Achieving Manufacturing Excellence through the Integration of Enterprise Systems and Simulation

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Abstract

This paper discusses the significance of the Enterprise Systems and simulation integration in improving the shop floor's short-term production planning capability. The ultimate objectives are to identify the integration protocols, optimization parameters and critical design artifacts, thereby identifying key 'ingredients' that help in setting out a future research agenda in pursuit of optimum decision making at the shop floor level. While the integration of Enterprise Systems and simulation gains a widespread agreement within the existing work, the optimality, scalability and flexibility of the schedules remained unanswered. Furthermore, there seems to be no commonality or pattern as to how many core modules are required to enable such a flexible and scalable integration. Nevertheless, the objective of such integration remains clear, i.e. to achieve an optimum total production time, lead time, cycle time, production release rates and cost. The issues presently faced by existing Enterprise Systems, if properly addressed, can contribute to the achievement of manufacturing excellence and can help identify the building blocks for the software architectural platform enabling the integration.

Keywords: Enterprise Systems, simulation, integration, production planning horizon

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1.   INTRODUCTION

In June 2005, a non-profit association called Technology Initiative SmartFactory[KL] was established (Zuehlke 2010) as an extension of the vision of the future world under a slogan of ubiquitous computing. The members of SmartFactory[KL] represent various industry sectors whose common goal is in the development of innovative manufacturing technologies and fostering the widespread use in research and practice. Since then, the Euro vision for 2030 (European-Union-EFRA 2010) has further expressed the solidarity to the same concern and brought to reality, the very concept of manufacturing excellence through the Smart Factory and relevant initiatives for digital Factories of Future (FoF) (Pfeiffer *et al.* 2007).

The Smart Factory philosophy is focused on the *hyper-efficient* manufacturing under dynamic changing scenarios and under highly turbulences market conditions (Zhen et al., 2009). This is based on the state-of-the-art ubiquitous/pervasive computing technologies capable of real-time production using Advanced Planning Optimization (APO) systems embedded within the ERP core structures (Zuehlke, 2010). The operations management and optimization in midst of the global economic crisis, has emphasized the needs for an adaptive and flexible network of intelligent machines/robots/sensors hereby termed as the *society of machines*.

Contextually, a smart factory can be seen as a societal system of intelligent and networked machines with smart sensors. These are miniaturized for low-power consumption ensuring go-green and clean operations (Zuehlke 2010). An effort is in hand to integrate production plans and the human workforce through miniaturized devices or smart hand-held digital devices for optimum operations management (Aziz *et al.* 2005). The ERP (enterprise solution) by SAP, SAP/Siemens (Product Lifecycle Management or PLM) (Boza *et al.* 2014, Kale 2014) and Infor System (BAAN) are in fact part of the solutions to support intelligent manufacturing (Prasad 2000, Nagalingam and Lin 2008) (Ganesh *et al.* 2014) ensuring information integration of smart devices from enterprise level to shop floor level (Bangemann

et al. 2014). Enterprise Systems have provided exemplary benefits for information integration at a shop floor level. It has been reported that Air France witnessed significant benefits from successful ERP implementation in terms of enhanced competitiveness, growth and enhanced operational productivity (Maldonado Beltrán 2010). Similarly, Rolls Royce witnessed reduced cost, enhanced Supply Chain Management and high productivity as a consequence of the ES implementation (Yusuf *et al.* 2004).

While the business imperatives on the one hand require a state-of-the-art intelligent ES/ERP system with focused strategies across all business ventures, on the other hand, the society of machines necessitate flexible, adaptive systems coupled with centralized OnP/OnC via simulation engine to manage market dynamics under extreme uncertainties (Moon and Phatak 2005, Pfeiffer *et al.* 2007). The success of these businesses as well as operational imperatives is possible through seamless integration of society of machines and intelligent production scheduling.

While large enterprises like Airbus (Nicolaou 2004) (Stark 2011), Boeing (Rothman 2006, Shen *et al.* 2008), Rolls Royce (Yusuf *et al.* 2004), Lockheed Martin (Gargeya and Brady 2005, Da Xu 2011), Dassault Aviation (Lee *et al.* 2008) (Gao *et al.* 2003), BAE System and Jaguar (Van der Velden *et al.* 2007) have now utilized state-of-the-art ES/ERP (SAP, mySAP, IBM Asset Management Systems) for operations management, yet the desired integration functionalities from these systems is still below expectations. For instance, ES like many legacy systems have inherent limitations as they are rather inflexible (Møller 2005) and monolithic to changes in business process (Moon and Bahl 2005, Moon and Phatak 2005) and under fluctuating market demands. While (Umble *et al.* 2003) has argued that ERP provides more reliable delivery dates and better customer service yet as per recent research, it has been identified that the major issue with the smart factory's Master Production Plan (MPS) is with its ERP (Moon and Phatak 2005, Van Nieuwenhuyse *et al.* 2011) whereby the core of ERP planning logic is still based in its predecessor; Manufacturing Resource Planning (MRP II) (Kuehn and Draschba 2004, Moon and Bahl

2005). Under dynamically evolving scenarios, organizations have to be reactive and swift to adapt to alternative planning and scheduling decisions (Kanet and Stößlein, 2010, Koh and Saad, 2003). The dynamic variation in availability of a resource or demand (man-power, machine, material etc.) is therefore often forecast inaccurately (Moon and Phatak 2005, Ruiz et al. 2010, Van Nieuwenhuyse et al. 2011).

In reality, MRP follows a deterministic approach with an initial, top-down rough planning in which the structures, routings, bills of materials, inventory status and production schemas are defined. In the next step, MRP schedules are exploded, whereby plant resources in terms of man-power, machine, materials, methods and routes are selected and holistically managed (Shahid et al. 2006) (Esposito and Passaro 1997, Moon and Phatak 2005, Infor Systems (BAAN) ERP 2007).

Even though SAP APO/APS (Advanced Planning Optimization/Scheduling) (SAP 2011) modules have in fact embedded intelligence (AI) techniques (genetic algorithms, artificial neural networks etc.) (Vandaele and De Boeck 2003, Zhang et al. 2006, Van Nieuwenhuyse et al. 2011)for deterministic planning of MRP-logic, they are incapable of solving dynamic variations of NP-hard job scheduling (Kádár et al. 2004, McKay and Black 2007, Arsovski et al. 2009). The APO system typically provides a constraint-based, non-stochastic scheduling approach which cannot effectively map all the uncertainties at shop floor (Kovács et al. 2003).

Despite the fact that ERP system integrates all business processes, existing ES (MRP modules) lack sophistication for OnP/OnC and acceptable standardization of data integration, and have limited capability to congregate shop floor dynamics under demand uncertainty. Simulation, on the other hand, can capture *dynamic behavior* at the shop level with stochastic details (Phumbua and Tjahjono, 2012) and ideally a link has to co-exist between ERP and simulation whereby integration and coupling of the two may well resolve this industrial challenge.

The smart factories could be achieved as an output of a holistic planning with a systems thinking in mind. Based on the same theme, it is proposed that for real-time computing and realistic (OnP/OnC), "one for all - all for one" Enterprise Systems with embedded simulation engine could be an option or part of the solution.

This paper thus aims to explore and examine recent work in the area of ERP systems and simulation integration with the ultimate goal to better understand the extent to which the integration of ERP with simulation can improve the shop floor short-term planning horizons. The objectives include the identification of integration, optimization parameters and critical design artifacts, thereby identifying key "ingredients" that help in setting out a future research agenda in pursuit of optimum decision making and production planning at the smart factory.

2.   RESEARCH METHOD

2.1   Scope and Research Questions

This research hypothesized an integration of ERP and simulation which is paramount for the competitiveness of enterprises that aim to predict precise future delivery dates to their customers (referred to as *business imperatives* hereafter). Every company strives to predict its capacities and product delivery to its customers, termed as *operational imperatives*. Every state-of-the-art shop floor demands a best-of-breed software platform for seamless integration of the society of machines, robots, computers and sensors for optimum human-computer interaction, termed as smart factory future *techno-architectural imperatives*. The business, operational and architectural imperatives need to be harnessed in light of the present functional capabilities of these ES/ERP systems. This ultimately can provide the much needed research direction for the future of ERP and simulation integration during production uncertainties in pursuit of manufacturing excellence.

This paper has adopted a desk-based research method whose data have been obtained from various sources including textbooks, journal papers, conference proceedings, regulatory requirements and official publications. The review considers no specific time

frame in order to provide a global vision of the subject matter. The scope of this work is also not limited to the industrial sectors considered but rather in terms of the type of data sources used.

