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Discipline Research Contributions to the Modelling and Design Of Intelligent Manufacturing Systems

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Abstract: This joint paper is the result of the work of cluster 3-4 within the Esprit WG No. 21955 on Intelligent Manufacturing Systems (IMS) working group. The paper conveys the results of a co-operative research effort between LAR Patras (Greece), DTU (Denmark), CRAN/GSIP (France) and Aachen WZL (Germany). It aims at highlighting the contribution of each of the partners to some common issues related to the modelling and control of an autonomous and co-operative system under dynamically changing conditions. Yet, it does not provide a global solution since this would require further investigations and research, but it stimulated us to continue working towards the integration of our individual approaches within the IMS perspective.

Keywords: Modelling, Control, Intelligent Manufacturing Systems

Chrysostomos Stylios, Ph.D, received his Ph.D. degree from the University of Patras, Greece in 1999, and the diploma in Electrical Engineering from the Aristotle University of Thessaloniki, Greece in 1992. He is currently a post-doctoral researcher at the Department of Electrical and Computer Engineering at the University of Patras, Greece. His interests include intelligent control, supervisory control, fuzzy logic, neural networks, Fuzzy Cognitive Maps and generally soft computing techniques. His research interests are Hierarchical Systems, Decision Support Systems and Intelligent Manufacturing Systems. He is a member of IEEE and of the National Technical Chamber of Greece.

Gilad Langer, Ph.D, has a MSc. in Industrial and Manufacturing Engineering and a Ph.D degree from the Technical University of Denmark (DTU). He is now Assistant Professor at the Department of Manufacturing Engineering. His research is centred on advanced concepts for highly agile manufacturing systems, specifically shop floor control, based on the Holonic Manufacturing Systems paradigm. His research interests are Manufacturing control, Manufacturing integration, Shop Floor Control (SFC), IT integration in manufacturing and Simulation of manufacturing systems.

Dr. Benoit Iung was born at Nancy, France, in 1962, obtained the master degree in Manufacturing and Process Control in 1986 and an engineering degree in Automation Engineering in 1987 from the University of Nancy I, France. In 1992, he got his Ph. D degree in Manufacturing Engineering also from the same University.

He is currently Assistant Professor at the University Henri Poincaré-Nancy I where he is involved in engineer school E.S.I.A.L. by ensuring the responsibility of the Manufacturing Engineering channel. He belongs also to the Automatic Research Centre of Nancy (CRAN) in the Production Integrated System Engineering team managed by Professor G. Morel. His research and teaching activity focused on the dependability and the maintenance of the Production System and, more precisely, of the Integrated – Distributed System based on Interoperable and Intelligent field components. In this way, he participated in different national projects (CIAME, CNRS-S3, GRP) and managed tasks in several European projects as ESPRIT DIAS, PRIAM, EIAMUG. He ensured also scientific co-responsibility for the CRAN participation in European and International Projects as ESPRIT REMAFEX, INCO-DC EIAM-IPE (with China), ESPRIT IMS-WG long -term research in the maintenance and intelligent system fields.

One objective of his current research is to apply the Multi Agent System modelling technique for the development of proactive maintenance intelligent system.

Mr. Yong Tak Hyun is researcher at the Department of Control Technology and Automation of WZL, RWTH Aachen. He received BSc. and MSc. degrees in Mechanical Design and Production Engineering from the Seoul National University, Korea. His research interests include object-oriented data modeling and data interface for NC machine tools and manufacturing systems.

Christian Sørensen, Ph.D. candidate, has a MSc. in Manufacturing Engineering from the Technical University of Denmark (DTU). He is currently working on his Ph.D thesis at the Department of Manufacturing Engineering at DTU. His research is centred on advanced concepts for integration of highly agile manufacturing systems (shop floor control systems) based on the Holonic Manufacturing Systems paradigm with enterprise planning and control systems. His research interest are Manufacturing control, Manufacturing integration, Shop Floor Control (SFC).

