Software Engineering Methods for Intelligent Manufacturing Systems: A Comparative Survey

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Abstract. In order to survive, manufacturing systems need to adapt themselves at an ever-increasing pace to incorporate new technology, new products, new organizational structures, etc. Distributed intelligent manufacturing systems are very large and complex systems that require appropriate technologies and tools, not only to operate but also to be designed. In the specialized literature there is a large number of approaches to develop this kind of systems, but not all of them are suitable to deal with the requirements of the new manufacturing era. In this paper we make a deep analysis of the different approaches reported in the field and make a comprehensive analysis on the appropriateness of every approach for coping with the requirements of today's Intelligent Manufacturing Systems.

Keywords: Intelligent manufacturing system · Design · Engineering methodologies

1 Introduction

The manufacturers success is no more measured by their ability to cost-effectively produce a single product, success now seems to be measured in terms of flexibility, agility and versatility. But manufacturing systems are often very large-scale and complex systems [9]. Despite this complexity, appropriate technologies and tools are required to make them operate efficiently to meet the introduced manufacturer' success. An approach consists in designing distributed intelligent manufacturing system that breaks this complex system into smaller manageable systems. This approach has motivated researchers in academia and industry to create and exploit new production paradigms on the basis of autonomy and co-operation because both concepts are necessary to create flexible behaviour and thus to adapt to the changing production conditions. Distributed intelligent manufacturing systems (or for short Intelligent Manufacturing Systems - IMS), and Holonic Manufacturing Systems (HMS) are considered as important approaches for developing industrial control systems. In the specialized literature

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there is a large number of approaches to develop this kind of systems, but not all of them are suitable to deal with the requirements of the new manufacturing era. In this paper we make a deep analysis of the different approaches reported in the field and make a comprehensive analysis on the appropriateness of every approach for coping with the requirements of today's IMSs.

Section 2 overviews the features of IMSs, identifying the key technologies used in the field. Section 3 identifies the modelling requirements for IMS that will guide the analysis presented in Section 4. Section 5 summarizes the analysis with a discussion. Finally some conclusions are drawn.

2 Intelligent Manufacturing Systems

It is well known that manufacturing systems are large-scale and complex systems for a number of operational and structural reasons [9]. This complexity makes such systems difficult to control and predict[1]. The rapidly changing needs and opportunities of todays global market forces to fully integrated enterprises to be replaced by business networks in which each participant provides others with specialized manufacturing services [24]. Probably the most important reason for a collaborative environment and the need to interconnect different systems is that the market has extended and became global. This means that a new kind of integration is required with third party partners that are not even known in advance or that are subject to change. Providing personalized, high-quality and low-cost product has brought challenges to the traditional production paradigm.

Techniques from Artificial Intelligence have already been used in Intelligent Manufacturing for more than twenty years. However, the recent developments in multi-agent systems have brought new and interesting possibilities. The holonic manufacturing approach (HMS) for IMS is based on the concept of "*holonic systems*", developed by Arthur Koestler [16]. In the HMS field the manufacturing system is viewed as consisting of autonomous modules (holons/agents) with distributed control. For an extensive review of the different theoretical developments and applications of industrial agents see [19].

Over the last few years, new technologies are revolutionizing the way manufacturing and supply chain management are implemented. The convergence of Internet and manufacturing control systems provides the basis for the creation of a new generation of computing solutions that can dramatically improve the responsiveness of organizations to better communicate with their customer and suppliers. This new approach is called Service Oriented Manufacturing Systems. This new situation makes possible the rapid and easy on-demand creation of virtual manufacturing enterprises (open manufacturing systems) made up of different manufacturing partners that collaborate by means of services in order to fulfill the customer needs. Moreover, the areas of Service Oriented Architecture

[1] In order to coupe with the complexity of manufacturing systems, researchers and practitioners have used successfully the "divide and concur" approach in which the large system is decomposed into smaller and simpler components that are more easily manageable reducing the overall system complexity.

(SoA)/Service Oriented Computing (SoC) and Multi-agent Systems (MAS) are getting closer and closer, this fact leads to think on these two technologies as good candidates to achieve the requirements of the factories of the future.

3 Modeling Requirements for Intelligent Manufacturing Systems

3.1 Functional Requirements

Manufacturing control systems are large-scale complex systems designed to carry out a clearly defined task in a standardized and well structured environment. Although manufacturing processes undergo several changes and disturbances, the levels of uncertainty and unpredictability are not comparable to spacial, traffic, or service application systems.