In order to guide the process and effectively execute the research, the following research questions have been formulated:

> *Q1: Why is the ERP and Simulation (ERP/SIM) integration needed?*
>
> *Q2: What are the operational optimization objectives for such integrations?*
>
> *Q3: What is the technical architecture of the ERP and Simulation integration based on scope and the specific manufacturing scenario?*
>
> *Q4: To what extent does the state-of-art ES/ERP architecture support ERP and Simulation integration for automation, optimum shop floor management, and production planning?*

2.2   Novelty of Research

It is pertinent to note that past research has neglected this very niche domain since 2000 as remarked by previous researchers for instance (Kovács *et al.* 2003, Zhang *et al.* 2006, Pfeiffer *et al.* 2007, Ruiz *et al.* 2010, Van Nieuwenhuyse *et al.* 2011, Samaranayake 2013). However, previous research combining a conceptual and comprehensive literature review for isolating the realistic-prerequisites of ERP and Simulation integration appears to be lacking. Additionally, even though the context of ERP and Simulation integration requirements have been highlighted, the context and content of the operational optimization objectives were not embarked for detailed future analysis in any previous research. Contextually, very few papers contributed towards a conceptual analysis of technical architecture of ERP and Simulation integration. It is noteworthy that no previous research has perpetually formulated and categorized the needs of research agenda of published-research for further structured analysis. It is pertinent to register that the research in the domain of ERP and Simulation

integration is evolving in large number of databases and academic domains that were not apparently include by us. Conversely, it may be noted that ERP is a complex term and may include considerable proliferation of information on this very niche area of topic.

2.3   Search Strategy

The search strategy was established by first identifying the relevant data sources and keywords. The data sources included Scopus, IEEE Xplore, Web of Knowledge and ACM. The search was initially set out by choosing a set of keywords and possible combinations that could be significant to ERP and Simulation integration, but later on, it had to be extended to cover some other aspects such as APO (Advanced Planning Optimization) due to the limited numbers of papers on this topic. The concept of "scheduling for shop floor" and "job shop" were also covered to capture all the aspects that characterize those shop floor simulations, such as lead time, cost, production schedules, supply chain, uncertainty and other issues. While a more elaborative and in-depth research survey may improve the domain of research, a baseline for proposing artifacts of ERP and simulation integration were carefully collected. Since the term ERP is also used in the "medical-science research", the search criteria were carefully constructed.

The initial search without limitation to timeline and "shop floor" identified more than 1,800 articles. However, by adding the context through intelligent and intended suffixes the results were reduced to 127. The context and content were further analyzed by reading the abstract, the keywords and the scope of each paper which eventually excluded undesired papers from further consideration. The review focused on the papers shop floor "*Job Shop*" as an additional criterion. Hereupon, the number of papers was reduced to 26. Limiting the search to *Enterprise Resource Planning shop floor integration + APO + Simulation* resulted in only 3 publications. The papers collected via ACM search results, however, did not yield the intended objective since most were not found to be relevant to smart factory concepts, or in other cases contained too little information to be included as quality research papers. The

Web of Knowledge forward looking and reverse looking tool did not provide any significant results. Consequently, a more flexible and wider search strategy was formed and papers were sorted out manually depending on the relevance. The survey statistics results are depicted in Table 1.

Subsequently, eighteen publications were identified as being available and suitable to the present work and an analysis was conducted on these papers because of the higher level of detail compared to the rest of the papers. The results of these searches help provide a series of key findings.

<Insert Table 1 here>

2.4   Results and Analysis

The eighteen publications retrieved have canvassed integration stratagem for optimum factory decision making under demand uncertainty. The smart factory risk management context for ERP and simulation has been discussed mostly in journals like; Computers in Industry, International Journal of Production Research, Industrial Management and Data Systems, Intelligent Manufacturing Systems, The International Journal of Advanced Manufacturing Technology and in conferences such as Simulation Conference, CIRP international seminar on manufacturing systems as well as European Simulation Multiconference. The techniques employed by the researchers for simulation optimization were Discrete-Event Simulation (DES), multi-agent systems (MAS) and combination of DES with Artificial Intelligence (AI) to develop an expert system. The details relevant to context of multi-agent systems (MAS)/Artificial Intelligence have been covered in journals like "Expert Systems with Applications and Decision Support Systems". However, the articles in this journal were either too generic in nature, specific to simulation or specific to AI algorithm developments with no relevance to ERP-simulation integration issues, thus did not serve the purpose as per the scope of this research. The journal based statistics results are depicted in Table 2.

<Insert Table 2 here>

It was observed that focus of research remained on framework formulation, automatic model generation, features (characteristics/factors) identification for optimum and seamless integration of simulation with various ERP modules or functionalities. The fundamental architectural considered for simulation integration were; "supply chain, warehouse, production-planning and scheduling. More recently research tried to integrate simulation for effective decision making at the shop floor by integrating MRP with advanced planning optimizer (APO) modules (SAP 2011) . These advanced planning and scheduling modules employ state-of-the-art approaches such as Artificial Intelligence/MAS. Conversely, APO has the ability to cope with the contingencies and what-if scenarios for the management of shop floor uncertainties as they deviate from the Master Production Schedule (MPS) (Caputo et al., 2009). These APO modules, however, cannot solve NP-hard problems due to their inherent limitations of heuristics, which are designed to generate short-term horizon production planning horizon through local minima or local maxima suboptimal solutions (Caputo et al., 2009). As a next logical resort and in search of optimal solutions, the researchers (e.g. Benedettini and Tjahjono, 2009) have employed mainly Discrete-Event Simulation (DES) in addition to multi-agent based simulation techniques (MAS) (Kwon and Lee 2001, Baumgaertel and John 2003, Zhang *et al.* 2006, Jiang *et al.* 2010, Ruiz *et al.* 2010) for self-converging and self-steering voyages towards optimal solutions The simulation packages used are, for instance Witness, Arena etc., but in the majority of cases, researchers were confined to JAVA-XML based run-around solutions to bridge the integrations gap of simulation software with ERP software (mainly SAP).

3. KEY FINDINGS

3.1 ERP and Simulation integration: an inescapable requirement

ERP is a business solution which harnesses the entire enterprise's functional departments (Al-Mashari 2003, Møller 2005). The benefits of ERP include quick information response,

reduced order cycle, optimum production cycle, optimum on-time delivery, reduced inventory and reduced operating costs (Lea, 2007). ERP, however, does inherit certain limitations from its predecessor, i.e. Manufacturing Resource Planning (MRP) (Hirata 2009), especially for production management (Yusuf *et al.* 2004). Therefore, based on the previous research, the major findings and reasons for the ERP and simulation integration have been identified, and have in fact emerged as an inescapable requirement for intelligent manufacturing that can be identified as follows:

1. ERP's MRP module calculates the schedule planning through a deterministic approach (Kovács *et al.* 2003) or precisely through non-stochastic logic (Moon and Phatak 2005). This is mainly because ERP assumes infinite availability of resource and has scheduling based on fixed lead time presumption. The overall outcome is inaccurate prediction of short term horizon (weekly schedules). The collateral management of resources by ERP is lacking when a resource shortages or resource fail to disembark (Man-power, Machine, Material, Method, Master-tooling, product supply, production line stoppage, etc.) (Zhang *et al.* 2006). Consequently, semi-automated or manual production schedules are often introduced, although these could be seen as "workarounds" that distort the whole idea of effective automation through these ERP systems (De Vin *et al.* 2006, Van Nieuwenhuyse *et al.* 2011). The simulation solutions on the other hand can predict with flexibility and accuracy the short horizon variation in plans (Bergmann and Strassburger 2010).

2. ERP inherits major shortcomings associated with its central MRP planning function, i.e. the assumption that the capacity of resources is unlimited, which causes inaccuracies in resource utilization and is generating significant errors in short horizon planning at a shop floor (Moon and Phatak 2005).

3. The digital manufacturing requires data integration between PLM-PDM and ERP. The present architecture of ERP systems has limited capabilities for this Digital manufacturing for product data integration and transformation of engineering bill of

materials (EBOM) to manufacturing bill of materials (MBOM). Moreover, this very process of MBOM transformation must correspond and harmonize to manufacturing plant resource-demarcation and plant peculiarity. The solution could be fetched through logical computer modelling of ERP-PLM (PDM-CAD/CAPP) modules through simulation technique for based on the process and resource models which reflect the particularities of each manufacturing site. The proposed technique for MBOM and the process and resource data, verified and appropriate for each manufacturing site, can be sent to the ERP system for online planning (OnP) and online control (OnC) (Lee et al. 2011).

4. ERP systems need additional external systems to monitor and collect real-time shop floor data for production control and decision support (Moon and Phatak 2005, Benoît et al. 2006). The shorter the planning horizon or time period, the more the lead times, cost, order cycle data will tend to vary. Again, under all such situations simulation can capture short planning horizon variations. These variations can then be bridged to the ERP planner to fix its inherent long term-planning horizons (Lendermann et al. 2001, Moon and Phatak 2005, Bergmann and Strassburger 2010).

