Enterprise Systems: State-of-the-Art and Future Trends

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Abstract—Rapid advances in industrial information integration methods have spurred tremendous growth in the use of enterprise systems. Consequently, a variety of techniques have been used for probing enterprise systems. These techniques include business process management, workflow management, Enterprise Application Integration (EAI), Service-Oriented Architecture (SOA), grid computing, and others. Many applications require a combination of these techniques, which is giving rise to the emergence of enterprise systems. Development of the techniques has originated from different disciplines and has the potential to significantly improve the performance of enterprise systems. However, the lack of powerful tools still poses a major hindrance to exploiting the full potential of enterprise systems. In particular, formal methods and systems methods are crucial for modeling complex enterprise systems, which poses unique challenges. In this paper, we briefly survey the state of the art in the area of enterprise systems as they relate to industrial informatics.

Index Terms—Emerging technologies, enterprise information systems (EIS), enterprise systems (ES), industrial informatics, industrial information integration engineering (IIIE).

I. INTRODUCTION

Information Systems (EISs). In the past decade, ES has emerged as a promising tool used for integrating and extending business processes across the boundaries of business functions at both intraorganizational and interorganizational levels. This emergence of ES has been fueled by the global economy and the development in information technology including industrial informatics. The development of information technology and the technological advances in ES have provided a viable solution to the growing needs of information integration in both manufacturing and service industries, as evidenced by the fact that a growing number of enterprises worldwide have adopted ES, such as Enterprise Resource Planning (ERP), to run their businesses instead of using functional information systems that were previously used for partial functional integration within many industrial organizations.

We have witnessed that, in the global economy and in global business operations, there has been a need for ES such as ERP to integrate extended enterprises in a supply chain environment with the objective of achieving efficiency, competency, and competitiveness. For example, the global operations have

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forced enterprises such as Dell and Microsoft to adopt ERP in order to take the advantage of a global supply network. Today, not only the large and medium sized companies but also small companies are quickly learning that a highly integrated ES is a requirement for the global operation. For instance, business-to-business (B2B) integration generally comprises connections to ES [1]. ES has become a basic information processing requirement for many industries. Thus, the ERP market is one of the fastest growing and most profitable areas in the software industry.

It is well recognized that ES has an important long-term strategic impact on global industrial development. Due to the importance of this subject, there has been a growing demand for research about ES to provide insights into the issues, challenges, and solutions related to the design, implementation, and management of ES. In June 2005, at a meeting of the International Federation for Information Processing (IFIP) Technical Committee for Information Systems (TC8) held at Guimarães, Portugal, the committee members intensively discussed the important role played by ES in the global economy and the innovative and unique characteristics of Industrial Information Integration Engineering (IIIE) as a scientific subdiscipline. Broadly speaking, 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 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 SMC Society. To further respond to the needs of both academicians and practitioners for communicating and publishing their research outcomes on ES, the science and engineering journal entitled Enterprise Information Systems, exclusively devoting itself to the topics of ES and IIIE, was launched in 2007.

Simultaneous with the progress made in the *IFIP* and the *IEEE SMC Society* regarding ES and IIIE, new opportunities in the field of industrial informatics were discovered by Wilamowski, Kaynak and other researchers [2]–[4]. They found that, driven by information technology, there has been a paradigmatic shift from industrial electronics to industrial informatics, in which the industrial application of IT has been emphasized more than ever before; in addition, one of the new trends in Critical Infrastructures shows its intensifying interconnections

via information and communications technology [2]-[4]. This led to the realization of how important industrial informatics could be for various industry sectors and, consequently, led to the launching of the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS. This paper is intended to provide the IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS readers an avenue to gain a fresh perspective on ES, an emerging information technology for industrial organizations, as the dialogue among researchers and practitioners in both the industrial informatics and enterprise systems areas are growing. The topics of interest to industrial informatics readers include, but are not limited to, the cross-disciplinary study of enterprise integration, enterprise information architectures, and enterprise information integration techniques. The objective of this paper is to introduce to the communities of industrial informatics the current development and future opportunities that exist in the exciting field of ES, but it is by no means meant to be exhaustive. In Section II, we briefly discuss the advances in ES in terms of three milestones. Section III describes major techniques or technologies in ES development, while Section IV concludes this paper.

II. OVERVIEW OF ENTERPRISE SYSTEMS

A. ERP and ERP II (General Purpose Systems Versus Industry-Oriented Systems)

ES provides a single system that is central to the organization and ensures that information can be shared across all functional areas. The main characteristic of the early ES is to ensure the integration of the internal business processes for an enterprise's coherent internal operation. The tools for bridging the various isolated systems include focusing on common databases and intraorganizational coordination. ES provides an IT platform that enables industrial organizations to integrate and coordinate their business processes; it is considered a revolutionary advance in the continuous evolution of computer applications in business and industry.