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Professor Peter P. Groumpos received his Ph.D in 1978 in Electrical Engineering from the State University of New York at Buffalo. He is Professor at the Department of Electrical and Computer Engineering, the University of Patras. He is also the chairman of the Division of Systems and Control and director of the Laboratory for Automation and Robotics. He was formerly on the faculty at Cleveland State University, USA, 1979-1989. He was the director of the Communication Research Lab., 1981-1986, and a member of the Technical Committee of the Advanced Manufacturing Center, 1985-1987. He participated in a Technology Transfer Program with the Ministry of Higher Education of Egypt from 1981 to 1984. He was an Associate Editor for Book Reviews for the *IEEE Control Systems Magazine*, 1980-1985. For the academic year 1987-1988 he was a Fulbright visiting scholar at the University of Patras. He was the Greek National Representative to the High-Level Group for EUREKA and for ESPRIT, 1991-1994, consultant to a number of companies in the USA and Greece.

Professor Groumpos is the Greek NMO representative to IFAC and he is the vice-president of the IFAC TC «Large Scale Systems».

He is Associate Editor for the international journals *Computers and Electrical Engineering* and *Studies in Informatics and Control*. Professor Groumpos is a member of the Honorary Societies Eta Kappa Nu and Tau Beta Pi. He is the Coordinator of the ESPRIT Network of Excellence in Intelligent Control and Integrated Manufacturing Systems (ICIMS-NOE). He has published over 70 journals and conference papers, book chapters and technical reports. His main research interests are intelligent manufacturing systems and CIM, process control, simulation methods, hierarchical large-scale systems control and adaptive control.

1. Introduction

The requirements for new generation manufacturing systems, which will be characterised by high autonomy and intelligence, have led to the investigation and invention of new techniques that will integrate and combine known advanced methodologies and will be the core of these sophisticated systems. Powerful computers, advances in communication and other technological and scientific areas would be integrated and utilised in the area of Intelligent Manufacturing Systems. It has become quite clear that the requirements in the modelling and control of systems cannot be met only with the existing conventional theories. It is necessary to investigate and use new methods that will exploit human experience, will have learning capabilities, will be supplied with failure-detection and identification characteristics and it will include imprecision and uncertainty. An Intelligent Manufacturing System should utilise effectively all the company resources, especially the insights and experience of front-line operators and experts, in order to achieve continuous improvements in productivity. One of the major objectives of the Intelligent Manufacturing System initiative [1] is to contribute to the development of new production systems that can fulfil technical, economic and environmental requirements for optimality and sustainability while maintaining their competitiveness. This necessitates enhancement of the flexibility, reusability, availability, dependability of the production system [2]. This leads to a system organisation that has to be a compromise between the current hierarchical enterprise architectures, which are inherently integrated, and the new distributed architectures, which are more flexible, reactive and agile [3].

2. Frame of Reference

Indeed an integrated organisation requires that information is made available for use by all the operational activities and throughout the entire business environment. In that way, "intelligence" embedded in the field components (e.g. devices such as actuators, sensors, PLC's, etc.) [4] and digital communication (e.g. field-bus) provide a solution to an informational representation of the production process as efficiently as possible. The resulting shop floor architecture is therefore constituted by a network of field components integrating a "technical form of intelligence" (local capacities) that offer a greater reactivity while interoperating among them to ensure the integration (co-ordination) of operational activities. These architectures advocated by the IMS initiative are characterised mainly by properties of flexibility and adaptability that are required to quickly face up with internal and external disturbances while preserving the global goals of the application.

Thus in order to portray and investigate the different researches described in this paper a frame of reference has to be established. This reference can then be used as a basis for comparison of the different researches, to reveal possible fields of collaboration for further research.

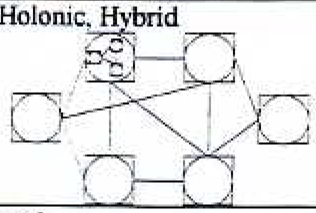
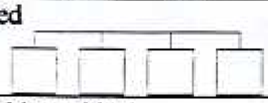
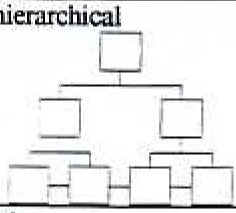
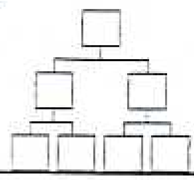
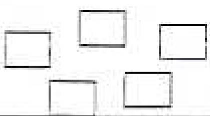
From a production point of view, a compromise has to be reached between:

- **Integration paradigm** that focuses on integrating the Operational domains (Control, Maintenance and technical Management: **CMM** concept [5]) at the shop floor level in accordance with the Business domains at the Enterprise level. Thus it comprises a coherent architecture in order to gain real business advantages, and requires the use of a well-known **CIME Enterprise hierarchical modelling framework** [6] as promoted by the EP 21859 "EI-IC" and the world-wide "Enterprise Integration" initiative [7]. The resulting "hierarchical" systems are optimised for performances and as a consistent whole but with considering the problems that unforeseen disturbances may cause.
- **Distribution paradigm** that focuses on embedding "intelligence" at the shop floor level producing an adaptable architecture that achieves hardware and software interoperability and adaptability. It requires the use of a prospective IMS (Intelligent Manufacturing System) **Enterprise distributed modelling framework** as proposed by the world-wide IMS initiative. The resulting "intelligent" systems (distributed, heterarchical) that enhance interoperability, adaptability, ability to react to disturbances, still have problems related with optimising global functionality.

This compromise asks for the definition of the expected characteristics of such type of production systems. This implies not only the need to characterise the architecture resulting from the engineering process, i.e. the model of the system (hierarchical, heterarchical), but also the engineering process itself. The engineering process can be formalised by use of meta-models, reference models, emergence mechanisms, etc. Finally a modelling framework (Cartesian, systemic, etc.) has to be used in order to provide a framework thereby the architecture can be implemented, based on the engineering process [8].

Kosanke and Nell [7] introduced **an Enterprise Integration Capability Model** in order to characterise architectures using five levels (interpreted as hierarchical, integrated, distributed, and intelligent by Iung et al [8]). Weston in [9] also proposed some

Table 1. Frame of Reference adapted from B.W. Hollocks et al [7] and by Iung et al[8]

Architectures	Modelling Frameworks	Structures
Adaptable	Intelligent *Kinetic:* *HMS, RCS4*	Agile: Holonic, Hybrid 
Interoperable	Distributed *Object oriented:* *UML, Ontology, DAI*	Distributed 
Visible	Integrated *Systemic:* *CIMOSA, GERAM, SAGACE*	Modified hierarchical 
Rigid	Hierarchical *Cartesian:* *SADT, IDEF, RCS3*	Hierarchical 
Fragmented Islands	Fragmented *None*	None 

classifications of the systems and system engineering process.

The relationship between architecture and modelling framework is illustrated in Table 1. It is based on the Enterprise Integration Capability Model proposed by Kosanke and Nell [7], and on a classification of modelling frameworks proposed by Iung et al [8]. The Table illustrates five levels, which are named Fragmented, Rigid, Visible, Interoperable and Adaptable, respectively. At the first level (Fragmented Islands) no integration exists and thus no modelling framework can be used. The Rigid level is characterised by purely hierarchical structures and the modelling framework is based on the Cartesian approach. This modelling framework results in structures that ensure optimal overall performances but are too rigid and respond only poorly to changes and disturbances. In order to loosen the hierarchy the Visible level allows communication between sub-units. However this structure is still too rigid and slow in responding to disturbances. The modelling framework approach is Systemic in such frameworks as GERAM.

the hierarchy and thus, to the IMS paradigm in general.

The evolution of modelling frameworks has not been consistent with the evolution of production system architectures. For instance, the Distributed Artificial Intelligence paradigm currently does not seem to be operational enough for modelling Intelligent Systems. It is however adequate for modelling and control of autonomous and co-operative system, since it considers the system as an interaction between autonomous and independent entities (**agents** or **holons**), which work together according to operating modes [10]. So, all these architectures can be implemented through modelling framework, but on the basis of an engineering process.

The engineering process can be characterised by the **Capability Maturity Model** (Table 2) used in software engineering [11]. This model of graded maturity (not a continuous maturity model), similar to the Software Capability Maturity Model proposed by the Software Engineering Institute of Carnegie Mellon University , suggests five levels of classification: Initial, Repeatable, Defined,

Table 2. Capability Maturity Model [11]

Quantitative	***Optimising***	*Continuous process improvement is enabled by quantitative feedback from the process.*
	Managed	*Both the software process and the software itself are observable.*
Qualitative	***Defined***	*It is documented, standardised, and integrated into a standard software process for the organisation.*
	Repeatable	*The software process is explicit and can be re-used from an application to another.*
	Initial	*Software is characterised as ad hoc, occasionally even chaotic.*