It is pertinent to note that in today's highly dynamic and uncertain markets the business condition changes perpetually, under such scenarios ERP system may not guarantee that the logic/process embedded in ERP is still best (Kwon and Lee 2001). Moreover, ERP system is considered to be even more complex than the most complex systems housed in any aircraft or space shuttles, hence, maintaining the system by trial and error is very costly. In such scenarios, the ERP and simulation integration emerge as the most potent and viable solution to reduce the business uncertainties.

Simulation techniques have been traditionally used to model operations under dynamic conditions and can provide a feasible short-term planning horizon which seamlessly suits the needs of an integrated business through the ERP system (Bergmann and Strassburger 2010). Simulation is capable of accurately sensing and evaluating various what-if scenarios

(Lendermann *et al.* 2001, Mönch *et al.* 2003, Kuehn and Draschba 2004, Benoît *et al.* 2006, Caputo *et al.* 2009, Bergmann and Strassburger 2010) to a highly plausible dynamic situation and therefore can serve as a decision support tool for the ERP Business Intelligence (BI) module. Simulation tools should ideally integrate more closely with ERP, PLM, MES or other legacy systems from which a model can possibly be generated automatically, on-the-fly. Users can then experiment with the models, evaluating various scenarios to give the answer to the problems in production planning and control (Bergmann and Strassburger 2010).

Finding 1:   ERP's short-term planning horizon logic is typically based on non-stochastic presumptions (Lendermann *et al.* 2001, Moon and Phatak 2005, Bergmann and Strassburger 2010). As a consequence, the shop floor managers have no accurate lead times to enable equal distribution of workloads for the scheduling of machines, materials, routes and resources (Caputo *et al.* 2009). Simulation tools can sense and map the uncertainties due to their capability of evaluating dynamic changes at shop floor level and offer a more realistic prediction of the production schedules (Kovács *et al.* 2003, Kuehn and Draschba 2004, Moon and Phatak 2005, De Vin *et al.* 2006).

3.2   Optimization objectives for ERP and Simulation integration

The optimization variables which have been mostly addressed in past research were a combination of time and cost. For instance, a hybrid of time with queues as optimization objective was initially evolved in 2003 (Kovács *et al.* 2003). Contextually, the most credible set of highly scalable range of optimization objectives for a full job shop solution was evolved in 2004 (Kuehn and Draschba 2004).

The conceptual framework and philosophy for tactical and operational planning parameters utilizing HLA/UML tools were initially offered in Rhythm Suite by i2 ERP vendor. These Tactical decision making features were fully integrated in various modules (Lendermann *et*

al. 2001). This very fusion of highly integrative ideas gave birth to brand new core architecture for ES/ERP and simulation integration. This first generation of application, however, was too generic in nature with omission of prerequisite planning and scheduling optimization parameters. As the research in this dimension advanced a state-of-the-art framework for cycle time enhanced forecast was formulated (De Vin *et al.* 2006). Later on, the gap was bridged by proposing a generic set of parameters to support optimization objectives. In order to integrate ERP (MPS the APO planner side) with Arena simulation tool; (Caputo *et al.* 2009) eleven key parameters were proposed with comprehensive details for tight integration with APO (Scheduler side).

The past research also lacked details about set of rules for optimization parameters so as to how such rules will ensue planning and scheduling optimization. To address these issues a more comprehensive and realistic full job shop solution with highly scalable range of optimization parameters/objectives (Kuehn and Draschba 2004) was evolved with annotated as hi-scalable-range depicted below :

a) **Resource data:** Parameter of production resources, work centres, machines etc.
b) **Operating data:** Production data, workflow definition, individual process definitions, calendar assignment etc.
c) **Job data:** Job lists, job dates, priorities etc.

Most of the past research did not consider any planning horizon, i.e. a medium-term aggregate capacity production planner or a short-term scheduler for such optimizations. The issue of erratic planning relevant to mid-term /short term horizons with detailed optimization parameters was holistically researched in 2005 (Moon and Phatak 2005).

The research rendered realistic lead time information for production optimization by introducing a concept of classification of objective parameters as fixed factors and dynamic factors. The fixed optimization factors were time, capacity, routings data, work center etc., whereas the dynamic optimization factors considered were shift-schedules, labor, preventative plant maintenance, etc. This in turn could serve as part of solution to achieve

online planning and online control (OnP/OnC) of a smart factory. The deficiency for focused optimizing delivery times for SAP-ERP-PPC were latter promulgated in 2013 (Samaranayake 2013). Yet there were apparently three deficiencies in these parameters; a) these parameters by no means were exhaustive; b) did not render a holistic picture or flow of information about ERP and; c) simulation integration in terms of objective parameters to manage futuristic sensitivity analysis.

A very important and vital issue in past research remained that no in-depth study existed that covered the details about the set of parameters as input and output so as to render optimization objective which perhaps seems to be a missing for advanced planning horizons, i.e. a medium-term aggregate capacity production planner or a short-term scheduler for such optimizations. The classification based on various techniques and the associated algorithms for different optimization objectives used by employed by various researchers, are shown in Table 3.

<Insert Table 3 here>

There seems to be a scattered set of patterns across various classifications. However, the researchers mostly employed either multiple sets of algorithm (Zhicheng et al. 1992, Kuehn and Draschba 2004, De Vin et al. 2006, Ruiz et al. 2010), linear programming approaches (Lea 2007, Pfeiffer et al. 2007, Caputo et al. 2009, Van Nieuwenhuyse et al. 2011) and in certain cases, simulated annealing algorithm (Zhang et al. 2006) for varying optimization objectives (lead times, cost etc.) were used. A prominent research in this regard has proposed an expert system with an aims to adjust ERP system to environmental changes by employing Petri net to manage the complexity and dynamics of agents behavior (Kwon and Lee 2001).

Finding 2:   The past research mostly utilized Discrete-Event Simulation (DES) and multi-agent systems (MAS). The combination of DES with Artificial Intelligence (AI) combination and MAS with Petri net was also employed for ERP and

simulation integration in order to reduce uncertainties. The objectives of such optimization include total production time, lead time, cycle time, production release rates and cost, which can be summarized as some sort of multiple of time or cost. Generally researchers considered Man-power, Money (Cost), Material in manufacturing (batch size, BOM, eBoM), Method, Machine, Resources, Routings, Capacities as core optimizations parameter. Whilst the optimization objectives were to optimize schedules through lead times and equitable distribution of load, yet, the question of optimality, scalability and flexibility of the schedules remained unanswered in most of the papers. There were apparently many deficiencies in optimization parameters and did not render a holistic picture about **Business parameters (Demand, planned orders or release-jobs)** as well **operational parameters** like BOM or run parameters. Most of the papers did not consider any planning horizon, i.e. a medium-term aggregate capacity production planner or a short-term scheduler for such optimizations except (Moon and Phatak 2005, Ruiz *et al.* 2010, Van Nieuwenhuyse *et al.* 2011). Moreover, the precise flow of information about ERP and simulation integration in terms of objective parameters was not covered in depth to manage futuristic sensitivity analysis. Similarly, the exact rules or configuration of desired input or output from and to ERP modules to the simulation-engine and vice versa have not seemed to be deliberated in depth in most of the studies.

3.3 Architecture for ERP and Simulation integration

3.3.1 Integration impediments: scarce semantic harmonization

In past research varying terminologies were employed to explain the same characteristics or variables, for instance terminology static data and dynamic data (Mönch *et al.* 2003) was used for fixed data and dynamic data to explain the same set of variables/factors (Moon and Phatak 2005). Some research used the term process time where as others used the term

cycle time to explain the same concept. The use of terminologies with varying latency brings a spiral of uncertainties when the intentions is to harness the complete range of operational parameters (variables) that effect the production at a shop floor. Nonetheless, substantial effort was made to identify the range of integration paradigms and artifacts of framework for ERP and simulation integration. The themes identified therein were capitalized by various recent researches to establish state of art frameworks and interface engines.

