An Approach for Real-Time Control of Enterprise Processes in Manufacturing using a Rule-Based System

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1 Introduction

Today's enterprise business environment is complex, volatile and driven by uncertainties. To address this situation, enterprises strive for flexibility and adaptability. Real-time (re)actions to events occurring in the business environment of an enterprise are essential to remain competitive. In this context, the integration of business functions into a single system utilizing information technology can be seen as a prerequisite for establishing a real-time control of processes (Lee et al. 2003, p. 54-56) and the vision of a Real-Time Enterprise (RTE) (Drobik et al. 2002, p. 1-3).

Enterprise Resource Planning (ERP) has traditionally aimed at achieving an integrated system incorporating various business functions within an enterprise to enhance enterprise processes (i.e., business and engineering processes). To recognize and respond to events in the business environment of an enterprise, the integration of ERP systems with Supply Chain Management (SCM) and Customer Relationship Management (CRM) systems has received considerable attention. This horizontal integration of ERP with other business applications leads to Real-Time Business (RTB), where an enterprise can appropriately (re)act in real-time to events in the supply chain and/or customers' behaviour (Alt and Oesterle 2004, p. 1-52). In addition, the realization of RTE requires the vertical integration of ERP systems with the manufacturing execution (Karnouskos et al. 2009, p. 2127-2132). Available Enterprise Application Integration (EAI) systems can be used to horizontally integrate existing business applications (Linthicum 2000, p. 1-22). Nevertheless, EAI lacks in incorporating manufacturing resources (e.g., CNC machines) in vertical direction. Hence to achieve vertical integration of an enterprise, Manufacturing Execution Systems (MES) were introduced (e.g., Kletti (2007, p. 13-34)).

However with MES, major problems still remain open with respect to the interface between ERP system and the manufacturing execution (Panetto and Molina

2008, p. 641). Different time granularities associated with various enter-prise levels in the vertical direction of an enterprise result in asynchronization of enterprise planning and manufacturing execution (Gronau and Lindemann 2008, p. 155). Actual achieved performance values (AS-IS) from manufacturing execution together with the planned performance values (TO-BE) from ERP system are not used to enhance the performance of manufacturing activities (e.g., production, maintenance). In addition, AS-IS and TO-BE values are not used to identify new knowledge for control of enterprise processes.

Based on an IT-framework for digital enterprise integration (Grauer et al. 2009), in the current contribution a methodology is elaborated to identify and externalize knowledge from processes, and subsequently, use it for real-time control of processes. The current paper is organized as follows. Section 2 introduces enterprise integration concepts and elaborates the aforementioned challenges. Literature review is presented in Section 3 and is related to enterprise integration, monitoring and control and data mining. Section 4 provides a concept for real-time control of enterprise processes in manufacturing using a Rule Based System (RBS). Finally, conclusion and future work are presented in Section 5.

2 Problem Description

An enterprise can be hierarchically classified into various levels. From business perspective, for example, Scheer et al. (2005, p. 2-5) have classified an enterprise into enterprise strategy; design, optimization and control of processes; and process execution. Similarly, different business perspectives were presented by various researchers (e.g., Aier et al. (2008, p. 292-304); Ferstl and Sinz (2008, p. 1-63)). For future manufacturing enterprise, Gausemeier et al. (2009, p. 50-52) state that the enterprise levels - anticipation, strategy, processes, and IT-systems have to be aligned. In addition, an enterprise can also be described from an engineering perspective. For instance, VDI 5600 categorizes an enterprise into different MES levels – enterprise control level, manufacturing control level and manufacturing level. In either perspective, enterprise levels are associated with different time horizons and dominated by different types of processes (i.e., business and engineering processes) as shown in Figure 1.

Business processes are concerned with achieving the enterprise's long term strategies. Hence, these processes are located mainly at the enterprise control level. These processes are offline and business applications (e.g., ERP system) produce planned performance values (TO-BE) to be achieved to sustain competitive advantages. In addition, these planned values are transactional (Kjaer 2003, p. 50) and generated in non-real time i.e., months or weeks. Similarly to business processes, engineering processes are employed to realize the objectives set at the enterprise control level. Automation systems (e.g., CNC machines) are available at manufacturing level to execute engineering processes. Enormous amount of data is generated by these systems in real-time i.e., seconds or milliseconds and this data indicate actual performance values (AS-IS). As a consequence, the different characteristics of enterprise levels result in a vertical integration gap (Karnouskos et al. 2007, p. 293-294).

