From Factory of the Future to Future of the Factory: Integration Approaches

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Abstract: Nowadays, manufacturing systems transform themselves to become Factories of the Future (FoF) that is to say highly flexible, rapidly adaptable to external changes and aiming for a high degree of sustainability. This trend has generated several research streams that we analyse in this paper through a deep bibliographical review. This review leads us to conceptualize 3 main approaches: Computer Integrated Manufacturing, role of human work force and other integration approaches. A potential issue identified within the research is the interplay between computer-based and organization based approaches to manage the dynamic interactions among product, processes and production systems. The conclusions and orientations of future works are thus outlined to support the development of this co-evolution perspective for the successful transformation of Factories.

Keywords: Enterprise integration, Architectures and software tools for enterprise integration and networking in manufacturing, Interoperability and sustainable enterprise, Information Systems, Factory of the Future

1. INTRODUCTION

In the present era of greater Information Technology (IT)-based manufacturing systems, several initiatives are committed to the transformation of industry to attain the Factory of the Future (FoF) - highly flexible, rapidly adaptable to external changes and aiming for a high degree of sustainability (Herrmann et al., 2014). For instance, the Advanced Manufacturing Partnership in USA, the Horizon 2020 in the European Union, as well as the Industry 4.0 by the German government, among others, launch projects in this area. As a consequence the literature related to FoF is in constant growth with a variety of concerns, underlying approaches and application areas.

Therefore, this paper aims to provide a comprehensive insight of the underlying approaches and evolving conditions of production systems under the concept of the FoF. To succeed in, a bibliographic analysis is addressed following a defined methodology that will be detailed in the next section. This analysis will enable us to depict a global picture of what has represented the ‘Factory of the Future’ over time - particularly in the last three decades. Sections 3 to 5 are dedicated to the description of the three research streams we identify: (i) CIM (Computer Integrated Manufacturing) approach, (ii) the Role of Human Workforce and (iii) Other Integration Approaches. Section 6 pinpoints the possible work directions stemming from the bibliographical analysis. Section 7 concludes with further aspects to develop a collaborative framework based on the co-evolution of product, processes and production systems.

2. METHODOLOGY OF RESEARCH

To structure the literature review we perform, we look for general guidelines providing the steps to follow. We found several works focusing on meaningful recommendations for crafting a literature review. For example, in (Kitchenham et al., 2007) guidelines for performing a systematic literature review in Software Engineering are proposed. They suggest a three-phased approach: i) Planning the review, ii) Conducting the review and iii) Reporting the review. As well, vom Brocke et al. (2009) propose a framework that points out a circular process which characterizes a literature review. It integrates 5 main steps: i) Definition of review scope, ii) Conceptualisation of topic, iii) Literature search, iv) Literature analysis and synthesis and iv) Research agenda. This framework is interesting because it details the planning review and the reporting review steps proposed in (Kitchenham et al., 2007). That is why our work is based on the framework of (vom Brocke et al., 2009) (see Fig. 1). This framework helps us to select,analyse, classify and report studies collected according to our review scope: “What does the manufacturing vision referred as the ‘Factory of the Future’ (FoF) entail?”. Hence, we set up our bibliographical research using the key word ‘Factory of the Future’ by querying the database ISI Web of Knowledge from all years. Seeing the number of publications in the field, we delimit the type of documents as ‘Articles’ and ‘Reviews’; and the areas of research as follows: ‘Engineering’, ‘Computer Science’, ‘Business Economics’, and ‘Operations Research Management’.
This query gives us a result of 60 papers. After reading abstracts, we excluded a certain number of papers for the following reasons: i) one anonymous paper and ii) 17 papers without clear evidence (between 1982 and 1990) because their abstracts are not available or are out of the scope. At the end, 42 articles are analysed.

To observe the context in which these investigations are positioned, we analyse the number of different journals in which the considered papers are published. They are distributed over 32 different journals from the 1982-2015 period. This evidence shows that the publication sources for the FoF topic are quite various. Moreover, Fig. 2 shows that there are certain variations in the annual number of publications. From the 1984 to 1996 period, there are consecutive publications, indicating 1985, 1991 and 1992 as the most outstanding years with 9% and 10% of publications. Though, there is a drop from 1993 to 2007 with a recovery from 2012 to 2015.

Another important feature of this research is to indicate the origin of these studies. Most of the articles are issued from authors stemming from USA (36%), Germany (12%), England (12%) Australia (7%), Italy and Netherlands (5%) The remaining articles are distributed equally (2%) within 9 member countries of the European Union (EU), besides Norway, Japan, Canada and Brazil. Fig. 3 shows a pie chart with the distribution of the works published by countries.