3.3.2 Architecture-Framework for ERP and Simulation Integration: vital approaches

a.   The First Generation of Traditional Frameworks for Job Shop Scenarios

The first generation of framework for OnP/ OnC was a six-core-component architecture, for integrating production planning and control (PPC) with simulation for a hierarchical PPC system for a job shop scenario (Zhicheng *et al.* 1992). The framework utilized SIMAN simulation language, Fortran 77, and database engine to establish interfaces for integration of scheduling with simulation. The expert system successfully generated a stable master production schedule for capacity, orders status, service levels, and profits. The framework deliberated the shop floor uncertainties and inherent limitations of Master Production Schedule (MPS-MRP logic) to formulate the realistic schedules due to dynamic breakdowns and changes in priority of orders/jobs. This framework was in line with the modern concept of ERP-MPS integration with simulation in pursuit of Euro vision 2030 for manufacturing excellence. The research advocated MRP integration with simulation as part of a solution to achieve online planning and online control (OnP/OnC). The research proposed an expert system approach to solve the issues in terms of five key success elements like a knowledge base (rules), model base, database, inference engine and simulation engine for decision support of production management (Zhicheng *et al.* 1992).

As the research for Architecture-Framework for ERP and Simulation integration advanced for online planning (OnP) and online control (OnC) a four-core-component architecture for tactical planning and integration framework was evolved. This four-core component

architecture was meant for the integration of ERP-PPC with Simulation utilizing the High Level Architecture (HLA) and Unified Modeling Language (UML) tools. The scheduling-module had three sub modules: a) PPC, a medium-term aggregate capacity with production planner, b) a short-term job shop scheduler and c) a discrete-event simulator. The framework was sufficiently generic in nature with generic set of uncertainties thus lacked scalability of optimization objectives as advertised by Rhythm Suite by i2 ERP (Lendermann et al. 2001).

De Vin et al. (2006) formulated a state-of-the-art and scalable Architecture-Framework for ERP and Simulation Integration utilizing an expert system for a cycle time enhanced forecast. The Architecture-Framework for ERP and Simulation Integration for online planning (OnP) and online control (OnC) incorporated Artificial Intelligence (Artificial Neural Network or ANN) for shop floor production planning and control decision support. However, the details about architectural interfaces with ERP and Simulation engine were not correlated or even mapped which is a much needed prerequisite.

b.   The Second generation of Classical Frameworks for Collaborative Enterprise

The second generation of framework-research for OnP/ OnC focused on a more advanced Architecture-Framework for ERP and Simulation integration with agent-based system techniques. Contextually, scenarios focused on collaborative intelligent manufacturing integrating whole supply chain embedding warehouse and shop floor were deliberated in depth (Wang et al. 2011) (Moon and Phatak 2005) (Venkateswaran and Son* 2005) (Van Nieuwenhuyse et al. 2011).

In pursuit of a more refined Architecture-Framework for ERP and Simulation integration, some generic rule-based expert systems were also formulated. These were based on ARENA and VBA, integrating PPC with Simulation for a complex hierarchical production control of a job shop scenario relevant to Automobile industry (Volvo) (Wang et al. 2011). However, the proposed Architecture-Framework for ERP and Simulation Integration for online planning (OnP) and online control (OnC) did not deliberate the architectural

interfaces. The well thought and state of art architectural artifacts were later proposed, and until now, they are still evolving (Moon and Phatak 2005) (Venkateswaran and Son 2005) (Caputo *et al.* 2009) (Van Nieuwenhuyse *et al.* 2011).

A refined and comprehensive framework integrated ERP with Simulation based on a three-core component architecture was introduced by Venkateswaran and Son (2005). The three-core architecture incorporated a hierarchical PPC system for a job shop scenario which included enterprise-level planner with embedded decision rule base, a short-term scheduler and a simulation engine. The coupling among these modules was managed through the planning-control-loop and scheduler-control-loop. The process success was contributed to system dynamics model which use to trigger scheduling-operations based on predetermined rules. The architecture has foundation in PowerSim®, (HLA/RTI) and Arena®. While detailed description on the architecture and the functionalities of the simulation module were considered, the framework suffered from little focus and mention of competing operational parameters for shop floor ERP and Simulation modules.

A more realistic Architecture-Framework for OnP/OnC was a two-core-component architecture for integrating SAP/R3 ERP with Arena® to achieve the more realistic prediction of production outputs by resolving non-stochastic limitations of ERP (Moon and Phatak 2005). The optimization objective in this regard was lead time. In this architecture, core logic of management (man in the loop) was introduced to determine the optimality of schedule. Schedules were then passed on for MRP-rerun for long term planning horizons and short term schedule executions. Their classification of fixed factors and dynamic factors with a careful understanding was inscribed for planning dynamics at a shop floor. While the architectural aspects were comprehensive, the exact configuration of the desired input or output from and to the ERP modules and simulation-engine and vice versa was not inscribed. Another limitation of the proposed framework was the manual feedback-loop to transfer data between ERP and the simulation engine. This gap was fulfilled via a fully automated solution using an expert system and were discussed and implemented in varying

research work (Zhicheng *et al.* 1992, Kuehn and Draschba 2004, Zhang *et al.* 2006, Van Nieuwenhuyse *et al.* 2011).

c. The Third generation of Architecture-Frameworks: digital factory with APO functionality

The various dimensions for vital and realistic Architecture-Framework for OnP/OnC in line with the Euro-vision 2030 dictated realistic and well thought Architecture-Framework. In this regard initial work was comprised of a knowledge-base, collaborative-agent with inter/intra communication skills, ERP-database, APO (planer and scheduler) and a simulation engine as key parameters for success of ERP and simulation integration. Whilst various set of parameters for optimization, were deliberated however architectural manifestations for integrating PPC with Simulation were absent in early cited works in this regard (Ruiz *et al.* 2010).

The initial research in pursuit of hyper-efficient APO for OnP/OnC were also deliberated by Pfeiffer (Pfeiffer *et al.* 2007) and Caputo (Caputo *et al.* 2009) with slight variation in the scheduling process execution. The advanced three-core-component architecture for digital factories as part of Euro vision 2030 in pursuit of optimum shop floor decision making was initially based on the dynamics under extreme uncertainties at the shop floor (Pfeiffer *et al.* 2007). The three-core component architecture was capable to integrate the production scheduling with simulation for a hierarchical PPC-job shop scenario. The proposed solution was scalable in a sense that it could be customized for various input parameters with flexible modeling capabilities (Pfeiffer *et al.* 2007).

The more advanced, comprehensive plus realistic Architecture-Framework embedded three-core-component architecture via the Advance Planning Scheduling (APS) concept utilizing set of algorithms as a tool to optimize the ERP varying scenarios (Caputo *et al.* 2009). In this specific research, APO planner sub-module had 11 operational parameters whereas, the APO Scheduler sub module had 10 operational parameters for Arena based simulation engine. The "ERP-Simulation integration-process" (Caputo *et al.* 2009) strength was based on specific operational parameters for data transactions among scheduler,

planner and simulation engine. The time triggered transactions, based on order-input utilized a sophisticated algorithm to trigger the scheduling optimization for job creation and inventory order creation. The rules and criteria of the desired input or output from and to the ERP modules and simulation-engine and vice versa were inscribed within the logic, but the exact criterion was not disembarked. Although the framework of (Caputo *et al.* 2009) was deemed efficient and capable of accurately planning the MPS to manage market dynamics under extreme uncertainties, the framework has not yet been tested at the shop floor.

d.   The fourth generation of Architecture-Frameworks: the APS for *holonic* manufacturing

An exceedingly pragmatic framework for the hyper-efficient OnP/OnC based on APO-ERP module was proposed by (Van Nieuwenhuyse *et al.* 2011) containing middle-ware and a simulation engine. The framework can be considered as one of extraordinary ERP-Simulation integration framework to improve the decisions at the midterm planning horizon level utilizing C++ and Visual Basic. The "ERP-Simulation integration process" was designed carefully incorporating automatic updating logic after due approval from management (man in the decision loop). The framework concurrently considered the shop floor dynamics and the supply chain management based on APO. The APO module managed the process of planning by taking approval from management before transferring the optimized data to ERP module from the simulation engine. This important logic for *management-decision* was found missing in the frameworks being reviewed. The proposed advanced resource planning as a decision support module for ERP was implemented in real two world cases based on parameter-setting process, with the ultimate goal of yielding realistic information. The framework helped sales, demand and management sides of the organization for optimum business excellence.

While the success of ERP and simulation integration has emerged as an inescapable requirement, the research agenda for technical integration of "architecture and process" need to be pursued in a more pragmatic way to reap the benefits from the optimum decision support through business intelligence (BI) in pursuit of manufacturing excellence. However,

this "ERP-Simulation integration process" is based on the BI solution specific to conventional shop floor dynamics and does not cater for implausible future shop floor scenarios. Further research is therefore needed to harness the implausible scenarios beyond human management control to recognize, prioritize and mobilize resources to avert disruptions at a modern *holonic* manufacturing shop floor.