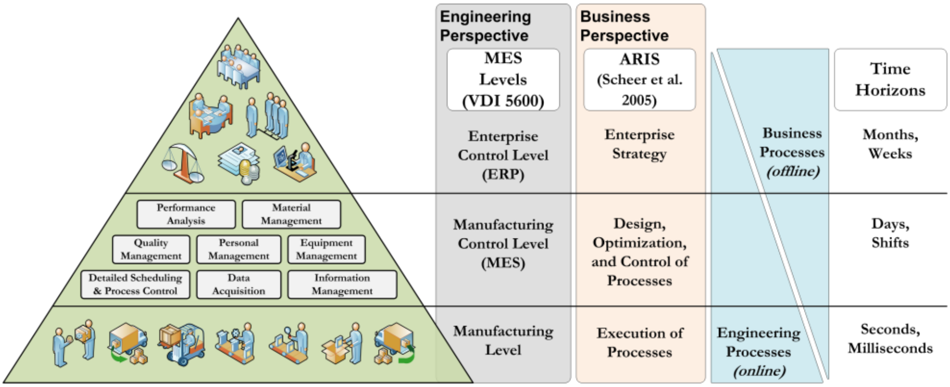

Figure 1: Engineering and business perspectives of an enterprise, and correspond ing enterprise processes' contribution and time horizons

Due to this inadequate vertical integration, the establishment of an enterprise-wide knowledge and learning cycle is hindered. Knowledge is crucial for an organization to remain competitive and innovative. In many cases, know-how (procedural knowledge) embedded in the enterprise processes is tacit knowledge and context specific. Extensive research has been carried out to convert tacit knowledge embedded in processes into explicit knowledge using analytical methods (e.g., data mining, process mining) but this research focuses mostly on transactional data (e.g., finance, sales) at the enterprise control level. For example, Grob et al. (2008, p. 268-281) have presented a rule based approach for control of business processes in financial enterprises by identifying operational knowledge from process data. In contrast, only 7% of data mining approaches address manufacturing enterprises (Kuntze et al. 2008, p. 1-4). The limited usage of data mining in manufacturing enterprises originated in the perception of relatively high efforts required to achieve enterprise integration (Kuntze et al. 2008, p. 1-4).

For AS-IS and TO-BE values to make sense and to be utilized, it is necessary to integrate these values. Integrated values can be utilized to identify tacit knowledge (e.g., using data mining) and the resulting explicit knowledge (e.g., production rules) can be used for real-time control of enterprise processes. Considering the aforementioned challenges, the goals of the current research are supporting vertical integration of an enterprise form ERP to manufacturing, and subsequently, establishing an enterprise-wide knowledge management for real-time control of enterprise processes in manufacturing.

3 Literature Review

In engineering and business literature, enterprise reference architectures and frameworks have been developed to close the vertical integration gap conceptually. Existing enterprise architectures and frameworks have been reviewed from business (Aier et al. 2008, p. 292-304; Schönherr 2004, p. 3-48) and engineering perspective (Chen and Vernadat 2004, p. 235-253).

Around the mid 1990's, several Enterprise Integration (EI) reference architectures (e.g., CIMOSA, PERA, ARIS and GRAI/GIM) were available (Chen and Vernadat, 2004, p. 236-240). These enterprise reference architectures are different in terms of their theoretical background (Chen and Vernadat, 2004, p. 235-253), and enterprise understanding, modelling approaches, and purposes (Aier et al. 2008, p. 292-304). Hence, GERAM - Generalized Enterprise-Reference Architecture and Methodology (Bernus and Nemes 1997, p. 175-176) has been developed to address these differences. Various architectures mentioned above have contributed in defining GERAM and it has been standardized as ISO 15704 - Requirements for Enterprise Reference Architecture and Methodologies. Reference architectures guide the design and implementation of an integrated enterprise. However, these architectures do not mention about how to realize the reference architecture in terms of technologies.