A general purpose ES such as SAP R/3 is a software package designed for a wide range of enterprises. The benefits of a general ES are: integrated data and applications, implementation of a generic business model based on the "best practices," standardized solutions of business problems, and opportunities for customizations. Such systems have been categorized into systems specifically designed for traditional or selected nontraditional industries.

For industries within specific sectors with specific needs and tasks, customized ERP packages are generally preferred. For example, in the textile and apparel industry, the bill of material (BOM) for textile production has a "one-to-many" characteristic. Although the production of yarns with different counts, colors, and warp types is made of the same raw material, the difference in the BOM creates a long list of requirements that spans almost all aspects of development including the planning, production, dyeing and finishing, quality control, and sales and distribution specific to the textile industry. Under such circumstances, extraordinary customization efforts are required for a general ES to meet specific requirements and needs. Since many industries have their own processing requirements, general purpose ERP packages may not exactly fit a specific industry for the

reasons such as limited flexibility for customization and the inadequacy of addressing real-world problems in specific industry sectors; in these circumstances, the scale of business process reengineering (BPR) and the customization tasks involved in the software implementation process are considered the major insufficiencies of general purpose ERP [5].

The concept of ERPII was proposed in 2000 and emphasizes two specific aspects: business coordination and industry orientation along with the role and function of the system that is expected to expand to those required by an industry sector or a particular industry [6]. In 2009, ERP systems were further classified into two categories according to their applications, i.e., general purpose systems and industry-oriented systems [7]. An industry-oriented ERP (IERP) system is designed for enterprises belonging to a specific industry sector and often supports specific business needs which are not covered by existing general purpose systems. Implementing an IERP can tackle problems such as low adaptation to specific business processes, the complexity of configuring thousands of parameters, and especially low industry relevance.

An IERP system is designed for a specific industry sector and thus can satisfy most of the processing requirements of the target industry or industries. Due to the fact that the processing requirements in a specific industry can be closely examined and continuously refined, it is not difficult to make continuous improvements to IERP software. As a result, the software modules of IERP systems are able to incarnate more industry-specific requirements, to eliminate redundant modules and functions, and to maintain a moderate scale and size; meanwhile, they deliver this with a much shorter implementation cycle and a higher success rate. Besides, explicit industry orientation is also helpful for ERP vendors to benchmark the best practices within a specific industry sector.

IERP is mainly characterized by more adaptability for a specific industry and by a software componentization approach [7]. The connotation of IERP-oriented componentization mainly includes the following aspects. First, IERP componentization means a software development process through which organizations identify common functionality among applications within a domain and build reusable components to benefit future development efforts [8]. Second, it is a domain-specific componentization process which involves using Domain Specific Software Architecture (DSSA). DSSA is one of the most important approaches in Domain Engineering (DE). Third, business components are considered the most important reusable artifacts. A business component is the software implementation of an autonomous business concept or business process. It consists of the software artifacts necessary for representing, implementing, and deploying a given business concept as an autonomous, reusable element of a larger distributed information system [9]. Fourth, each business domain is composed of many business functions. It is common that there are significant amounts of similarities in business domains, business functions, and business processes among subindustries. However, it is well recognized that the logic of business processing even within the same business function may vary depending upon the industry; similarly, the requirements of specific business processes in enterprises even within the same industry may be somewhat different.

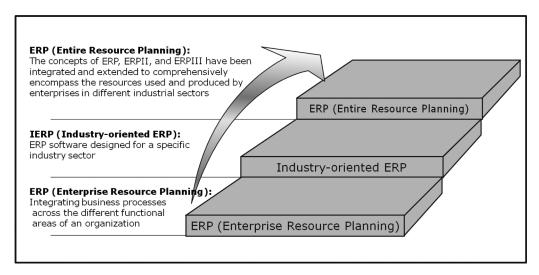


Fig. 1. Diagram of ERP, Industry-oriented ERP, and ERP.

B. ERP III and ERP (Entire Resource Planning)

Since the 1990s, ES have been mainly developed and implemented for managing the physical assets of an enterprise. Surviving in today's highly competitive and ever-expanding global economy requires efficiently managing corporate knowledge. It is well recognized now that knowledge is a compilation of an enterprise's invisible assets. Increasing requirements for extended enterprises have also stimulated the integration of the knowledge management (KM) function into ERP systems for knowledge asset management. In 2007, Lorincz indicated that the real asset of any organizations is its knowledge (in broad sense); it was also predicted that the next stage of the coevolution of business and enterprise systems will be developing ES with KM capability [10]. Due to the fact that both types of assets need to be properly managed, the integration of KM and ERP becomes a strategic initiative for providing competitive advantages to enterprises. In 2006, the concept of deploying KM and ERP concurrently in the framework of ES was proposed, and thus the concept of ERP III was developed [11]. ERP III enables ES applications to transform an enterprise into a knowledge-based learning organization and to capture know-how for developing business solutions to create real competitive advantages.