The most vital and realistic Architecture-Framework for online planning (OnP) and online control (OnC) was deliberated in line with Euro-vision 2030 based on full Job Shop Production Analyzer (Kuehn and Draschba, 2004) featuring modern Java and database technology. The architecture/framework for ERP/Simulation Integration were comprehensive enough based on future production concepts /operative production planning and control and deliberated following features:

a)   Automatic model generation
b)   Integrated simulation concept
c)   Powerful separated/independent simulation kernel
d)   Integrated database interface
e)   Fast and powerful simulation runs
f)   Fully integrated in a client server environment
g)   Open concept for user specific extensions.

Finding 3:   While most of the researchers recommended integration of the ERP planner with a simulation engine to resolve the issues with ERP short-term planning horizon, there seems to be no commonality or pattern of recognition as to how many core artifacts or modules are necessary for such a flexible and scalable ERP-simulation integration, although in general, they suggested to adopt a two to six core framework of ERP-Simulation integration architecture.

Findings 4:   A rational "*architecture*" as well as a logical "*process*" of "ERP-simulation integration" has emerged as an inescapable requirement. The analysis indicated that Architecture-Frameworks considered man-power, resources,

capacities, outsourcing-options (Kovács *et al.* 2003, Mönch *et al.* 2003, Moon and Phatak 2005, Caputo *et al.* 2009, Van Nieuwenhuyse *et al.* 2011) as the Traditional-parameters/artifacts for ERP and Simulation integration. The most comprehensive set of classical-parameters were deliberated by (Kuehn and Draschba 2004). However, the **exact rules** or configuration of desired **input or output** from and to ERP modules to the simulation-engine and vice versa were not elaborated in depth. While many Architecture-Frameworks used the Manufacturing Execution System (MES) as an independent system from ERP, most of the state of art CIM-based-ERP systems, e.g. SAP and BAAN, provide MES as a built in module for the business process integration (Yusuf *et al.* 2004, SAP 2011). In most of the past research from 1995 to 2010, a vital research gap was classical design artifacts for logical "ERP-Simulation integration process". This was later captured and canvassed (Van Nieuwenhuyse *et al.* 2011) by introducing an optimum schedule decision support management (man in the decision loop). The proposed framework holistically considered shop floor dynamics coupled with the supply chain limitations based on advanced planning and optimization (APO) concepts.

A generic framework of ERP and simulation integration based on Findings 3 and 4 and existing research gaps is further deliberated in Section 4 (Figure 3).

3.4   The capability ERP-simulation integration offered by ERP System's architecture

3.4.1   *Architecture of ES/ERP for digital factory shop floor integration*

The Computer Integrated Manufacturing (CIM) is a method of manufacturing philosophy as well as the operative label for computer automated systems, whereas the Product Life Cycle management (PLM) is the extension of CIM for Computer Aided Processes (CAx), for instance, Computer Aided Product Design (CAD), Computer Aided Process Planning (CAPP), Computer Aided Manufacturing (CAM), Computer Aided Quality (CAQ), Computer

Aided Engineering (CAE) and Manufacturing Execution Systems (MES) (CASA/SME 1993, Nagalingam and Lin 2008). Conversely, CIM (CASA/SME 1993) also extends its concept as an umbrella for MRPII/ERP that optimizes all business functions for fulfilling an order and targets at business-processes. Nowadays, many ERP packages like Infor System (BAAN), Oracle, IBM and Siemens-SAP collaborative business suites provide integration of both concepts through middleware technology. For instance, SAP bolt-on architecture of enterprise solution provides integration with and among all business-functions, including the project management (PM), supply chain (APO), production planning (PP) (Jim Hagemann Snabe *et al.* 2008, SAP 2011) and product life cycle management (PLM) (Kale 2014) bolt on modules.

In other words, the functions of ES are in the domain of product innovation, product planning, product-data-management (PDM), Product Life cycle management (PLM) i.e. CAD/CAPP/CAM/CAE, engineering-BOM (MRP). Managing the time to market is the domain of PLM suites, while business aspects of order management, SCM, manufacturing BOM (MRPII) and invoicing is the domain of ERP suites (Wu *et al.* 2014). The concurrent e-synchronization of these value creation activities can lead to the optimization of efficiency and effectiveness across business-functions through ES, for instance mySAP suites. The CIM as a grand-philosophy aims at integrating all functional areas of manufacturing industry under one unified Enterprise System (CASA/SME 1993). The CIM objective in 1980s to 1990s was to convert the islands of automation into intelligent enterprise systems for engineering (CAD/CAM/CAE/AGV), utilizing production philosophies (JIT/FMS/SCM/TQM), marketing, accounting, administration, management and support functions of a manufacturing enterprise (Prasad 2000).

3.4.2   ES/ERP system architecture to support Holonic manufacturing
Due to global competition, aircraft industries including Lockheed Martin, Boeing and Airbus are using best-of-breed (BoB) ERP, PLM and simulation systems (Hirata 2009). The top 500 fortune enterprises have incorporated enterprise systems (Davenport 1998), to gain

competitive advantage through integrated business processes. The chronological enhancement in ES/ERP system, for instance mySAP technology which is one of the state-of-the-art Enterprise-systems, provides seamless integration of best-of-breed (BoB) ERP, PLM and e-commerce modules as well as BoB philosophies like TQM, balanced-scorecard cockpit, productivity, BPR and SCM (SAP 2011).

The manufacturing industry has employed SAP-based ES/ERP systems with embedded product life cycle module (PLM) (Lee *et al.* 2008). This module has functionality to manage product data configuration, the bills of material (BoM), bills of process (BoP), the engineering change termed as the master data and product structure management. While the PLM module defines how to manage the process of manufacturing, the associative MRP module harnesses the MPS coupled with shop floor routing by taking into consideration the optimum inventory levels, the lead time offsetting the stock level. The cooperation of two modules delivers what is required to be produced, by exploding and netting the BoM and BoP thereby leveraging financial aspects. The whole concept is termed as 'logic of MRPII'. The addition of supply chain management and marketing functionality transforms MRPII logic into an ERP-logic. BAAN and SAP have also recently enhanced the functionality for optimization of schedules vis-à-vis optimum machine vs capacity loading coupled with the supply chain management (SCM) (Akyuz and Rehan 2009, Monroy and Vilana Art 2010). This new enhancement is in fact an integration of MRPII functions with SCM operations with limited embedded algorithms for optimization of capacity. The SAP's bolt-on module for business intelligence (BI) termed as the Decision Support System (DSS) for top management, provides the balanced scorecard performance dashboards (Yusuf *et al.* 2004, SAP 2010, SAP 2011). The schematic of SAP functional domain is illustrated in Figure 1.

<insert Figure 1 here>

3.4.3 The ES integration status: where we are

The integration of ERP with PLM, CAPP and CAD is still in its infancy stage as presumed from past research by (Yusuf *et al.* 2004). In 1996, Rolls-Royce decided to switch over from

the IBM asset management Enterprise-system to the new SAP-ERP for "aerospace and defense industry". The aim was economic globalization, internationalization of operations and collaborative advanced planning and optimization. The project completed within a projected budget of £7.5M but it still had major inaccuracies in terms of interoperability and scheduling, as well as an unfortunate legacy CAD system (semi-manual files data interchange) which was considered too expensive for core implementation of ES (Yusuf et al. 2004). The SAP project had three phases and was completed in four years. The additional reason for not undertaking ERP and CAD integration was the high cost of integration and apprehension about a delay in project completion DLDs. Previous literature hardly discussed any aspects of SAP integration with simulation in terms of CAPP which is considered as the next higher level of sophistication in the product development hierarchy. The recent work by (Moon and Phatak 2005, Pfeiffer et al. 2007, Ruiz et al. 2010, Van Nieuwenhuyse et al. 2011) support the argument that while the efforts in this dimension are there, however, a strategic-cum-collaborations are needed by system engineers, industrial engineers, software engineers, business and marketing consultants. This indeed would go a long way to provide embedded simulation capability in BAAN, Oracle, IBM and SAP ERP-engines.

3.4.4   The future Roadmaps: where we want to be

While ERP modules have been adopted by the top 500 fortune companies and the remaining industry partners are scrambling for ERP adoption for optimum control over industrial and financial sectors, the actual success of ERP is far lower than the desired expectations. What seems to be missing is a simulation-engine as well as the shop floor production automation. A concept floated in 1985 by CIM-philosophy was an "island of automation" which was to have a single authoritative ES/ERP system for manufacturing excellence (Nagalingam and Lin 2008). The international markets reiterate integration with the shop floor as vital for holistic control of business activities. This makes APO integration with the shop floor machines/robots, PLCs (programmable logic controllers), automated

storage and retrieval systems (AS/RS) and AGVs (Automated Guided Vehicles) possible. The simulation tools are considered vital for the optimized and accurate calculation of production schedules, Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), rapid prototyping (CAPP), automated mock up; for instance wind tunnel testing, performance parameters evaluation, performance parameters analysis, computer assisted research and development for prototype product manufacturing (Asif and Uzma 2008). The road map for an enhanced ERP system has been harnessed in past research work (Markus et al. 2000, Møller 2005, Nagalingam and Lin 2008) (Asif et al., 2011) and (Manarvi. and Ahmad, 2008).