The Interoperable level represents a distributed structure, where all decision-making is carried out locally at each unit. This results in a flat structure, where the units co-operate. The modelling frameworks used are object-orientation and distributed artificial intelligence (DAI) methods. These systems are easy -to-re-configure and therefore they respond well to changes and disturbances. However . the decentralisation hinders the overview of the performance of the systems whereby sub-optimisation is likely to result. The Adaptable level corresponds to the ultimate "relaxation" of

Managed and Optimising. Moreover the model divides these categories into qualitative and quantitative ones, in order to clarify the "invariants" of the modelling process, such as the genericity, reusability and validity of the architecture. This reference model can be used to classify the architecture obtained as a result of the engineering process, specifically in terms of the research described in this paper.

The main goal of this paper is to use the frame of reference shown above to describe how any of the partners' research contributes to the modelling and control of autonomous and co-operative system. By clarifying issues related to the manner of implementation of the architecture at the adaptable level (Table 1) through the use of new modelling framework, these issues will additionally show the general shift from the Visible level (CIM) to the Adaptable level (IMS). It is important to note that this shift has to be realised at and between two levels, namely the shop floor level and the business level. This corresponds to realising the integration between the symbolic world and the physical one. Co-operation at the physical level is more difficult to achieve than it is at the symbolic one due to the difference between the hard constraints (time, physical location, variations, unexpected behaviour, etc.). The new intelligent systems will thus have to emerge from these special integration requirements.

3. Summarising Research Contributions

All four partners have different approaches regarding the modelling and design of Intelligent Manufacturing Systems; yet with the same aim namely an agile production system. The different approaches are presented in Figure 1, where the investigation of the borders between these fields is one of the goals of this paper.

The Laboratory for Automation and Robotics (LAR) proposes a hierarchical approach to describing the upper production level and the lower enterprise level. This modelling approach can be classified according to Figure 1, and it belongs to the hierarchical and integrated approaches class. This approach examines the shop floor system from a behavioural point of view and it utilises an abstract methodology in modelling this behaviour. This methodology is named Fuzzy Cognitive Map (FCM) and it belongs to the soft computing approaches, modelling the shop floor level from a behavioural point of view. Moreover a hierarchical structure is proposed, that establishes a shop floor level with supervisory control, which is linked with the business level in Figure 1 (see Section 4).

DTU has attempted to develop an architecture and methodology for the design of agile shop floor control systems and has focused their research on the holonic approach. By founding the control system on autonomous and co-operative entities (holons), a highly adaptable manufacturing system can be realised. The main interest at DTU is in developing a system architecture defining the functionality of the basic entities, structures of the entities and their co-operation mechanisms. This research aims at building a Holonic Multi-cell Control System (HoMuCS) architecture that can be used for the design and development of a multi-cell control system at the shop floor level (see Section 5).

The CRAN-GSIP work is more dedicated to an engineering process based on reference models and dealing with the architecture of shop floor