In 2008, a new theory on material flows (MFs) called Comprehensive Material Flow Theory revealed the essence of MF objects and phenomena [12]. In this theory, material flows are specified in terms of the MF in the economic dimension, the MF in the social dimension, and the MF in the natural dimension, as well as their interrelationships. It was pointed out that the material flow is not only an economic phenomenon, but also a social and a natural one. In other words, there not only exists economic material flow, but also social and natural flows. The economic material flow is the core of the material flow, whereas the social and natural material flows are the basis of the material flow.

This theory provides extremely important insights into future enterprise architecture and integration, especially in the consideration of sustainable economic and societal development and growth. Based upon this, as well as on the fact that considerations such as environmental factors and the scarcity of natural resources have been a concern in industrial informatics [13],

and the fact that the theory involves with Critical Infrastuctures [14], the concept of next-generation enterprise systems has been proposed [7], [15]. The next-generation ES is called Entire Resource Planning (ERP) or Complete Resource Planning (CRP); in it, not only have the concepts of ERP, ERPII, and ERPIII been integrated together, but its design has been extended to comprehensively encompass the resources used and produced by enterprises in different industrial sectors, within the context of economic and societal development. In ERP, not only is economic material flow included, but social and natural material flows are included as well. Entire Resource Planning is considered a significant step forward in the evolution of ES. Fig. 1 shows the evolution of ES in terms of three stages of development efforts.

The major factors that have contributed to the birth of Entire Resource Planning are obvious. The past decade has brought fundamental changes to the global economy and to global business operations. The main challenges facing the enterprises are that: 1) both the globalization of operations and implementation of Supply Chain Management (SCM) are moving toward a deeper level, and that 2) the expectations for sustainable economic growth and global environmental protection are rising. The limitation of the existing systems restrains their flexibility to cope with the challenges described above, i.e., global operations at a deeper level, and the increasing requirements of sustainable economic growth and global environmental protection. The existing systems are just a part of the solution, and mere modest modification of the existing ES will not meet the requirements. Only a new type of system will be capable for coping with the challenges. The key characteristic of the new system is the provision of comprehensive coverage of all relevant types of resource planning. Its main objective is to close the gap between the existing systems and the proposed systems.

III. ENABLING TECHNOLOGIES

Advances in computing technology provide us with an enormous amount of quality information for use in industrial operations. One of the challenges we face is to make use of industrial informatics to collect, analyze, distribute, and utilize the information in the industrial processes [16]. As an integrated information system, ES can contribute to this objective. For instance,

ES generally comprise many complex business processes. Integrated design which has broad applications in numerous industry sectors provides another example. Previously, computeraided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), and product data management (PDM) systems that are heterogeneous to some extent were separately developed. But for data collection, analysis, and utilization purpose, such systems should not be considered as isolated systems. They can be integrated to a certain extent through ES to realize data, function, and process integration, and to support the production life cycle (PLM). So far, many of the industrial informatics requirements for this type of applications have not been comprehensively covered in existing literature. Therefore, it is not surprising that there has been great interest in the development of new techniques or methods for such purposes.

Rapid advances in industrial information integration methods have spurred tremendous growth in the use of ES. Various techniques have been used for probing ES so far. These techniques include business process management, workflow management, EAI, SOA, grid computing, and others. Many applications require a combination of these techniques, which gives rise to the emergence of an ES that requires techniques originated from different disciplines. At present, we are at a new breakpoint of the evolution of selected enabling technologies for ES. In this section, we introduce the basic techniques that are significant for ES.

A. Business Process Management (BPM)

ES enables the integration of business processes throughout an organization with the help of Business Process Management (BPM). BPM is an approach which is focused on aligning all of the aspects of an industrial organization to promote process effectiveness and efficiency, with the help of information technology. Through business process modeling, BPM can help industries standardize and optimize their business processes, increasing agility to respond to changing environment for competitive advantages, accomplishing business process reengineering, and realizing cost reductions [17].