The modules, or entities (agents/holons), which implement the control of these systems should cooperate in order to achieve the global manufacturing objectives. With regard to these objectives, a module never rejects the cooperation of another module deliberately. It only rejects their execution, when the actions requested are impossible or strongly unfavorable for the manufacturing process. In this sense, manufacturing entities are semi-autonomous. In order to implement semi-autonomous entities the specialized literature has used agent technology (made up by autonomous entities) together with some engineering constraints/requirements in order to have semi-autonomous components. The engineering constraints used successfully, by researchers and practitioners, to restrict the full autonomous execution of agents are: organization regulations (such as: master-slave and/or client-server relationships, explicit norms/regulations that restrict the scope of the agents' actions), temporal hierarchical structures and communication constraints, among others. These issues impose the following functional requirement.

(R1)*: Manufacturing control systems require autonomous entities to be organized in hierarchical and heterarchical structures.*

The second requirement is related to the kind of behavior that the control unit at factory level should exhibit. Manufacturing control units are continually handling a high number of repeated events which are known, but unpredictable. This flow of events should be handled in an effective way and with temporal constraints. The handling of the events can consequently be fixed a-priori by routines, while the beginning and execution of these routines should be performed in real-time. The set of events and their occurrence patterns change over time.

(R2)*: Manufacturing control units require routine-based behavior which is both effective and timely [4].*

The third requirement is related with standardization. The standardization is pointed out by industry as a major challenge for the industrial acceptance of any technology. The large number of different components, different layers, different communication and controlling protocols, impose this requirement to any technology used in a manufacturing control system.

(R3)*: Manufacturing control systems require standardized structures, standardized functional units that can be connected to the different levels in the system by means of standardized interfaces and communication protocols [19].*

The fourth requirement is related with sustainability. Sustainability in manufacturing systems is an urgent requirement for todays manufacturing companies due to several established and emerging causes: environmental concerns, diminishing non-renewable resources, stricter legislation and inflated energy costs, increasing consumer preference for environmentally friendly products, etc. Efforts to develop sustainable manufacturing systems must consider issues at all relevant levels (product, process, and system), and not just one or more of these in isolation. The information systems that manage and control the different levels in manufacturing systems must take into account sustainability issues of the solutions proposed, executed and controlled.

(R4)*: Manufacturing control systems require sustainable production processes [26].*

3.2 Software Engineering Requirements

Besides functional requirements, any control system (which is used in a manufacturing environment) should satisfy general industrial standards (as is stated by *R3*). These standards specify, among other things, requirements for reliability, fault tolerance, diagnosis, and maintenance. The control systems should achieve certain reliability levels which guarantee a continuous operation. This is also true for the control software. However, product dependability is only achieved if the software development process is carried out following an engineering methodology, instead of developing it in an ad-hoc way with no engineering methods or techniques.

From fundamental Software Engineering principles the following requirements are derived:

(R5)*: Programming methods should provide data and process encapsulation*[2].

(R6)*: Control programs should have clear semantics.*

[2] It is important to point out that this requirement is fulfilled automatically by almost all of todays' programming languages, since the great majority of them follows a class-based approach. This fact is demonstrated in the analysis we present in next section, see Table 1. Nevertheless, it is important to keep this requirement as an important one when developing complex systems.

Specialized literature in the field of intelligent manufacturing basically takes two approaches to problem decomposition. (i) Physical decomposition (the most obvious): agents are used to represent the entities of the physical world, such as workers, machines, tools, schedules, products, orders, attributes and operations. This approach defines different sets of state variables that should be handled by the agents in an efficient way and with a limited number of interactions. However, with this approach a great number of agents per resources are required. A common example of this approach is the use of order agents and machine agents for the planning and scheduling of manufacturing [8]. (ii) In the functional decomposition approach the agents are used for encapsulating functionalities such as work order acquisition, planning, scheduling, material handling, logistic, etc. In this approach the agents do not have an explicit relationship with the physical entities. Moreover, in last recent years, the Service Oriented Manufacturing System research community tackled the problem decomposition in terms of services. In this approach any manufacturing ability that may/or may not be associated with a resource is virtualized as a service and made available to consumers by means of a new computation paradigm, Cloud Computing. In it Service Oriented Architectures (SoA) are used to implement the computational components to execute the system. From these approaches the following requirement is derived.