Web services as a means for implementing SOA have emerged as the de facto standard for EAI (Linthicum 2003, p. 25-114) and recent research has been carried out to extend SOA paradigm to manufacturing level. The EU-funded project SIRENA has proposed a SOA based framework to seamlessly connect heterogeneous (resource constrained) devices from several engineering domains (Bohn et al. 2006). Based on SIRENA, the EU-funded project SOCRADES aims to further exploit SOA paradigm for (embedded) devices (de Souza et al. 2008, p. 50-67). Karnouskos et al. (2007, p. 295-298) have proposed SOA-ready networked embedded devices to integrate shop floor activities with enterprise systems. A prototype of vertical integration of SOA-ready devices with SAP MII leading to RTE has been presented (Karnouskos et al. 2009, p. 2128-2131). Groba et al. (2008, p. 415-427) state that real-time requirements usually demand close coupling making the applicability of SOA paradigm at manufacturing level complicated. Nevertheless in maintenance management, these researchers have proposed a service-oriented approach for communication of devices and have used an enterprise service bus (ESB) for integration.

Sauer and Sutschet (2006, p. 33-37) have presented an agent-based production monitoring and control system (PMC). The PMC Provis.Agent integrates various IT-systems and machine control devices, and establishes the use of information between various systems. Similarly, NIIIP-SMART architecture provides horizontal and vertical integration and interoperation, and utilizes workflow, enterprise rules, agents and STEP (Gilman et al. 1997, p. 160-171). Several automation systems' vendors have developed MES solutions to bridge the gap between enterprise levels (e.g., Kletti (2007, p. 81-98)). But with MES, the exchange of data between enterprise control level and manufacturing execution is done manually or at most semi-automatically due to inflexible and proprietary interfaces (Karnouskos et al. 2007, p. 293).

An enterprise data model is a prerequisite for achieving vertical integration, monitoring and control, and knowledge discovery in databases (KDD). Huge amount of data is generated at manufacturing level and this data should be mapped onto an enterprise data model. Standard IEC 62264-2 describes data models and terminologies that enable to implement control between enterprise- and manufacturing- control level. These data models can be further augmented with technical models based on various types of manufacturing enterprises, like DIN 8582 for metal forming process, and DIN EN 61512-2 for batch production. In addition, researchers have also proposed various data models for enterprises (e.g., Zhou et al. 2005, p. 913-922; Harding et al. 1999, p. 2778-2788).

Usage of data mining in manufacturing is limited (Kuntze et al. 2008, p. 1-4), nonetheless data mining methods have been used in manufacturing domains, like design, manufacturing system, and maintenance (Choudhary et al. 2008; Harding et al. 2006, p. 969-976). In addition, Neaga and Harding (2005, p. 1092-1097) provide an enterprise modelling and integration framework based on KDD by extending the views of CIMOSA by adding knowledge and mining views. Explicit knowledge is denoted as rules, identified by using data mining, and manually from domain experts. In most of the enterprises, explicit knowledge is codified using RBS (Alaavi and Leidner 2005, p. 122).

4 Real-Time Control of Enterprise Processes

Grauer et al. (2009) have articulated an IT-framework for vertical integration for different types of manufacturing enterprises. The IT-framework is based on available standards (e.g., ISO 15704, IEC 62264) and technologies (e.g., SOA, OPC UA), and involves various IT-systems (e.g., ERP, Workflow Management Systems (WMS)) and manufacturing resources. The IT-framework also describes a methodology for monitoring and control of enterprise processes in real-time using WMS and RBS. Further, offline KDD can be utilized to identify new knowledge from integrated data. The current research presents KDD process in manufacturing enterprise and elaborates real-time control of enterprise processes based on the IT-framework articulated by Grauer et al. (2009).

Knowledge is crucial for an enterprise to remain innovative and competitive. Enterprise members' tacit knowledge is embedded into enterprise processes. These knowledge needs to be identified and utilized to monitor and control enterprise processes. In Figure 2, the IT-framework for digital enterprise integration, adapted from Grauer et al. (2009), is illustrated. AS-IS values and TO-BE values are integrated according to enterprise data model and stored in relational databases. The stored values are periodically utilized in offline KDD process to identify tacit knowledge and externalize it as rules to be managed in RBS. In addition, traceable objects are created from AS-IS and TO-BE values to be evaluated in RBS. These traceable objects represent parts, orders and resources that are relevant for enterprise process control. In addition, the whereabouts of traceable objects in certain enterprise processes can be tracked utilizing WMS. Based on the aggregated context information of traceable objects, rules are fired in real-time to align the processes according to business objectives, as indicated by the control data. Control data need to be incorporated both at the enterprise control level and manufacturing level. Section 4.1 describes KDD process and data mining in manufacturing enterprises. Control of enterprise processes using traceable objects and RBS is presented in Section 4.2.