The significance of process modeling to industrial informatics is obvious. The modeling, monitoring, and controlling of industrial processes is important, as it enables us to understand and optimize such processes [18]. Manufacturing process modeling is a typical example. Modeling of manufacturing processes is important, since it enables manufacturers to understand the processes and to optimize the process operation [19]. Chan, Dillon and Kwong emphasize that manufacturers need to control variability at each of the many processing steps in a manufacturing line [19]. All of the process details in a manufacturing process which relate to the desired outputs of the process need to be understood and optimized. Therefore, a precise process model which relates processes is required. As the successful applications of industrial control draw from the domain expertise of multiple disciplines/subjects including information technology, process technology, and factory automation, and as industrial communication systems are increasingly deployed in important fields of applications such as process automation

and factory automation, the control and predictive capability of BPM offers significant insights into industrial informatics [16], [20]. Research affirms that process modeling is one of the main concerns in industrial informatics.

To track process-related information and the status of each instance of the process as it moves through an organization, the concept of workflow was developed [21]. Workflow systems have been considered as efficient tools that enable business process management, 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., Workflow Management System (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 in Zisman's Ph.D. dissertation, the early idea of automation of business processes was initiated [22]. Workflow management allows the managing of workflows for different types of processes, facilitating process automation and providing predictive capabilities, and enabling organizations to have control over their processes. Business processes and their related workflow systems have gained greater interest since the early 1990s; research on enterprise business processes and workflows has become a prominent area that attracts attention from both academia and industry.

A workflow is comprised of a number of tasks that need to be carried out and a set of conditions that determine the order of the tasks. Workflow Management Coalition (WMC) defines a workflow as a computerized facilitation for automation of a business process, in whole or in part. Three types of workflows are generally recognized in the literature [23]. Production Workflow is associated with routine processes, and is characterized by a fixed definition of tasks and an order of execution. Ad Hoc Workflow is associated with nonroutine processes, and could result in a novel situation. In Administrative Workflow, cases follow a well-defined procedure but the alternative routing of a case is possible. Compared with the other two types, production workflows correspond to critical business processes and possess a high potential to add value to the organization. Hence, they are usually the focus of most studies on workflow modeling [24].

Workflow management has been considered to be an efficient way of monitoring, controlling, and optimizing business processes through IT support; it is playing an important role in improving organizations' performance through the automation of business processes [23]. The initial focus of BPM was on the automation of business processes with the use of information technology, which is within the scope of traditional industrial informatics. However, with the increased prevalence of a global supply chain and more global operations, BPM is not only expected to automate business processes within the organization, but also to enable organizations in the supply chain to automate interorganizational business process. The main reason is that SCM has been rapidly developing worldwide, that the scope of enterprise integration and interoperation is extending from intraorganizational to interorganizational; and that more efforts

have been focused on the integration of interorganizational systems to form interenterprise architecture. For this purpose, it is necessary to study both intraorganizational and interorganizational business processes with a scientific approach, especially since today's enterprise systems are required to address more than the processes taking place within the walls of enterprises [10], [25]. Both intraorganizational business processes and interorganizational processes need to be addressed. As e-business continues to prevail as an important trend, the embracing of interorganizational business process management and the related workflow management is considered one of the best prospects for ES applications.

Today, workflow systems are increasingly applied to emerging e-businesses, virtual enterprises, and supply networks. Workflow management plays an important role in cooperative business domains such as SCM. The concept is simple: a business operation creates processes which operate across organizational boundaries; therefore, workflow management operates across multiple organizations. Such trends are leading to the tendency of managing workflows across organizational boundaries as today's organizations must often operate across organizational boundaries, interacting with each other to face increasing competitive challenges. As a result, IT efforts have led to a focus on cross-organizational business processes that link various organizations in the supply chain; meanwhile, companies have the opportunity to reshape their business processes beyond organizational boundaries. The use of the cross-organizational workflow of course also offers organizations the opportunity to reshape business processes beyond the boundaries of their own organizations [26]. Interconnecting business processes across systems and organizations would provide obvious benefits, such as greater process transparency, higher degrees of integration, facilitation of communication, and higher throughput in a given time interval [27]. Workflow management has now been accepted as one of the most successful types of systems in supporting cooperative enterprise operations.

Cross-organizational workflows are comprised of an intraorganizational workflow and an interorganizational workflow. A changing business environment requires an organization to adjust and integrate both the intraorganizational and interorganizational processes, both frequently and dynamically. Wolfert *et al.* define intra-, inter-, process, and application integration in this way: intraorganizational integration overcomes fragmentation between organizational units, interorganizational integration integrates enterprises in the supply chain, process integration aligns tasks through coordination, and application integration aligns software systems to reach cross-system interoperability [28].