However, the efforts to provide state of art ES/ERP with Global manufacturing capabilities for manufacturing process and resources and the product data management (PDM) integration for product data is still not close to expectations of the smart factory (Lee et al. 2011). Manufacturing excellence requires accurate product data integration and transformation of engineering bill of materials (EBOM) to manufacturing bill of materials (MBOM) for OnP and OnC which prevailing ERP-packages are devoid of (Kuehn and Draschba 2004, Moon and Bahl 2005). The PLM/PDM and ERP integration for Digital manufacturing, can be solved through logical ERP modelling through simulation engines (Lee et al. 2011) so as to Reduce costs, improve quality, reduce the lead times ensuring at the same time to act and think smartly for sustainable and *hyper-efficient* operations.

The future ERP framework that is most relevant to the SAP on-going passion for competitiveness was put forth by (Møller 2005). The road map is termed as web enabled ERP2 with all the MRP-cum-advance planning functionalities as the core of the ERP database. In recent times, the need for an Intelligent Information System (IIS) has emerged as an inescapable requirement to manage the market dynamics and production plant resource embarkation under uncertainties. The Idea of intelligent information system (IIS) was reviewed in depth by (Prasad 2000). Contextually the intersection of two abstract ideas

has been canvassed schematically for ERP as an enabling and Intelligent Information System (IIS) technology for manufacturing and is shown in Figure 2.

<insert Figure 2 here>

Findings 5:   While ERP and Simulation integration has emerged as an inescapable requirement yet the ERP vendors render far less than the CIM-philosophy of CASA (CASA/SME 1993, Nagalingam and Lin 2008). SAP yet had major inaccuracies in terms of interoperability and scheduling, as well as an unfortunate legacy CAD system (Yusuf *et al.* 2004). It is also identified that past literature has shed limited light upon topics like ERP integration with simulation in terms of CAPP which is considered as the next higher level of sophistication in the product development hierarchy (Moon and Phatak 2005, Pfeiffer *et al.* 2007, Ruiz *et al.* 2010, Van Nieuwenhuyse *et al.* 2011). The recent research work (Lee *et al.* 2011) further stresses the need for ES/ERP with Global manufacturing capabilities in pursuit of smart factory. Therefore, the embedded simulation capability ERP-engines reiterates the strategic-collaborations among BAAN, Oracle, IBM and SAP. This in turn would reduce costs, reduce lead times, improve quality, and at the same time ensure to act and think smartly in pursuit of Euro vision of 2030 for the smart factory.

4.   DISCUSSION

While many CIM/ERP vendors ever since 1990 have focused on automation integration capabilities, concurrently, the academic community have developed approaches to improve the built-in logic embedded in MRP scheduling and planning systems. However, these enhanced planning solutions are still not implemented as the core functionality in ERP systems. Previous research has used either stochastic- or agent-based techniques to fix up the non-scholastic planning horizons and logic of ERP under dynamic demand uncertainty at the shop floor (Moon and Phatak 2005, Ruiz *et al.* 2010, Van Nieuwenhuyse *et al.* 2011).

The aerospace industry case study (Yusuf *et al.* 2004) further confirmed the various issues with ERP systems that affect the long-term and short-term planning horizon during production planning and control at shop floor level.

4.1   General Research Gaps

The literature review of the past 20 years highlighted another dimension to the shortcomings and gaps in the research domain.

a)   It was inferred that ERP's MRP module has non-stochastic demand planning logic. Due to this presumption, the module cannot give accurate prediction about the short term planning horizons (Moon and Phatak 2005, Ruiz *et al.* 2010, Van Nieuwenhuyse *et al.* 2011). Simulation tools can handle such deficiencies efficiently and therefore there is a strong case that simulation should be integrated with ERP so to render part of the solution.

b)   Assuming that the integration is taking place, the general optimization for ERP and simulation integration, fall in the range of cycle time, cost, materials, capacities, and labor-hour optimization (Kovács *et al.* 2003, Mönch *et al.* 2003, Kuehn and Draschba 2004, Moon and Phatak 2005, Benoît *et al.* 2006, Pfeiffer *et al.* 2007, Caputo *et al.* 2009, Ruiz *et al.* 2010, Van Nieuwenhuyse *et al.* 2011, Samaranayake 2013). To achieve optimization objectives, numerous algorithms have been employed; although, there are no patterns or clear classification criteria (see Table 2). The question of optimality, scalability, and flexibility of the schedules leveraging optimization variables remained unanswered in most of the past research.

c)   The integration framework presented in past research lacks harmonization and coherence for standard terminologies and the use of semantics ontology may solve the issue. This aspect has affected the quality of derivations for clear and precise set of rules to classify architectural artifact (see Finding 3). Furthermore,

although numerous papers proposed a range of architectural artifacts (from simple to comprehensive) for ERP integration with simulation. However, a complete set of architectural "ingredients" or parameters leveraging flexibility and scalability seem to be missing (see Finding 4).

d) In most of the past research from 1995 to 2013, a vital research gap was design artifacts for logical "ERP-Simulation integration-process". While in 2011 (Van Nieuwenhuyse *et al.* 2011) introduced optimum schedule decision support management (man in the decision loop) to manage shop floor dynamics yet further research is needed to harness implausible scenarios beyond human management control.

e) ERP system by Infor System (BAAN), Oracle and SAP have lavish features for business forecasting, MRP (push production operations), JIT (pull production operations) and APO (Yusuf *et al.* 2004, Møller 2005). However, ERP lacks sophistication in terms of integration with shop floor machines/robots and simulation (Moon and Phatak 2005, Benoît *et al.* 2006, Bergmann and Strassburger 2010, Ruiz *et al.* 2010, Van Nieuwenhuyse *et al.* 2011). The future roadmap like ERP-II (Møller 2005) conceptual frameworks has addressed these shortcomings and has thus proposed the embedding APO and simulation as core functionality for future ERP systems.

4.2 Specific research gaps: optimum scheduling perspectives

Generally ERP and Simulation integration requires an ES/ERP Database, a planner and a scheduler module of ERP-APO that are connected to a simulation engine via middleware (interface) and a knowledge-base (rules-set and sequence) for managing the process of integration. A generic framework of ERP and simulation integration is shown in Figure 3.

<insert Figure 3 here>

A careful analysis of the literature review in the last 10 years (most relevant or most cited research papers) indicates that there are some vitally important artifacts or a set of artifacts which can ensure the success of such integration and these have been integrated in different ways by various researchers. The key success elements were a knowledge base (rules), model base, database, inference engine and simulation engine for decision support of production management.

The important artifacts were:

1. PPC – a medium-term aggregate capacity-cum-production planner,

2. A short-term job shop scheduler,

3. A discrete-event simulator

Several authors proposed a certain add-on like artificial intelligence (ANN) as one of the vital 'ingredients' for the process of ERP-Simulation integration in context of ERP as a Decision Support System (DSS). The framework presented by various researchers can help facilitate the organizations' sales department to holistically manage the customer orders for optimum business excellence. These can be managed through a seamless integration of machines, robots, computers and sensors. The smart factory future ERP and simulation integration architectural imperatives discussed above are the key ingredients or building blocks for business excellence. While the success of ERP and simulation integration has emerged as an inescapable requirement, the following research agenda for technical integration of "architecture and process" needs to be pursued holistically to achieve manufacturing excellence.

- **Artifacts of an open** and **high level architecture:** What could be the core artifacts for such integration? How could the architecture and interaction among modules be investigated in order to achieve an optimum scheduling for the short-term horizon at the shop floor level and for the long-term horizon planning at the enterprise level?

- **Scheduling and the appropriateness of rules:** How many rules need to be considered for the MRP-rerun for long-term planning horizons and short-term schedule executions?

- **Scheduling and optimization parameters:** How many key parameters need to be considered in terms of standardized fixed and dynamic parameters for execution of optimum schedules?

- **Scheduling data Process transactions**: What could be the desired process for input to or output from the ERP modules and simulation-engines, respectively, for the optimal schedules?

- **ERP-Simulation integration-process/Automation of articulated rule-base:** How would the process of data transfer be managed from the scheduler to the planner after due approval from management so as to rerun an optimum long-term plan?