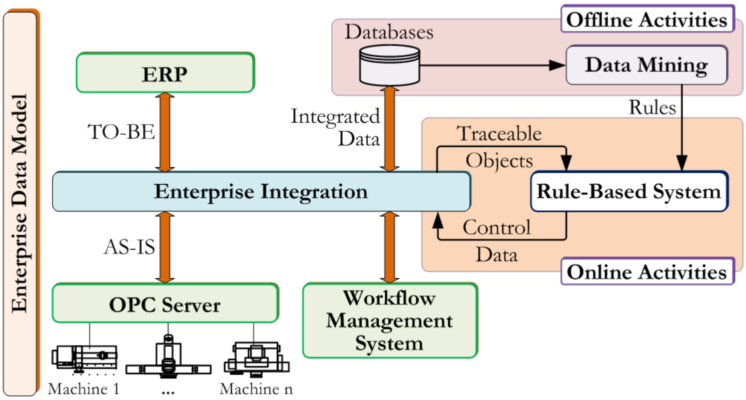

Figure 2: IT-framework for digital enterprise integration (Grauer et al. 2009)

4.1 Data Mining in Manufacturing Enterprises

KDD is a "process of mapping low-level data into other forms that might be more compact or abstract or useful" (Fayyad et al. 1996, p. 37). Data Mining is a particular process of KDD and is utilized to extract patterns from data, which needs to be further evaluated by domain experts to identify knowledge (e.g., production rules). KDD process starting with understanding of manufacturing domain in focus and defining the associated goals of KDD process is depicted in Figure 3.

Major activities of manufacturing enterprises are related to production, quality, maintenance and inventory (IEC 62264-3). These activities are defined by enterprise members associated with different enterprise processes. During the execution of these activities, huge amount of data is generated by automation systems at manufacturing level and together with business data from enterprise control level (i.e., from ERP system) correspond to tacit knowledge of enterprise members. This data will be stored in relational databases. Offline KDD process can be employed to identify tacit knowledge from this stored data and externalize it as production rules. The rules can be managed in RBS and modified by domain experts to suite the actual enterprise processes.

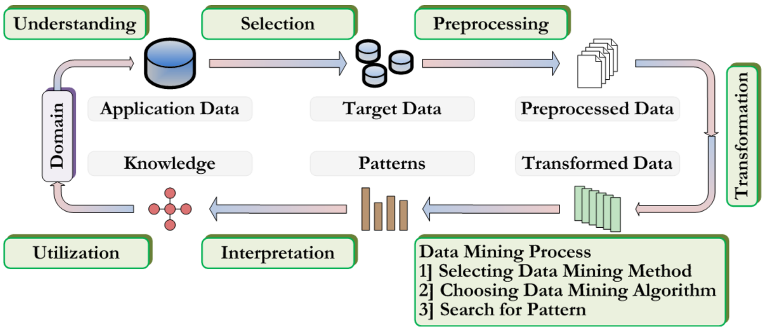

Figure 3: Knowledge discovery in database process (Fayyad et al. 1996)

As a prerequisite for the KDD process, data models defined in standards (e.g., IEC 62264-2, DIN 8582) need to be adapted to the manufacturing domain in focus to create an enterprise data model capable to relate data from various enterprise levels. Hence, enterprise data model guides in merging of data from different heterogeneous sources.

Data mining is based on proven techniques like machine learning, pattern recognition, database, statistics, artificial intelligence, knowledge acquisition, data visualization, and high performance computing (Witten and Frank 2000, p. 2-34). Manufacturing activities (e.g., quality, production) define the goals of the KDD process i.e., type of knowledge to be mined. Therefore, data mining methods have to be chosen in accordance to the goals of KDD process. For example, classification methods like decision-tree and rule-based induction methods can be utilized to determine production rules.

4.2 IT-Architecture for Realizing Real-Time Control

The IT-architecture for real-time control of enterprise processes is divided into three layers as depicted in Figure 4. Traceable objects are representatives of entities (e.g., parts, orders, resources) of a certain enterprise process which are managed in the control execution layer. The traceable objects are instantiated simultaneously with the corresponding workflow in the WMS and together with TO-BE values. In addition during execution of actual enterprise processes, AS-IS values generated by automation systems are used to update the traceable objects. This will assist the WMS to keep track of all traceable objects in the control execution layer. In summary, a traceable object contains condensed status information of an actual entity within an enterprise process.