In consequence, by the means of this analysis encompassing past and recent research, we have identified three major categories (with corresponding subcategories). They deal with the development of the CIM systems, the adaptive role of the human interaction within the entire organisation and last with the integration efforts of new approaches for enhanced processes and production systems. Thus, we introduce this classification to outline the main contributions underpinning the FoF, as follows:

A. CIM Approach
   A1. Technology enablers and barriers for CIM
   A2. Flexible Automation
   A3. Decision Support Systems
   A4. Production Models

B. The Role of Human Workforce

C. Other Integration Approaches
   C1. Continuous Improvement
   C2. Holistic Factory
   C3. Processes for Sustainable production

The distribution of the papers analysed according these categories and sub-categories is detailed in Table 1.
Table 1. Categories and Subcategories for the literature review of FoF

| A. CIM Approach |  
| --- | --- |  
| **A1. Technology enablers and barriers for CIM** |  
| 1. Jelinek, M. and J. D. Goldhar (1984) |  
| 2. Meredith, J. R. (1987) |  
| 3. Mulder, M. C. (1990) |  
| 4. Tie, H. Y. and G. C. I. Lin (1992). |  
| 5. Duimering, P. R., F. Safaveni, et al. (1993). |  
| 6. Brandon, J. A. (1994). |  
| **A2. Flexible Automation** |  
| 7. McElroy, J. (1984) |  
| 8. Godfrey, D. E. (1985). |  
| 9. Petre, P. (1985). |  
| 10. Ford, F. N., W. N. Ledbetter, et al. (1985). |  
| 11. Bullinger, H. J., H. J. Varnecke, et al. (1986) |  
| 12. Moore, G. (1986). |  
| 13. Yoshikawa, H. (1987). |  
| 14. Hiddle, A. R. and B. Zollner (1991). |  
| 15. Buxey, G. (1992). |  
| 16. Lee, K. M. and Y. F. Qian (1998). |  
| **A3. Decision Support Systems** |  
| 17. Jackson, R. H. F. and A. W. T. Jones (1987). |  
| 18. Jackson, S. and J. Browne (1992). |  
| **A4. Production Models** |  
| 19. Fluss, R. (1988). |  
| 20. Robstadas, A. (1991). |  
| 21. Wortmann, C. (1992). |  
| **B. The role of Human Workforce** |  
| 22. Thompson, H. and R. Scalpone (1985). |  
| 23. Cross, K. F. (1986). |  
| 24. Clancy, J. A. (1989). |  
| 25. Schultzwild, R. (1991). |  
| 26. Badham, R. (1991). |  
| 27. Brandon, J. A. (1994). |  
| 28. Ezzamel, M., H. Willmott, et al. (2001). |  
| 29. Gisbert, J. R., C. Palau, et al. (2014) |  
| 30. Slade, H. (2014). |  
| 31. Pedersen, M. R. and V. Kruger (2015). |  
| **C. Other Integration Approaches** |  
| **C1. Continuous Improvement** |  
| 32. Martins, K., R. Albrecht, et al. (1993). |  
| 33. Robstadas, A. (1995). |  
| 34. Harrell, S. (1995). |  
| 35. Gudogan, M., G. Groves, et al. (1996). |  
| 36. Souza, M. C. F., M. Saeco, et al. (2006) |  
| **C2. Holistic Factory** |  
| 37. Herrmann, C., C. Schmidt, et al. (2014). |  
| 38. Tolio, T., D. Ceglarek, et al. (2010). |  
| 39. Tepes, M., P. Krajnik, et al. (2015). |  
| **Processes for Sustainable production** |  
| 40. Fresner, J., H. Schnitzer, et al. (2007). |  
| 41. Matassa, S., N. Boon, et al. (2015). |  
| 42. Sagnella, A., C. Chieco, et al. (2015). |  

3. COMPUTER INTEGRATED MANUFACTURING APPROACH

At the outset of automation, CIM was conceived as the most suitable approach to integrate the flow of information within the production systems. CIM “represents the union of hardware, software, database management, and communications to automate and control production activities from planning and design to manufacturing and distribution” (Collier et al., 2011). The employment of appropriate software and hardware tools was promising for a wide range of improvements. This approach was the Factory of the Future of the 80s. Their implications required to set ad hoc strategies across the organization to meet the potential of technological progress.