As process integration is one of main types of integrations and since such integration can be either intraorganizational or interorganizational, an intraorganizational and interorganizational workflow monitoring and management capability can enhance overall performance of supply chains. An intraorganizational and interorganizational workflow monitoring and management capability can also enhance information sharing at both intraorganizational and interorganizational levels. Such information sharing in the supply chain should enable all participants in the

extended supply chain system to improve product quality, optimizing operation performance, enhancing collaboration, and gaining a competitive advantage.

Inter-enterprise workflow architecture supports SCM as it focuses on both the intraorganizational and interorganizational information systems, on the implementation of interoperability between independent enterprises, and on the deployment of business processes over multiple enterprises [29]. In the information-based economy featured by e-business, it is essential to realize workflow interoperability in a more complex and dynamic environment. Liu et al. provide an example of an inter-enterprise workflow architecture for SCM that is an integrated system while provides information exchange between customers and suppliers [30]. The architecture is comprised of a workflow-supported inner supply chain system and an integrated interface. Bechini et al. indicate the role played by interorganizational information systems in developing an industrial traceability system [31].

WfMS defines, manages, and executes workflow through the execution of software. WfMS has become a standard solution for managing complicated processes in a number of business 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 ES. By having a dedicated automated system in place for managing business processes, such processes could, theoretically, be executed faster and more efficiently. Workflow technology can be used to improve the business processes and to increase performance as the improvement can be quantified with respect to lead time, wait time, service time, and utilization of resources, etc., [32]. WfMS can also be used as a platform for knowledge sharing and learning in the supply chain. The knowledge workers in each organization can perform creative intellectual activities. WfMS can be employed as a repository of valuable process knowledge and can act as a vehicle for collecting and distributing knowledge across the entire supply chain. An additional workflow may need to be constructed to realize the benefits of knowledge sharing in the cross-organizational context.

Most traditional workflow management systems assume one centralized enactment service and are able to support workflows inside one organization, but have problems dealing with workflows crossing organizational boundaries [33]. It is critical to ensure that problems such as inconsistency and duplication of work do not arise due to the lack of transparency across different organizations. The inherently hybrid nature of business processes, particularly as such processes spread across multiple locations, resources, and organizational entities, presents challenges for researchers.

The workflow research can be viewed in terms of three layers [34], [35]. The first layer pertains to issues on intraorganizational workflows, which links activities between different departments within one organization. The second layer corresponds to the interorganizational workflow, which covers distributed processes between different organizations. Both of these together comprise the cross-organizational workflow. The third layer concerns the workflow technologies in e-business settings that have now been intensely investigated.

Effective management of business processes relies largely on perfect workflow modeling and analysis. The following are the perspectives from which workflows are commonly modeled and represented [26].

- Control-Flow/Process Perspective: Workflow processes are defined to specify which tasks need to be executed and in what order. This perspective also shows how a specific case is executed according to the specified routing.
- 2) Resource/Organization Perspective: Organizational structure and population (resources, ranging from humans to devices) are specified and focuses on problems such as defining which resources are involved in each task, etc.
- Data/Information Perspective: This perspective mainly deals with the informational entities involved in the process and the structure of these entities and their interrelationships.
- 4) Task/Function Perspective: This perspective describes the elementary operations performed by resources, while executing a task for a specific case.
- 5) **Operational/Application Perspective**: The elementary actions are described, and this perspective specifies what tools and applications are used to execute these actions.

Among the modeling techniques, most of them have shown the capability of using graphical representation and formal semantics to model workflows in an intraorganizational context [36], [37]. Currently, there is an urgent demand for translation between various models so that different workflow management systems can operate with each other. This is an interesting research topic that has not received much attention until few years ago. Further study could lead to methods for integrating heterogeneous models into a common framework.

Each modeling technique offers advantages as well as disadvantages. Interorganizational workflow modeling explores the architectures for combining different organizational workflows, while it continues to reconcile the relationships between each of the systems. Some approaches are specifically proposed for modeling interorganizational workflows such as the routing approach and the interaction model. Some cognitive approaches are also suggested to support the dynamic routing of information, and new languages are being proposed to handle the routing of information among organizations. The new language will deal with the patterns created for the coordinated partners to interact with each other. It also appears that a selective, yet partial, exposure of private workflow data to external partners will be possible in future.

In terms of evaluation, the qualitative analysis mainly be focused on checking the structural soundness, which can usually be done through the validation and verification of workflows. A quantitative analysis requires the calculation of the performance indices related to workflows. The existing techniques include computational simulation, Markovian chain, and queueing theory, etc.