4.3   Limitations and future work

While exhaustive search of databases was conducted to extract relevant papers, later on, the abstracts as well as full text of 127 papers from Scopus and 229 papers from IEEE were fully read to fetch results as per the research scope which in turn contributed meaningfully to address ERP-Simulation integration. The search results from various databases may not be termed as absolute but should at least serve as a tool to set future road map and research agenda towards ERP simulation integration and realizing the idea of future smart factory. Hence, research in future may be conducted to address areas not covered within the scope of this research.

An interesting area for future investigation could be the holistic-framework for ERP with online planning and online control functionalities leveraging ERPII (APO with Simulation for push production operations); MES, JIT (pull production operations) and other concepts such as capacity adjustment.

5. CONCLUDING REMARKS

This research aimed at rendering a structured and systematic approach for ERP-simulation integration. The shop floor complexity in terms of human-computer interaction and control systems has been challenging, due to inflexible monolithic manufacturing systems. The ERP offered technological solutions are more or less a burden rather than an enabler for ramping up preplanning, planning or re-planning the master schedules. The three major imperatives identified are: *business imperatives*, *operational imperatives* and *architectural imperatives*. The global businesses witness the dynamic changes every now and then at the shop floor level in the form of absenteeism, material unavailability, and method changes causing cycle time changes and cost (money) changes. The objective in every such case is to predict precise future delivery dates, to predict the ability to promise capacities through a state-of-the-art software architectural platform for an optimum human computer interaction. The identification of an integrated set of ingredients or building blocks for the software architectural platform has emerged as the ERP and simulation integration which has helped in identification of much needed research directions for the future of ERP and simulation integration.

The challenges towards the realization of a Smart Factory are numerous. These include engineering change management, order change, re-prioritization, re-customization or even cancellation. The abrupt breakdown, scheduled or unscheduled plant maintenance are few of the more uncertainties. A structural change is needed within the ERP systems to address such uncertainties and this paper presents an effort in this direction by bridging the gap between ERP and simulation integration as part of the solution to manage shop floor uncertainties. The missing research agenda to achieve manufacturing excellence could be summarized as follows.

1. What could be the classical approach for resolving the ERP's MRP module non-stochastic demand planning issues?

2. What is the core of ERP2? Should it embark on the MRP / advance planning functionalities as core of ERP database or should the core foundation consider tools like simulation to provide a holistic solution?

3. What could be the critical success factors for optimization objectives? What could be the winning criteria (since the question of optimality, scalability and flexibility of the schedules leveraging optimization variables remained unanswered in most of the past research papers)?

4. What semantics ontology framework could be used to classify architectural artifacts?

5. What unified comprehensive architectural artifacts for the simulated ERP integration process could ensure optimum architectural parameters leveraging flexibility and scalability?

6. What business process considerations need to be canvassed and planned in order to address the issues of "ERP-Simulation integration-process"?

7. What do the ERP system vendors need to plan to address the future factory issues in terms of business forecasting, MRP (push production operations), JIT (pull production operations) and APO. How would the automation and seamless integration sophistication of shop floor machines/robots and simulation be ensured in pursuit of optimum *holonic* manufacturing, decision making and production planning at a shop floor level?

It is hoped that future researchers will take the synergy from this effort to render worthwhile contributions towards this valuable yet rather neglected area of research.

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Table 1: The survey statistics of major databases

S#	Search Criteria	Web of knowledge (ISI)	Scopus	+IEEE Xplore	*+(ACM)
1	*Enterprise resource planning + Simulation	27	127	7742 (36,638)	1807
2	Enterprise resource planning + Simulation integration	27	715	17815 (2732)	1106
3	Enterprise resource planning integration with Simulation	27	127	22	1106
4	Enterprise resource planning shop floor integration + APO + Simulation	0	0	0(229)	3
5	Enterprise resource planning + Integration with shop floor Simulation	2	7	105(27)	138
6	Enterprise resource planning + Simulation Integration + shop floor "Job Shop"	0	0	15 (4)	22

Note:

*: ERP = the whole syntax Enterprise Resource Planning was used to avoid retrieving unwanted papers from other disciplines, e.g. medical science

+: IEEE Xplore rendered searches over 3,508,225 records. The IEEE search algorithm was found to be sensitive to spaces between search terms; the numbers in bracket contains results (for the search without spaces in between words)

*+: (ACM) Association of Computing Machinery; rendered searches over 2,132,334 records and its search algorithm was found to be sensitive to spaces.

*. The databases searched are likely to overlap, since IEEE and Scopus as per defined search criteria yielded overlapping results, hence, the final content and results shown in Table are accounted for this.

Table 2: Classification of Journal-based research

Journals /Conferences	
Computers & Industrial Engineering	1
Computers in Industry	3
Conference, Intelligent Manufacturing Systems	1
European Simulation Multiconference	1
Expert Systems with Applications	1
Industrial Management & Data Systems	2
International Journal of Production Research	2
Proceedings of the Winter Simulation Conference	2
Proceedings of the 37th CIRP international seminar on manufacturing systems	1
Proceedings of the Winter Simulation Conference	1
Robotics and Computer-Integrated Manufacturing	1
Sage Simulation Journal	1
WSEAS Transactions on Information Science and Applications	1
Grand Total	**18**

Table 3: Classification of author-based research for the simulation techniques algorithm employed vs the optimization objectives

Author	Simulation algorithm	Simulation techniques	Optimization objectives														
			Batch size and man-power	Capacity planning	Cost	Cost and time	Customer order prioritization	Cycle time	Cycle time (and its derivatives)	Cycle time and cost	Inventory cost reduction	Lead time	Lead time and cost	Lead time and deadline date	Lead time and queues	Optimum production release rate	Throughput, man-power, transportation and material usage
Caputo et al. (2009)	Linear programming(Capacitated Lot-Sizing algorithm)which optimizes operative production	DES									x						
De Vin et al. (2006)	Multiple	DES & AI						x									
Johansson et al. (2007)	Not discussed	DES	x														
Kovács et al. (2003)	Tree portioning Algorithm	DES		x													
Kuehn and Draschba, (2004)	Multiple Algorithms Technique	DES							x								
Kwon and Lee, 2001	Petri net	MAS														X	
Lea (2007)	Linear programming	DES			x												
Lendermann et al., (2001)	Not discussed	DES					x										
Mönch et al. (2003)	Beam-Search Algorithm	DES										x					
Moon and Phatak, (2005)	Not discussed	DES										x					
Pfeiffer et al. (2007)	Linear programming	DES											x				

Author	Simulation algorithm	Simulation techniques	Optimization objectives														
			Batch size and man-power	Capacity planning	Cost	Cost and time	Customer order prioritization	Cycle time	Cycle time (and its derivatives)	Cycle time and cost	Inventory cost reduction	Lead time	Lead time and cost	Lead time and deadline date	Lead time and queues	Optimum production release rate	Throughput, man-power, transportation and material usage
Ruiz et al. (2010)	Multiple Algorithms Technique	MAS								x							
Samaranayake (2013)	Not discussed	DES										x					
Van Nieuwenhuyse et al. (2011)	Linear programming														x		
Venkateswaran and Son (2005)	Non linear via LINGO	DES														x	
Wang et al. (2011)	Pre Defined Algorithms	DES															x
(Zhang et al., 2006)	Simulated annealing (SA)	DES											x				
Zhicheng et al. (1992)	Multiple Algorithms Technique	MAS				x											
	Grand Total		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**3**	**1**	**1**	**1**	**2**	**1**

Legend:

