tolerance information is developed that applies the polychromatic sets theory to describe the model, optimizes computer-aided generation of tolerance types, and provides a basis for developing tolerance network and designing tolerance. The research introduces the application of the hierarchical reasoning model as well as its reasoning method, based on assembly-oriented tolerance generation. Polychromatic sets theory is a mathematical theory tool that 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 life-cycle simulation, product conceptual design, concurrent engineering, and virtual manufacturing for product modeling, process modeling, and process optimization.

In recent years, engineering design has required more and more multidisciplinary design activities. Engineering designers from a number of different disciplinary areas may interact and exchange in the design process. Therefore, seamless integration and efficient processing of engineering data among numerous heterogeneous data sources plays an important role in engineering design. Hence, engineering integration is assumed to support multidisciplinary engineering design activities throughout product development cycles. The ubiquitous characteristics of data diversity, irregularity, and heterogeneity will distinctively differentiate engineering information integration from information integration in other domains in IIIE. This poses a challenge to effective engineering integration. There has been much ongoing research in this area. The topics cover: (1) the methodology for developing a virtualization-based simulation platform in support of multidisciplinary design of complex products; (2) approaches for engineering software integration and product data exchange to support interoperability among different engineering phases; (3) mathematical formulation and optimization method for engineering problems; (4) autogenetic design theory and distributed computing approaches and their applications to multidisciplinary design optimization; and (5) web services-based multidisciplinary design optimization frameworks, which provide data exchange services and integration.

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.

13.3 Enabling Technologies

In this section, we will introduce the main enabling technologies for engineering informatics as well as IIIE, which include business process management, information integration and interoperability, enterprise architecture and enterprise application integration, and service-oriented architecture (SOA).

Rapid advances in industrial information integration methods have spurred tremendous growth of a variety of techniques. These techniques include business process management, workflow management, EAI, SOA, and others. Many applications require a combination of these techniques. At present, we are at a new breakpoint in the evolution of selected enabling technologies.

13.3.1 Business Process Management

Engineering design process modeling can inherit methods and approaches developed in business process management. Theiben, Hai and Marquardt (2008) introduced a methodology 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, and Marquardt, 2008).

IIIE enables the integration of business processes throughout an organization with the help of Business Process Management (BPM). 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 process, increasing their agility in responding to the changing environment for competitive advantage, accomplishing business process reengineering, and realizing cost reduction.

Process modeling is an interesting topic in IIIE and engineering informatics. The modeling, monitoring, and controlling of industrial processes is important, as it enables us to understand and optimize such processes. Manufacturing process modeling is a typical example. All process details in a manufacturing process that relate to the desired outputs of the process need to be understood. In general, a precise process model that relates processes is required. As such, modeling manufacturing processes is important as it enables manufacturers to understand the process and to optimize the process operation. Modeling industrial control is an example also. Such modeling draws the domain expertise of multiple disciplines/subjects including ICT, process technology, and factory automation, and industrial communication systems. Process modeling results can be applied to process automation and factory automation. The control and predictive capability of business process management also offers useful insights into quite a few engineering fields covered in Figure 13.3. As previously mentioned, IIIE is interdisciplinary. Industrial process modeling can be listed in Figure 13.3 at a level below Level 3; as such, the industrial process control itself is a complex interdisciplinary subject. To track process-related information and the status of each instance of the process as it moves through an organization, the concept of workflow becomes important. Workflow 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 provides increased process efficiency through improved information availability, process standardization, task assignment on an automatic basis, and process monitoring using specific management tools (i.e., WfMS). 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 system was developed, the early idea of automation of business processes was initiated. Workflow management allows managing workflows for different types of processes, facilitating process automation and providing predictive capabilities, and it enables organizations to maintain control over their processes. Business processes and their related workflow systems have gained greater interest since the early 1990s; research about enterprise business processes and workflows has become a prominent area that attracts attention both from academia and industry.

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 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. Hence, the administrative workflow is usually the focus of most studies on workflow modeling.

Workflow management has been considered to be 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. Process modeling is not only expected to 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. For this purpose, it is necessary to study both intra- and inter-organizational business processes with a scientific approach. IIIE is required 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 also so does the inter-organizational process.

Today, workflow systems are increasingly applied to cooperative business domains including cooperative engineering design, and they are inter-organizational. As such, workflow management needs to be completed on an inter-organizational basis. Inter-organizational business process management also provides enterprises the opportunity to reshape their business processes beyond their organizational boundaries. A changing business environment requires an organization to dynamically and frequently adjust and integrate both its intra- and inter-organizational processes. Additional benefits of interconnecting business processes across systems and organizations include higher degrees of integration and the facilitation of the information and material flows.

Inter-organizational workflows are comprised of intra- and inter-organization workflows. Wolfert et al. (2010) defined intra- and inter- integration and process 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.

Process integration, as mentioned earlier, is one of main types of integrations and can be either intra- or inter-organizational. Due to the closed connections and transformations between process management and workflow management, an intra- and inter-organizational workflow management capability can enhance the performance of intra- and inter-organizational integration. Inter-enterprise workflow architecture supports the interoperations between independent enterprises. Meanwhile, an intra- and inter-organizational workflow management capability can also 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.

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 1990s. 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, both of which comprise the inter-organizational workflow. The third layer concerns the workflows in e-business settings. Effective management of business processes relies on sophisticated workflow modeling and analysis.

Among the 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.