At present, in the area of workflow management, there has been great interest in studying workflow modeling, workflow security management, and interorganizational workflow. System flexibility has been considered as a major functionality of workflow systems. Research is needed for such functionality in order to provide sufficient flexibility for coping with complex busi-

ness process. Other research topics include the communication among multiworkflows in complicated business process, simplifying the workflow modeling process, and automating workflows [29]. Existing techniques in process modeling still have limitations in addressing many modeling issues. For example, business process models may contain numerous elements with complex intricate interrelationships [17]. Efforts are needed to address how to properly capture such complexities.

B. Information Integration and Interoperability

It used to be that automated supply chain management was the purview of very large organizations such as Boeing and Lockheed Martin. SCM has experienced many changes in the past decade, a decade in which the key change is that supply chains are becoming more interconnected and are transforming into supply networks. The main reason is that, as the scope of enterprises has grown dramatically, different supply chains are increasingly integrated with each other, and an enterprise typically involves with several supply chains. The new trend is that today's businesses of all sizes need to share data with suppliers, distributors, and customers. Compressed product development cycles and lifetimes and just-in-time stocking imply that SCM systems must be interconnected, and the applications composing the information systems of enterprises increasingly need to work together [38]. The demand for supply chain integration has been increasing, as a consequence of global economy, and has been made possible due to the advancement of information technologies. Importantly, information integration is not only significant for large scale enterprises or supply chain integration, but also at a microscopic level. For example, information integration is one of most important aspects for accomplishing product development with high efficiency [39].

As a consequence of developments in ES since 1980s, ES has increasingly moved toward intraorganizational integration as the benefits of intraorganizational information sharing have becomes obvious. An intraorganizational system is aimed at providing a higher level system related to activities that involve the coordination of business processes within the organization and is able to provide an integrated architecture to an organization for enhancing organizational performance. Such early ES did not support SCM. Since the last decade, integrating both internal and external environment within and across organizations has been considered highly relevant to SCM, as SCM has rapidly developed worldwide. Now, more efforts have been focused on integration of interenterprise systems, and more and more enterprises have moved toward interorganizational integration to support SCM through ES. Interorganizational systems are now able to allow communication between partners in the supply chain. Such systems can collect valuable supply chain management information for all related business processes across the supply chain. With integrated supply chain management, businesses can predict market requirements, innovate in response to market conditions, and align operations across global networks. The Demand Activated Manufacturing Architecture (DAMA) project is an example. DAMA has developed an inter-enterprise architecture and collaborative model for supply chains which enables improved collaborative business across supply chains [40].

Similar to the way in which system integration constitutes a challenge in industrial informatics, the integration of enterprise 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 [41]. Hasselbring proposes a three-layer architecture that integrates different types of architectures [42]. In Puschmann and Alt's framework, data level is considered as a separate layer [43]. Giachetti's framework includes a typical characterization of the different types of integration [44]. As indicated by Wolfert *et al.*, the contents of these frameworks have not been comprehensive, and an overall framework of information integration has not yet been developed [28].

Grid computing is a new technology for distributed computing systems. The infrastructure of grid computing makes it possible to aggregate and share a large set of resources of different types which are distributed geographically to form a single system. Grid computing may provide an effective tool for integrating ES. Research indicates that the characteristics of grid computing systems meet the requirements of ES integration for extended enterprises on the global supply chain. A new grid-computing framework called Grid Service Architecture (OGSA) has recently been proposed for integrating grid resources into web-services. Wang et al. indicate that this trend implies that the integration of web-based ES and grid computing infrastructure is possible. A novel global ES architecture based on OGSA, called GridERP, has been proposed for solving the problem of noneffective sharing of distributed resources and the interoperability issue on the global deployment of ES, with the expectation of bringing ES integration on the global supply chain to a higher level [45].

The current ES integration may be limited by the sophistication of the relevant technologies or by the lack of techniques, and the successful execution of supply chain management relies upon more sophisticated ES integration than that is available now. It is expected that ES integration will attract more attention in automated supply chain management in which seamless integration with external systems has always been emphasized [46]. Among new technologies, Radio Frequency Identification (RFID) and Internet of Things (IoT) have attracted much attention. RFID is a contactless and low-power wireless communication technology which has applications in many areas of the supply chain [47], [48]. The envisioned applications include information to be collected from a network of RFID sensors and IoT combined.

C. Enterprise Architecture and Enterprise Application Integration

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 the relationship to the enterprise's environment [49]. As it describes the structure of an enterprise, it comprises the 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. As the 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 industrial informatics, as industrial informatics concern the information flow within the entire industrial organization.