DES: Discrete Event Simulation
DES & AI: Discrete Event Simulation and Artificial Intelligence
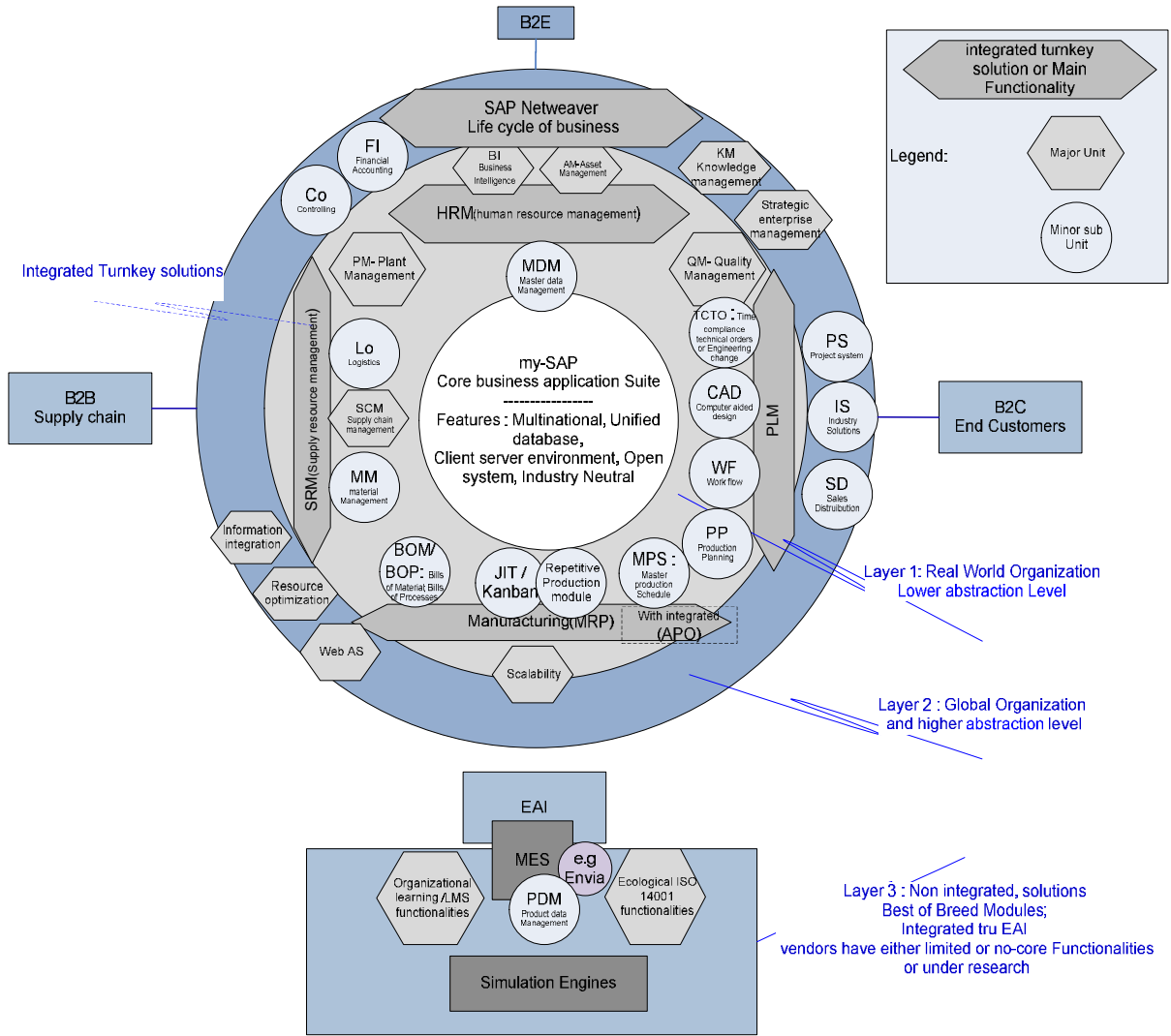MAS: Multi-agent Simulation (MAS)

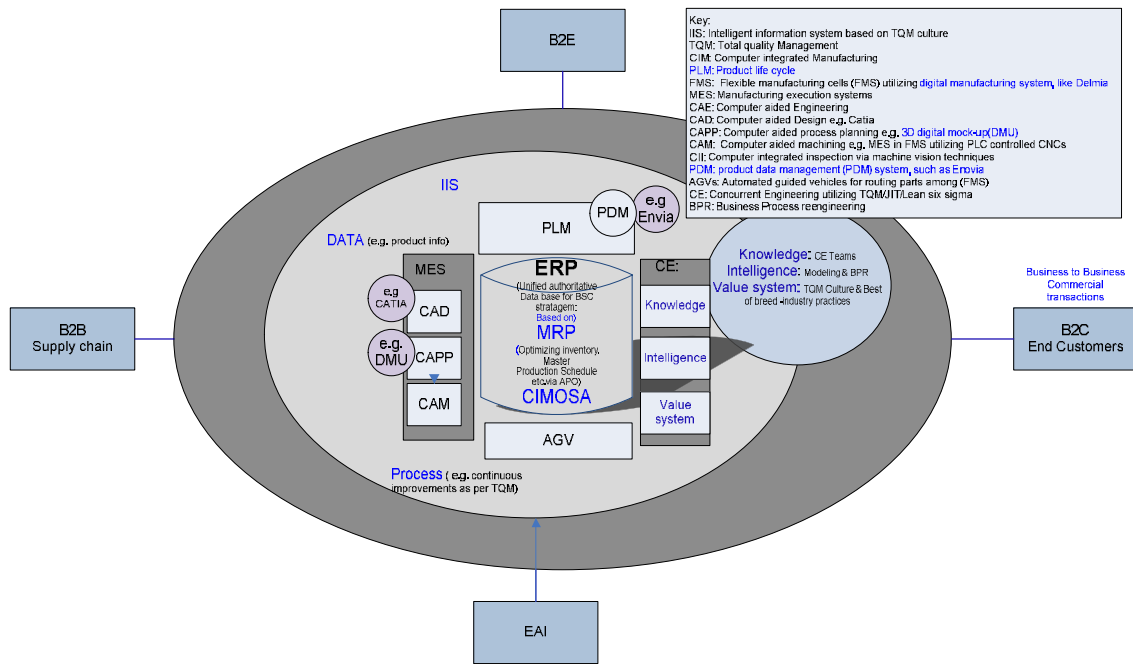Figure 1: SAP ES/ERP information system (adapted from SAP)

Figure 2: ERP intelligent information system for manufacturing (adopted from Prasad (2000) and Møller (2005))
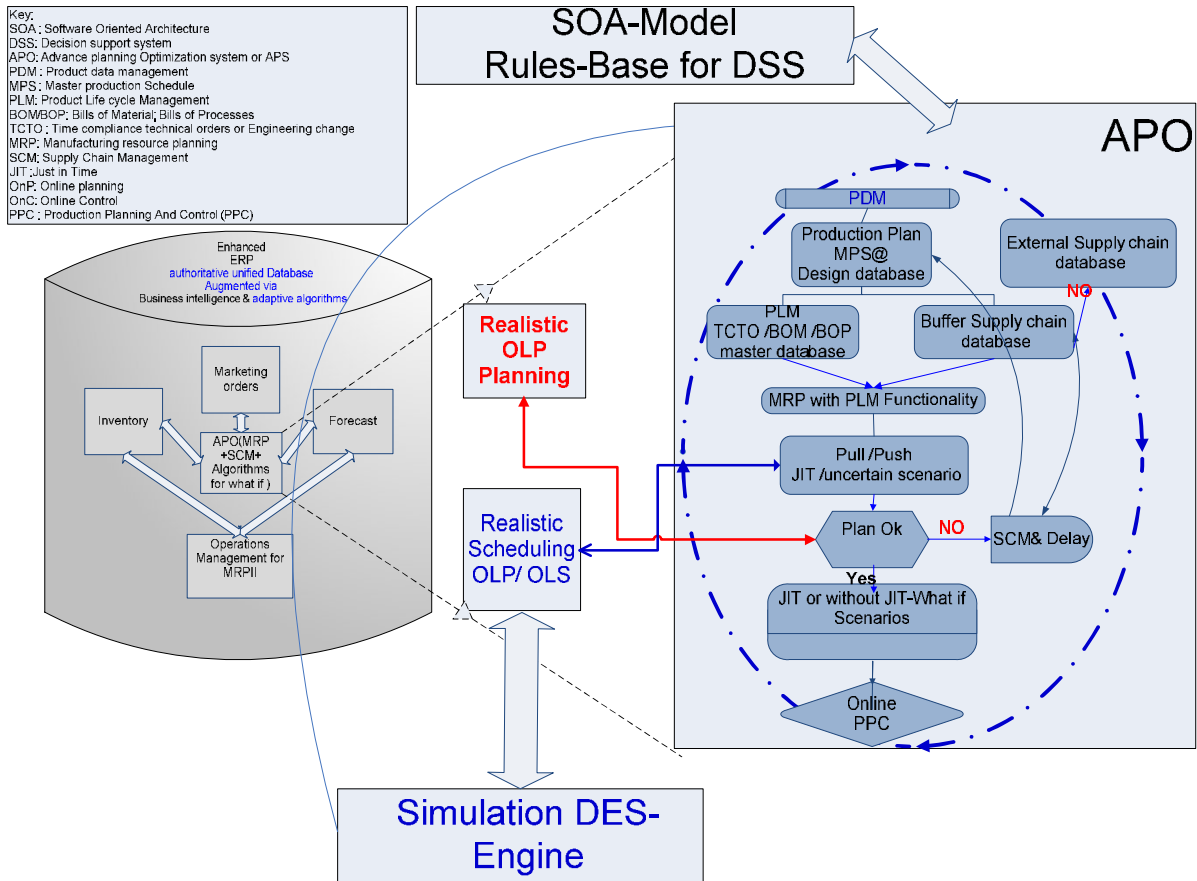
Figure 3: Framework of the ERP-Simulation integration for manufacturing excellence