For this section, the following subcategories characterizing the literature of CIM approach are detailed as:

- **A1. Technology enablers and barriers for CIM**
- **A2. Flexible Automation**
- **A3. Decision Support Systems**
- **A4. Production Models**

3.1 Technology enablers and barriers for CIM

The first sub-category is related to technology enablers and barriers for CIM. For example, Jelinek et al. (1984) describe the four major success features of CIM: i) Flexibility, the key characteristic to respond to market changes, ii) Broader information within processes collected by computer sensors, iii) Better control of processes and improved knowledge to assist management for optimization and iv) Highly integration between manufacturing and business functions to track changes and variability in production. As a result, the overall responsiveness in the organization is emphasized as the main source of strategic advantage. In (Meredith, 1987) the focus on services and customer satisfaction is a major competitive advantage for organizations. Concerning the work of (Tie et al., 1992), the authors highlight the importance of a total organization strategy to support management and optimization of CIM. They consider the strategic and economic potential in the use of technology. These elements aligned with the main targets of flexibility and productivity allow the improvement of integrated manufacturing systems. Furthermore, Duimering et al. (1993) analyse the strategies of CIM to handle variability. Higher flexibility and integration within this technological-driven approach are the main enablers to handle changes within production.

Concerning the barriers, herein Mulder (1990) points out the need to first identify the technical barriers at using intelligent machines to trigger a cross-disciplinary cooperation between computer science and robotics. Beyond the technical improvements in the algorithms and physical modelling, the author stresses the lack of methodologies for integration of intelligent robots and machines into the manufacturing cell processes. For Brandon (1994) managerial awareness is crucial to identify the deficiencies of technologies, to propose technical solutions and to analyse their organizational impact.

3.2 Flexible automation

The second subcategory within the CIM literature will regard the main premises underlying flexible automation approaches in manufacturing for higher productivity and competitiveness. Leading the way of CIM towards the FoF, industries need to associate flexible automation with the integrated use of computers. Herein, the modular concept in the design and implementation of systems is advocated (Bullinger et al., 1986; Ford et al., 1985; Yoshikawa, 1987). Under these concepts, the development of the Information System (IS) is associated to the success of integrated production systems.
Computer software is at the core of flexible automation. The major benefit of the software and hardware symbiosis pursued by factories is flexibility. For example, the work of Moore (1986) describes the launch of the Manufacturing Automation Protocol (MAP) stemmed from the need of intervendor communication. Additional aspects embraced by flexible automation are computer control, intelligent CAD-CAM systems, lower set-up times, quality and reliable products as well as lower lead times and costs (Buxey, 1992; Hidde et al., 1991; Yoshikawa, 1987). As we notice, one of the objective of flexible automation is to supply high-variety of products. By operating flexible systems, the changes in processes sequences can be handled with minimal set-up times. For instance, the work of Lee et al. (1998) presents a vision-based part feeding for robots. This has potential application within flexible manufacturing.

3.3 Decision Support Systems

In this category, the approaches related to the design of decision support systems in the CIM environment are discussed. These systems concern different decision types and levels. The work of Jackson et al. (1987) lies on the five level hierarchical architecture from the National Bureau of Standards. This architecture describes the various production and support activities needed to drive the FoF at different levels (facility, shop, cell, workstation and equipment). As a result, the authors propose a decision-making hierarchy that enables to break down the problems within each level of this hierarchy in smaller ones. Last but not least, in the work of Jackson et al. (1992), we find a rather knowledge-based approach for decision-making at a strategic level with uncertain informations.

3.4 Production Models

This subcategory concerns the overall conditions to support the production in evolving factories still within CIM environment. Plossl (1988) highlights four areas – Management, IS, material handling and physical plants – over which effective changes are required to develop plants of the future. Such practices regard, for instance, planning the adequate production capacity or having qualitative measures to monitor the performance of the plant. Rolstadas (1991) and Wortmann (1992) propose a model for “FoF Production Theory” consisting in a theoretical framework and a design framework. The theoretical framework consists of three views: workflow view, resource view and organizational/decisional view. The design framework consists of a connectance network of design choices (DC’s) and performance indicators (PI’s), and relationships between DC’s and PI’s. Such frameworks are suitable to successfully manage one-of-a-kind production (OKP) systems that concern the production in small batches of tailored products driven by customer orders.