Enterprise architects use a variety of business models, analytical techniques, and conceptual 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. The collection of these artifacts is considered to be as enterprise architecture. Software architecture, network architecture, database architecture are partial components of an information 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 information domain. The important components in this domain include information architecture, data architecture, etc. The other two domains with components that are also highly relevant to industry informatics are the Application Domain and its component "interfaces between applications" and the Technology Domain with its component middleware, networking, and operating systems.

Representing the architecture of an enterprise correctly and logically improves the performance of an industrial organization. This includes innovations in the structure of an organization, the reengineering of business processes, and the quality and timeliness of information flow that represent material flows [12]. It also ensures that efforts put on industrial information systems are effective.

Enterprise integration has become a key issue for many enterprises, in order 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 which aim to consolidate and coordinate computer applications. Typically, an enterprise has existing legacy systems, and they are expected to continue service, while adding or migrating to a new set of applications. To address this issue, an IT solution that can help to achieve quality integration is referred to as Enterprise Application Integration (EAI). Originally, EAI was only focused on integrating ES with intraorganizational applications, but now it has been expanded to cover aspects of interorganizational integration [50]. EAI facilitates the integration of both intraorganizational and interorganizational systems. Major EAI-enabling technologies range from EDI (Electronic Data Interchange) to Web Services and XML-based process integration, and provide flexible, scalable and adaptable EAI frameworks. Solutions comprise the efficient integration of diverse business processes and data across the enterprises, interoperation and integration of intraorganizational and interorganizational enterprise applications, conversion of varied data representations among involving systems, and the connection of proprietary/legacy data sources, ES, applications, processes, and workflows interorganizationally [50].

EAI entails integrating enterprise data sources and applications so that business data and processes can be easily shared. The integration of data and applications is expected to be accomplished without requiring significant changes to existing applications and data [50]. As such, EAI must be 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 process, applications, and platform as well as integration standards. Through creating an integrative structure, EAI connects the heterogeneous data sources, systems, and applications intraor inter- enterprise. EAI aims not only to connect the current system processes, but also to provide a flexible and convenient process integration mechanism. With EAI, intra- or inter-enterprise application systems can be integrated seamlessly, and can ensure that different divisions or even enterprises can cooperate with each other even with different systems. A complete EAI offers functions such as business process integration and information integration, as the core of the EAI technology is business process management. Through coordinating the business processes of multiple enterprise applications and by combining software, hardware, and standards together, enterprise systems such as ERP can share and exchange data seamlessly in a supply chain environment.

In general, those enterprise applications that were not designed as interoperable need to be integrated on an intraorganizational and/or interorganizational basis. As such, legacy and newer systems are expected to be integrated for providing greater competitive advantages. The constantly changing business requirements and the need for adapting to the rapid changes in the supply chain may require the help from Service-oriented Architecture (SOA), which will be introduced in the next subsection. Such enterprise architecture will not only provide new functionality but will also leverage investments in legacy systems running the enterprise's key applications [50].

EAI is providing the integration of both intraorganizational and interorganizational systems and databases and is moving toward integrating ES with both intraorganizational and interorganizational applications. The objective of EAI is to facilitate information exchange among business enterprises in a timely, accurate, and consistent manner, and to support business operations in a manner that appears to be seamless [1].

D. Service-Oriented Architecture (SOA)

Service-oriented architecture (SOA) represents the latest trend in integrating heterogeneous systems, has received much attention as an architecture for integrating platform, protocol, and legacy systems, and been considered as suitable paradigm that aids integration as it is characterized by simplicity, flexibility, and adaptability.

SOA is an architecture designed to improve group functionality in terms of interoperable services, based on business processes on top of the organization's existing enterprise system. A service is considered an abstract business concept that represents the functionalities of business [51]. As an architectural approach, SOA takes business applications and breaks them down into individual functions and processes as services. This paradigm allows the recursive aggregation of services into new business processes and applications [52]. Each of such existing services can be recomposited, reconstructed, and reused to create

new applications. In other words, discrete components of software functionality can be recomposed and passed to other functions and systems as services that enable different applications to reuse common parts. In turn, services can be pieces of application functionality that represent a reconstructed business task. Also, alternative applications can be built by assembling these reconstructible components. Researchers point out that SOA enables organizations to create new applications dynamically to meet changing business needs; its functionality is considered as an important benefit [53].

This is an architectural style of building enterprise applications that promotes a loose coupling between components with the following characteristics: 1) services are software components that have published contracts/interfaces; these contracts are platform-, language-, and operating systems- independent. XML and SOAP (Simple Object Access Protocol) are the enabling technologies for SOA as they are platform-independent; 2) users can dynamically discover services; and 3) services are interoperable [54].