The existing modeling techniques have advantages as well as disadvantages. Efforts regarding inter-organizational workflow modeling are exploring the better architectures 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.

In terms of evaluation, qualitative evaluation methods mainly focus on checking for structural soundness, which can usually be done through the validation and verification of workflows. Quantitative evaluation methods require the calculation of performance indices related to workflows. The existing techniques include computational simulation, the Markovian chain, and queuing theory, among others.

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 that 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. Existing techniques in process modeling 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.

13.3.2 Information Integration and Interoperabilty

Subrahmanian and Rachuri (2008) indicated the numerous incompatibilities in information exchange and coordination. The delays that occurred in Airbus 380 and Boeing 787 are examples of the problems of this nature (Suvrahmanian and Rachuri, 2008). The information integration within or across industrial sectors is still a dream. 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). Although there has been several different explorations of different theories of design and manufacturing, progresses yet to be made that can provide effective methods for information integration (Broy, 2006).

Today’s businesses of all sizes need to share data with suppliers, distributors, and customers. Information integration is not only significant for large-scale enterprise or for supply chain integration, but also at the microscopic level. Compressed product development cycles and lifetimes and just-in-time stocking imply that management systems must be interconnected, and the applications composing the information systems of enterprises increasingly need to work together. As such, the demand for integration has 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. By using integrated supply chain management, 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, Chionglo and Barbuceanu (1993) indicated that at the core of the supply chain management system lays a generic enterprise model. Hasselbring (2000) proposed a three-layer architecture for integrating different types of architectures. In Puschmann and Alt’s (2004) framework, the data level is considered as a separate layer. Giachetti’s (2004) framework includes a typical characterization of the different types of integration. However, as indicated by 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 sophistication of the relevant technologies or by the lack of techniques, and the successful execution relies upon more sophisticated IIIE integration than what is currently available. It is expected that IIIE integration will attract more efficient and effective methods for automated engineering management in which the seamless integration of inter-organizational systems is highly expected. Among the new technologies, IoT and radio frequency identification (RFID) have attracted much attention. RFID is a contactless and low-power wireless communication technology that has application in many areas of the supply chain. The envisioned applications include information to be collected from a network of RFID sensors and IoT combined.

13.3.3 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). To industrial organizations, an enterprise can be an organization, a part of a larger enterprise, or an extended enterprise. An enterprise architecture (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. 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, since IIIE concerns information flow within the entire industrial organization.

Enterprise architects use a variety of business models, conceptual tools, and analytical methods 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 EA. Software architecture, network architecture, and database architecture are partial components of an information architecture.

An EA's landscape is usually divided into various domains that 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 and data architecture. The other two domains with components that are also highly relevant to IIIE 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 reengineering, and the quality and timeliness of the information flow that represents material flows.

Enterprise integration has become a key issue for many enterprises looking to extend 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 that are expected to continue in service while adding or migrating to a new set of applications. Integrating data and applications is expected to be accomplished without requiring significant changes to existing applications and/or data. To address this issue, a solution that can help to achieve quality integration is referred to as Enterprise Application Integration (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. Major EAI-enabling technologies range from EDI to web services and XML-based process integration and provide a flexible, adaptable, and scalable EAI framework. 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 must be able to integrate the heterogeneous applications that 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, since the core of the EAI technology is business process management. 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 general, those enterprise applications that were not designed as interoperable need to be integrated on an intra- and/or inter-organizational basis. As such, legacy and newer systems are expected to be integrated to provide greater competitive advantages. The constantly changing business requirements and the need for adapting to the rapid changes in the supply chain may require help from service-oriented architecture (SOA).

EAI provides the integration of both intra- and inter-organizational systems and databases and is moving toward integrating ES with 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.

13.3.4 Service-oriented Architecture (SOA)

Srinivasan, Lammer and Vettermann (2008) indicated the importance of SOA in engineering informatics. Their paper describes how product information sharing service was architected and implemented using SOA. SOA represents the latest trend in integrating heterogeneous systems that has great potential in engineering informatics. It 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.

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 include the information integration based on SOA in agri-food industry (Wolfert et al., 2010), among others.

13.4 Summary and Challenges

Although the technologies and applications introduced in this chapter are currently not yet fully used in industry, 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.

Research indicates that the successful engineering informatics practice relies more upon sophisticated technologies than those that are available now. Research also indicates that training engineers with the capacity of using engineering informatics presents a challenge to us (Subrahmanian and Rachuri, 2008). Although there has been several different explorations of different theories of design and manufacturing, progresses yet to be made that can provide effective methods for information integration (Broy, 2006). Lack of a single stakeholder is another challenge. As such, it is difficult to evaluate economic costs and benefits of information interoperability (Broy, 2006). In addition, developing universal metrics for information integration and solving “system of systems” design can also be challenging (Broy, 2006). The interdisciplinary nature of engineering informatics implies another challenge as the complexity level rising as it involves a multiplicity of informatics and a variety of engineering subjects.

There are still many challenges and issues that need to be resolved in order for IIIE and engineering informatics to become more applicable. Engineering informatics involves complexity that mainly stems from their high dimensionality and complexity. In recent years, there have been significant developments in this newly emerging technology, as well as actual and potential applications; however, the development of advanced methodologies, especially formal methods and a systems approach, have to be synched with the rapid technological developments. For engineering informatics, there exists a gap between the level of complexity inherent and the rich set of formal methods that could potentially contribute. Despite advancements in the field of IIIE and engineering informatics, both in academia and industry, significant challenges still remain. 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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