The collected status information of a traceable object is evaluated in a RBS to dispatch process control activities i.e., control data. For establishment of real-time capabilities, the rule base of the RBS will be evaluated whenever traceable object has been updated. There are two implementations on how the RBS influences/controls actual enterprise processes and activities. First, the RBS uses interfaces and services provided by the integration layer (see Figure 2) to automatically dispatch control commands. Second, before manipulating enterprise processes, RBS exposes envisaged decision as a suggestion via graphical user interface (GUI) to the domain expert, who in turn accepts or declines the proposition. Obviously, the latter is used in cases where an domain expert should take liability.

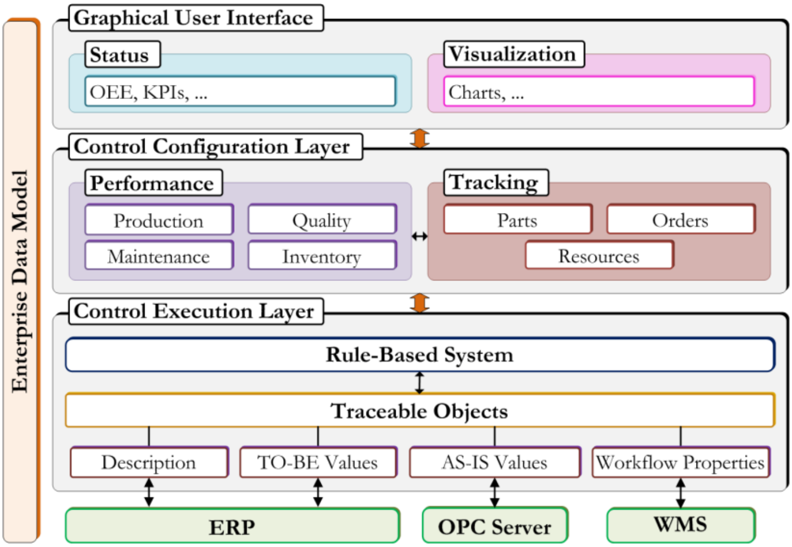

Figure 4: IT-architecture for online monitoring and control of processes using traceable objects and rule-based system

Traceable objects and rules are configured interdependently in the control configuration layer incorporating externalized knowledge from KDD process (see Section 4.1). The rule base is built in accordance to various relevant process objectives – production, quality, maintenance, and inventory. In manufacturing, traceable objects can be classified into parts, orders, and resources. A part is a physical output of the manufacturing process and the corresponding traceable object subsequently contains AS-IS and TO-BE values referring to the manipulation through various resources. An order usually comprises several parts to be manufactured and corresponding part traceable objects can be aggregated to derive an order status. The required manufacturing resources can be tracked independently from orders and parts. The actually assigned values of a traceable object are representing only a subset of all available values from integration layer (see Figure 2) that will be completely logged in a relational database (e.g., for KDD).

The status of enterprise processes and details of entities within these processes (i.e., parts, orders, and resources) are presented using GUI. In addition, a domain expert can accomplish configuration and query the relational databases of the integration layer as well as the RBS for resolving process control problems and examining actual process status expressed by means of Key Performance Indicators (KPIs) and Overall Equipment Efficiency (OEE). All layers of the aforementioned IT-architecture are incorporated utilizing enterprise data model.

5 Conclusion and Future Work

Methodology described in Section 4 is a concept and research attempts have been performed to put it into practice in different types of manufacturing enterprises - discrete and batch. Here, an attempt is made to realize the IT-framework for a batch manufacturing enterprise - casting. Enterprise processes have been analyzed and modelled using ARIS (utilizing EPC, Entity-Relationship-Model). IEC 62264-2 and DIN 61512-2 have been adapted to create enterprise data model. In addition, data flow diagrams (DFD) are created to reveal interdependencies between various automation and business systems. Data is acquired from different automation systems and made available as OPC items in OPC servers (see Figure 2). Acquired data is mapped onto the enterprise data model. A prototype is created to access these items and trigger rules, modelled using nxBRE rule engine. Similarly, visualization was provided to display process information. Due to use of standard concepts like OPC and SOA, implementation is planned using .NET framework.

Current contribution focuses on intra-enterprise integration in the vertical direction of an enterprise (see Figure 1). RBS and WMS enable to establish enterprise-wide monitoring and control. Also, stored AS-IS and TO-BE values facilitate enterprise-wide knowledge and learning cycle. Already existing functionalities from third party IT-systems (e.g., MES systems) can be integrated into the IT-framework by means of SOA. The presented IT-framework is based on several standards which will facilitate to establish inter-enterprise integration.

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