One of the key significances of SOA to SCM is that services can be made available to others in the supply chain; thus, SOA has been considered as one of the key technologies enabling globally integrated supply chains [55]. SOA enables accesses to supply chain information for many different partners. With SOA, an organization can create a more flexible and responsive environment for its supply chain partners. Services can be built and maintained in one place, but can be made available to applications in other places in the supply chain for incorporating them into their own functionality.

Many companies are currently adopting a demand-driven model [56]. A successful demand-driven supply chain requires prompt responsiveness along the entire supply chain. Throughout such supply chain, information processing continues to become more important as it requires a fully integrated ES characterized by real-time data exchange, real-time responsiveness, real-time collaboration, real-time synchronization, real-time visibility, and a sophisticated level of information integration. SOA is considered suitable for such demand-driven supply chains. SOA can integrate reconstructible "component business services" in the process of managing supply chains in real-time across organizational boundaries [55]. In particular, SOA can integrate supply chain process and information; and sharing such information can help create a better environment for real-time data exchange, real-time responsiveness, real-time collaboration, real-time synchronization, and real-time visibility across the entire supply chain.

Service-oriented computing (SOC) is a computing paradigm that utilizes services as fundamental elements for developing applications/solutions. Such services represent individual functions and processes in business applications; they can be reused and recombined to create new business applications. As the business processes are changed, services can be reassembled.

SOC relies on SOA to build the service model, as SOA is an architecture in which discrete sets of software functionalities can be componentized to deliver services that enabling different applications to use common or reusable components facing changing operations and building new applications [57], and other applications can access such service and incorporate

it into their own functionality [55]. Since SOA publishes business functionality in the form of programming and accessible software services, other application programs can use these services through published and discoverable interfaces that provide a new blueprint for software reuse and enterprise systems integration [58].

SOA represents an emerging paradigm for enterprises to coordinate seamlessly in the environment of heterogeneous information systems, enabling the timely sharing of information in the supply chain and the development of flexible large-scale software systems. Example applications include the InLife project [46], information integration based on SOA in agrifood industry [28], etc.

Since SOA can minimize the gap between business analysis and IT development work, SOA becomes a crucial foundation for BPM which supports rapid assembly and orchestration of process services into larger, end-to-end processes. SOA, in conjunction with BPM, are expected to be promising technologies for developing ES. In other words, the integration and coevolution of SOA and BPM are on the horizon [10]. As BPM on SOA enables combining business expertise and software capability for an organization, BPM and SOA technologies have been combined as a core technology for End-to-End Resource Planning (EERP) [59]. As an emerging information technology, SOA has advantages such as standard protocols, cross-heterogeneous platforms, flexible functional integration based on loosely coupled services, low cost of system establishment, reusability, and especially bridging the gap between business and IT through a set of business-aligned IT services using a set of design principles, patterns, and techniques [10], [45].

IV. SUMMARY AND CHALLENGES

The emergence of interest in ES has increased in recent years. However, many ES implementations have not yet employed the advanced technology, and new techniques developed under the umbrella of IIIE. Although the technologies and applications introduced in this paper are currently not yet fully used in ES, they are expected to have great potential to play a major role in near future. Technologies will prove that they allow ES as a basic enabler for effective supply chain management, and industrial informatics have been and will be supported by advances in ES. Efforts focusing on blending the capabilities of existing ES and the emerging technologies in ES are needed. With this blending, industries will be able to harness the power of current and emerging technologies to dramatically improve the enterprise and supply chain performance by adopting new ES technologies.

Research indicates that the successful ES relies upon more sophisticated technologies than those that are available now [56]. Research also indicates that quality SCM can be accomplished with proper integration of the existing and/or new technologies [56]. With more advanced technologies, the overall quality of SCM will improve. In fact, one of the goals of SCM is to develop extended enterprise cooperative systems capable of promoting cooperation between component enterprises in the supply chain. Such a system will become a reality in which independent enterprises are linked by information technologies such as ES.

There are still many challenges and issues that need to be resolved in order for ES to become more applicable. Designing enterprise systems involves complexity which 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 to various industrial sectors; however, the development of advanced methodologies, especially formal methods and a systems approach, have to be synched with the rapid technological developments [37]. Even for the designing of manufacturing systems, a component of ES, there exists a gap between the level of complexity inherent in manufacturing systems and the rich set of formal methods that could potentially contribute to the design of advanced manufacturing systems [60]. Despite advancements in the field of ES, both in academia and industry, significant challenges still remain. They need to be dealt with in order to fully realize the potential of ES. Industrial informatics will continue to embrace cutting-edge ES technology and techniques, and will open up new applications that will impact industrial sectors [47], [48], [61]-[88]. ES can and will contribute to the success of this endeavor.

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