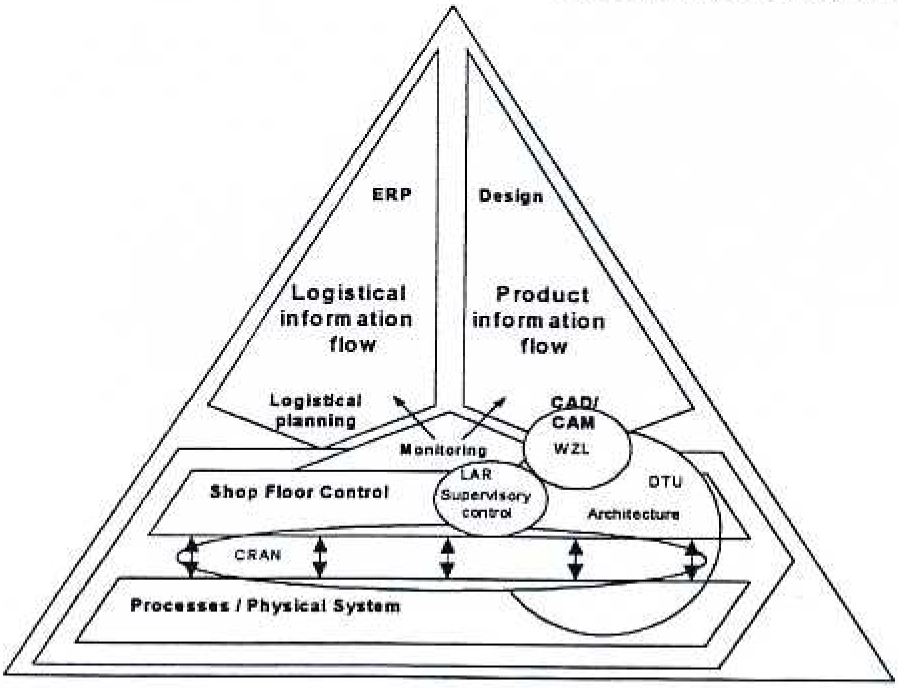


Figure 1. Enterprise Pyramid With Partners Research Fields

production systems. It means to provide solutions to the system structure change and adaptation as a dynamic organisation. The development of an operational system is based on the application of the reference models and leads to building a physical shop floor architecture, which is composed of co-ordinated and co-operating interoperable and reusable hardware/software field components (see Section 6). The co-ordination and the co-operation are required to form a functionally integrated and physically distributed shop floor architecture which is a first step towards a full intelligent manufacturing system using an engineering process based increasingly on emerging trends that would provide more adaptability (see end of Section 6).

In the development of new intelligent systems, the kinds of communication and information exchange between shop floor devices of the physical systems or agents that model the system have a great importance. In this framework Aachen WZL proposes a data and communication model, which can be used as a gateway between the shop floor and the business levels. The existence of a reliable means for exchanging information is a fundamental issue in all the research work described in this paper (see Section 7).

4. A Model Based on Fuzzy Cognitive Map (FCM)

4.1 Behavioural Model of Shop Floor Level

Hierarchical architectures are widely used and accepted in enterprise modelling. LAR is considering a general hierarchical architecture to model the shop floor level of the enterprise. Our research focuses on an abstract model that connects the shop floor level with the upper level at the enterprise pyramid (Figure 1) and thus it creates a more integrated modelling approach. In order to develop advanced modelling methodologies based on soft computing approaches, ideas and existing approaches from information theory, neural networks and fuzzy logic are investigated and utilised to represent and process information in a hybrid and hierarchical industrial system [12]. This hierarchical approach pays more attention, from a behavioural point of view, to the shop floor level and a new modelling methodology is resorted to in order to model the behaviour of the human operator at his level and of the system itself.

The proposed methodology is that of Fuzzy Cognitive Maps (FCMs), which can model dynamical complex systems that change in time following non-linear laws. Fuzzy Cognitive Maps use a symbolic representation for the description and modelling of the system [13]. A Fuzzy Cognitive Map consists of concepts that illustrate different aspects in the behaviour of the system and these concepts interact with each other showing the dynamics of the system. An FCM integrates the accumulated experience and knowledge on the operation of the system, as a result of the method by which it is constructed, i.e. using human experts that know the operation of the system and its behaviour. Experts represent the human accumulated knowledge on the operation and behaviour of the system, using concepts to stand for the main characteristics and factors of the system and they also express the causal relationship among factors connecting concepts with weighted interconnections [14].

At the shop floor level of the plant there is a common technical information system for the process control, the computerised and technical management systems that is shared between the production and the management teams [5]. This information could be unified and used to construct a Fuzzy Cognitive Map, which will represent a conceptual, organisational and operational model of the system [15]. The knowledge on manufacturing plants includes the layout of the plant, the expected behaviour of some parts of the plant, an aggregation of attributes or quality variables that are important. This information is captured using a Fuzzy Cognitive Map structure that exploits human operator's experience and knowledge. An expert relates a process or a succession of processes to a concept, or a concept can stand for a specific production procedure or a process can represent the operation or malfunction of a machine or the desired output, etc. All these concepts are closely connected to each other with a degree of cause and effect that is expressed by the weighted interconnections.

The development and design of the appropriate and efficient Fuzzy Cognitive Map model for the description of a system requires the contribution of human knowledge and experience on the operation of the system. Experts and operators of the system, who know the behaviour of the system, have created a mental model of the system and, according to this, they monitor, supervise, control and make decisions and take actions on the operation of the system. This model can easily be constructed as a Fuzzy Cognitive Map that is a conceptual model. Experts are asked to