4. THE ROLE OF THE HUMAN WORKFORCE

In this category, the literature refers to the organization of work and labour structures for the potential use of CIM components. According to (Clancy, 1989; Cross, 1986; Thompson et al., 1985), the major feature for competitive advantage of factories is stressed to be training and motivation of the workforce. Furthermore, as Schultzwild (1991) mentions, the choices for organizational advantages lie not only on the appropriate hardware and software of computer-aided technologies but on the type of strategy and their implementation process. This demands to create skill-based production work which calls for a labour-centred approach. Likewise, Badham (1991) considers the Human-centred approach as a major feature for flexibility and integration of manufacturing systems. In the light of advanced technology and automation, empowerment of staff is advocated in (Brandon, 1994) to deal with the possible resistance of autonomous work groups. The work of (Ezzamel et al., 2001) provides an empirical focus on the nature and organization of the employees resistance to new waves of technology and 'lean' working practices. They point out the significant condition of identity within workers to facilitate management control strategies. The work of (Gisbert et al., 2014) describes the platform developed within the FASyS project (Absolutely Safe and Healthy Factory) to sense the working environment in order to enhance workers’ skills and also safety conditions.

5. OTHER INTEGRATION APPROACHES

This last category addresses other methodologies or models to successful integrate the manufacturing system.

5.1 Continuous Improvement

Here we identify works that discuss different approaches for continuous improvement in the FoF context. For example, Mertins et al. (1993) discuss FoF development that shifts from CIM to lean production. They also analyse the methods that can be used to successfully implement lean production. Further more, Rolstadas (1995) points out the TOPP research program which aims to develop two sets of methodologies (self-audit and external audit) for measuring and improving productivity in a company. Harrell (1995) proposes seven areas of research for developing the FoF in the semiconductor industry. Gundogan et al. (1996) discuss how TQM can be exploited to move towards the Factory of the Future. The approach of Virtual Manufacturing (VM) is presented in the work of (Souza et al., 2006). It involves the strategic integration of the overall processes, from engineering to manufacturing- within a simulation and synthetic environment to improve them.

5.2 Holistic Factory

This category deals with approaches aiming to take into account the factory as a whole. For example, the concept of co-evolution of products, processes and production systems (P3S) (Tolio et al., 2010) brings together a deep insight to understand how to manage this concurrent evolution under the effects of unpredictable market changes. Additionally, to adapt manufacturing with external requirements and emerging trends, Herrmann et al. (2014) stress that the FoF
production needs to address the three dimensions of sustainability: economy, ecology and society. This proposed holistic vision strongly considers the human factor as well as the advantages of the production cloud linked to the introduction of Cyber Physical Systems (CPS). Moreover, in this change-based context, Tepes et al. (2015) support the use of holistic innovative solutions based on new organizational (virtual organizations, new business models) and technological approaches (ICT, sensors) to upgrade products to services in the future.

5.3 Processes for Sustainable Production

An even more significant factor within the FoF is the economically-feasible sustainable production processes. This category addresses the innovations that allow reducing the environmental footprint of manufacturing. Related to the effective use of resources, Fresner et al. (2007) develop an optimisation approach (ZERMEG) for galvanizing plants in order to reach the goal of zero-waste. In (Matassa et al., 2015) a wastewater treatment for sustainable FoF is proposed. It is based on hydrogen oxidizing bacteria. Last but not least, Sagnella et al. (2015) study the biotechnological applications of the regenerated silk fibroin (FSF) solution and how to upgrade it from the laboratory to industrial scale.

6. FUTURE WORK

The FoF literature focuses on the role of humans and on the definition of the integration approaches. On the one hand, the works dedicated to the role of humans emphasize the role of training and skill-based production work. On the other hand, the integration approaches can be classified according to the type of integration: computer based (CIM, CPS introduction, virtual manufacturing), organization based (lean production, TQM audit), life-cycle inter-lacing based (co-evolution of products, processes and production systems) (P’S).

The computer based integration approaches are IS and IT driven whereas the organization based integration approaches are Human driven. We consider that the life-cycle interlacing approaches pinpoint the way to couple computer based and organization based approaches. Indeed, this framework emphasizes the mutual influences between product/processes and production systems.

Therefore, our objective is to deal with the evolution of the production systems within a FoF paradigm that is to say we look for the role of the humans and the IS within this context. To succeed in we propose to exploit the product/process/production system co-evolution framework in order to redesign the factory as a whole. This framework has to be completed with the different strategies that will generally drive the change. In our view, the corresponding design is an interplay between these elements (see Fig. 4). Therefore, we should model them so as the links between them. On this basis, the role the humans can be integrated.

7. CONCLUSIONS

In this paper, we present a bibliographical analysis of the FoF literature. The presented classification aims to distinguish the major aspects between three main approaches: CIM, role of human workforce and other integration approaches. An important issue at stake is the integration of computer-based and organizational approaches to synchronize the gap between products, processes and production systems in a dynamic, highly information-driven environment. This synchronization will need a collaborative approach to design the production system and its IS according to the abilities of the production workforce and the set of strategies for a specific business activity.