(R7)*: A methodology for IMS should lead straight-forward translation from the control task on a factory resource or factory function to autonomous entities [15], that can encapsulate and provide to consumers their functionalities and abilities as services [18].*

In the field of intelligent manufacturing a kind of "loosely" hierarchical aggregation for real world systems has been recognized. These systems have to remain readable while they are expanded into a wide range of temporal and spatial scales. For example, a modern automobile factory, incorporates hundreds of thousands of individual mechanisms (each of which can be an agent) into hundreds of machines which are grouped into dozens or more production lines. Engineers can design, build, and operate such complex systems by shifting from the mechanism, to the machine or to the production line (depending on the problem at hand) and by recognizing the higher-level agents as aggregations of lower-level agents. This implies the following requirement:

(R8)*: A methodology for IMS should define a development process which is guided by abstraction levels, and should also provide modeling artifacts, tools and guidelines to manage this process.*

The traditional methods and techniques for manufacturing system modeling, such as CIM, are mainly based on a top-down approach. The user's requirements and the global conceptual design constitute the whole set of modeling constraints. With these approaches very rigid hierarchical architectures are built [15]. On the other hand, traditionally IMS were characterized as being bottom-up. Nevertheless, in order to coupe with the complexity of the distributed system made up by a network of intelligent entities, IMS modeling requires a mixed development process, bottom-up and top-down depending on the level being modeled. It is not necessary to define the whole set of constraints at the beginning. A mixed development process allows the generation of reconfigurable and scalable architectures. This characteristic implies the following requirement.

(R9)*: A methodology for IMS should define a mixed top-down and bottom-up development process.*

Finally the following requirement is inferred from the characteristics of "new manufacturing".

(R10)*: A methodology for IMS should integrate the entire range of manufacturing activities (from order booking through design, production, and marketing) to model the agile manufacturing enterprise [15].*

Taking these requirements into account we will now analyze the different methodologies reported in the specialized literature. The goal of this study is to determine to what extend these methodologies take into account the requirements for modeling IMS. Firstly, we present a brief summary of the different methodologies (more details can be found in specialized literature). Finally, we will make a comparative summary based on the requirements we have cited in this section.

4 Methodologies for Engineering Intelligent Manufacturing Systems

In IMS specialized literature there are few studies on IMS development methods. There is a recognized need, however, for design methodologies which provide clear, specific and unambiguous development processes and guidelines [22]. In this section we summarize the most relevant approaches of the field. The methods presented in this section deals with the development of systems that are made up by intelligent entities, holons or agents.

The first proposals in the specialized literature were focused on the identification and specification of the agents/holons that made up the system. The first pioneering work is from Van Brussel et al. [27]. Most of the ideas proposed in this work where adopted by other approaches in the field. For example the method for the identification of agents in a manufacturing system of Ritter et al. [23]. Also, Colombo et al. [5] extended the approach of Petri Net based modeling [10] for the modeling of agent based manufacturing systems. Bussmann et al. [4] propose the methodology DACS (Methodology for the Design of Agent Based Manufacturing Control Systems), which, among other things, includes a specification of the manufacturing components to be controlled and their physical behavior. Leitão and Restivo in [20], attempt to formalize the structure and behavior of an IMS, combining UML notation for the static aspects of the system, and Petri Nets to model behavioral aspects. Another proposal is [11].

Here an agent organization is proposed for modeling each holon/holarchy. In [21] Martinez-Lastra and Colombo propose an engineering framework for simulation and visualization of agent societies in an IMS. In ANEMONA [13], the manufacturing system is specified by a top-down recursive analysis phase, followed by a bottom-up design stage to produce the system architecture. The Agent Development Environment (ADE) [29] is an integrated tool in which the user designs the templates of holonic agents from which automatic code is generated to implement the system.

Over the last few years the focus of the different proposed approaches where mainly targeted to service oriented manufacturing systems, reconfiguration, self-adaptation, sustainability, among others. In [24] the authors use agent-based service-oriented approaches for the business level of virtual enterprise cooperation. Shin et al. [25] propose a conceptual framework for self-evolutionary manufacturing system. Borangiu et al. [2] propose an engineering approach for intelligent manufacturing systems in which the system is characterized by a flow of active entities which run on a guided network. In [18] Leit*ã*o presents a Service Oriented MAS approach in order to engineer Service Oriented Manufacturing Systems. Autonomous Cooperative System (ACS) [28] is a platform of Rockwell Automation Logix controllers that enable the control system developers to run the holonic agents directly on PLCs. The method proposed in [6,7] aims to expand the scope of analysis beyond functional boundaries to apply sustainability at factory level. ROMAS [12] is a methodology that addresses the open problem of engineering normative open systems using the multi-agent paradigm. ANEMONA-S + Thomas [14] is a service oriented framework for the development of Service Oriented Intelligent Manufacturing Systems. Self-adaptation is a very important feature when engineering Intelligent Manufacturing Systems. In [17] the authors make an interesting review of the key aspects to take into account for self-adapting systems and also a large review of the state of the art in terms of models, methods and tools.

5 Comparative Overview

In this section we provide an analysis of the different approaches presented in previous section with respect to the requirements for engineering IMS described in Section 3. Table 1 shows the studied methodologies, indicating, for each one, how it copes with the different IMS modeling requirements.

The proposals of Ritter et al. [23], Colombo et al. [5], Leit*ã*o and Restivo [20] and Fischer et al. [11] only take into account a small phase of the development process of manufacturing systems. They are focused on the control of production processes and the identification of agents that will control the process. DACS [4] is focused on the controlling elements of the manufacturing system. The output of this method is an agent-based design, but it does not offer development guidelines or a tool for the implementation of the system. On the other hand, ANEMONA [3] is a complete and specific methodology for IMS that provides the designer clear and manufacturing-specific modeling guidelines.

Table 1. Development Methods and Modeling Requirements for IMS. Note: √ means complete coverage, ∼ means partial coverage, and S refers to services identification for *R7*

Method	Requirements									
	R1	***R2***	***R3***	***R4***	***R5***	***R6***	***R7***	***R8***	***R9***	***R10***
Van Brussel et al. Method	√	√			√	√	√	√	√	√
Ritter et al. Method	√				√	√	∼			
Colombo et al. Method	√				√	√	∼			
DACS	√				√	√	∼			
Leitão and Restivo Method	√				√	√	√			
Fischer et al. Method	√				√	√	√			√
Martinez-Lastra and Colombo Method	√	√			√	√	√	√		√
ANEMONA	√	√			√	√	√	√	√	√
ADE	√	√			√	√	√	√		√
Shen et al. Framework	√	√			√	√	√S	√		√
Shin et al. Framework	√	√			√	√	√	√		√
Borangiu et al. Approach	√	√			√	√	√S	√		√
Leitão's SoMAS Approach	√	√	√		√	√	√S	√		√
ACS	√	√			√	√	√	√		√
Despeisse et al. Method		√		√	√	√				√
ROMAS	√	∼			√	√	∼ S	∼		
ANEMONA-S + Thomas Framework	√	√	√		√	√	√S	√	√	√

The second group of analyzed approaches show a more complete coverage of the requirements. Nevertheless, there are some requirements (*R3*, *R4* and *R9*) that need urgent attention since they are not considered by most of the approaches. From Table 1 we can conclude the following.

- Requirement *R3* refers to the need in industrial environments to enforce the usage of standardization for implementation, communication protocols and control. This requirement is only taken into account by two approaches, the SoMAS proposal of Leitão and ANEMONA-S + Thomas. Both approaches define components and process guidelines to connect with layers of the ISA'95 standard [1].
- Requirement *R4* is the sustainability requirement for manufacturing systems. Only one approach deals with this requirement. Nevertheless, in the specialized literature there is a large list of different proposals for specific isolated components/layers of a manufacturing system [26]. There is an urgent need to include sustainability aspects in the engineering methods of the whole manufacturing system in order to assure a correct and complete coverage of it through out the complete components and layers.
- Requirement *R9* refers to mixed development methods (bottom-up and top-down). Almost all of the methods analyzed follow one approach or another without combining them, except for Van Brussel et al. method, ANEMONA, ANEMONA-S +Thomas which have mixed top-down and bottom-up development process.

6 Conclusions

The modeling of Intelligent Manufacturing Systems constitutes the fundamental interest of this paper. Intelligent Manufacturing Systems are large and complex systems that require appropriate methods and tools to design and operate. In the specialized literature we can find many proposal for engineering manufacturing systems. Nevertheless, some of them do not cope appropriately with the specific and complex requirements of this kind of systems. These facts motivated us to study the main development methods of the specialized research field, and to compare them in order to obtain a qualitative measure of the adequacy of each one for today's Intelligent Manufacturing System development. To carry out this comparison we have defined ten modeling requirements for the factories of the future. These requirements have been divided into two groups: functional requirements and software engineering requirements. The first ones refer to the type of programs that should be developed applying a methodology, while the second refers to the properties of the software engineering method. All of these requirements are specific for Intelligent Manufacturing Systems. We have carried out the comparison based on the ten modeling requirements and the different methods. The result is Table 1. From this analysis we can conclude that there are three requirements that are not well treated by most of the methods in the research field and are identified as open problems: (i) Standardization, (ii) Sustainability and (iii) Mixed top-down and bottom-up development process. From our review it was also faced that the maturity and the available quantity of theoretical and applied (specialized) models in IMS enable now researchers to address in depth methodological and software engineering aspects. A step beyond these existing developments would be to propose to the whole community a set of IMS-oriented software development kits and software tools as a basis for holonic and multi-agent control of manufacturing systems, including a robust performance evaluator based on the generic and dynamic emulation of various manufacturing systems to be tested. This would also speed-up the development of proof-of-concepts and help industrialists and researchers to design, test and evaluate different IMS-friendly strategies and control architectures. Indeed, evaluating a single control architecture on a single manufacturing system will never convince industrialists. Researchers must then now address methodological aspects and software engineering of IMS-oriented control systems.

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