Implementation and Validation of a Holonic Manufacturing Control System

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ABSTRACT

Flexible manufacturing systems are complex, stochastic environments requiring the development of innovative, intelligent control architectures that support agility and re-configurability. ADACOR holonic control system addresses this challenge by introducing an adaptive production control approach supported by the presence of supervisor entities and the self-organization capabilities associated to each ADACOR holon. The validation of the concepts proposed by ADACOR control system requires their implementation and experimental testing, to analyze their correctness, applicability and merits. This paper describes the implementation of ADACOR concepts in a flexible manufacturing system, verifies their correctness and applicability, and evaluates the ADACOR control system performance, considering not only quantitative indicators directly related to production parameters, e.g. manufacturing lead time, but also qualitative indicators, such as the agility.

1. INTRODUCTION

Flexible manufacturing systems are complex, stochastic environments requiring the development of flexible, agile and intelligent control architectures that support small batches, product diversity and high quality at low costs, as imposed by global markets. The holonic and the agent-based manufacturing paradigms allow a new approach to the manufacturing control problem, based in concepts like modularity, decentralization, autonomy and re-use of control software components. Holonic Manufacturing Systems [1] translates to the manufacturing world the concepts developed by Arthur Koestler for living organisms and social organizations [2]. Holonic manufacturing is characterized by holarchies of holons (i.e., autonomous and cooperative entities), which represent the entire range of manufacturing entities. A holon, as Koestler devised the term, is a part of a (manufacturing) system that has a unique identifier, may be made up of sub-ordinate parts and, in turn, can be part of a larger whole.

Several architectures and developments in agent-based and holonic manufacturing were reported in literature, such as those reported in [3-6]. One of these holonic control architectures is ADACOR (ADAptive holonic COntrol aRchitecture for Distributed Manufacturing Systems) [7], which aims to improve the performance of control systems in industrial stochastic scenarios, characterized by the frequent occurrence of unexpected disturbances. The validation of the concepts proposed by ADACOR control system requires their implementation and experimental testing in a real situation, to analyze their correctness, applicability and merits. This paper describes the implementation of ADACOR concepts in a flexible manufacturing system, and verifies their applicability and the conformance of system operation to specifications, both in normal operation or in presence of disturbances. The experimental results extracted from the implementation and testing allows to evaluate the ADACOR control system performance, considering not only quantitative indicators directly related to production parameters (e.g. manufacturing lead time), but also qualitative indicators, such as agility.

The paper is organized as follows: first, Section 2 presents an overview of the main concepts associated to the ADACOR control architecture. Section 3 describes the experimental case study used to test the ADACOR concepts, defining the production system and the manufacturing scenarios. In Section 4 the implementation of the ADACOR concepts using the JADE framework is described and in Section 5 the experimental results are analyzed. Finally, Section 6 rounds up the paper with conclusions.

2. ADACOR HOLONIC CONTROL SYSTEM

The ADACOR holonic control system is build upon a set of autonomous, cooperative and self-organizing holons, each one representing a manufacturing component that can be either a physical resource (operators, robots, pallets, etc.) or a logic entity (plans, orders, etc.) [7]. ADACOR architecture defines four holon classes: product, task, operational and supervisor. Each available product to be produced in the factory plant is represented by a product holon and each production order launched to the shop floor to execute a product is represented by a task holon. Operational holons represent the physical resources available in the shop floor. The supervisor holon is an innovative characteristic of ADACOR and introduces coordination and global optimization in decentralized control.

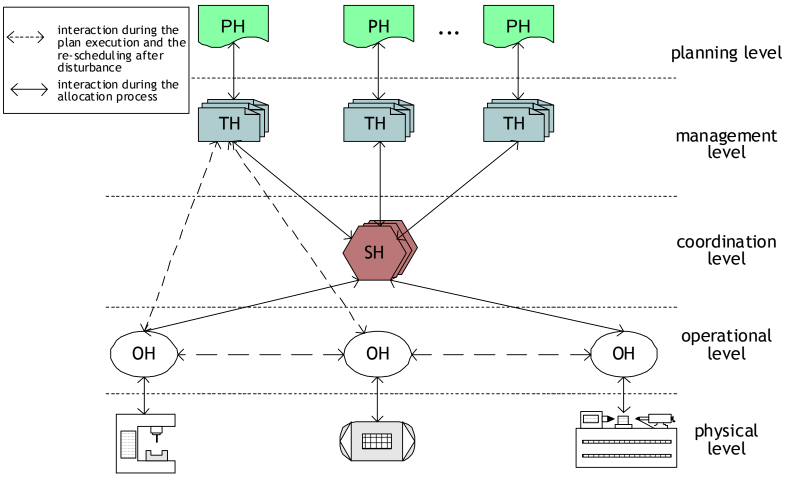

Figure 19: ADACOR Components

The ADACOR holonic control system is formally specified (modeled and validated) using a formal methodology to specify distributed production control systems, based in High-level Petri nets, which ensures a rigorous specification and validation [8]. The formal validation of the behavioural models, elaborated for the ADACOR holon classes and based on the mathematical theory of the Petri nets, allows to verify the correctness of the models and its conformance to the system specifications. Properties of the nets like liveness (necessary condition), boundedness and reversibility can be formally proven and used to validate the structural properties of the modeled system. Moreover, the quantitative analysis of the net offers a very broad spectrum of results that can be easily mapped to a set of performance indexes of ADACOR [7].

ADACOR introduces an innovative adaptive production control approach to address the need for agility and re-configurability of control systems at the shop floor level. This production control approach is neither completely decentralized nor hierarchical, but balances between a more centralized and a more flat approach, passing through other intermediate forms of control. The presence of supervisor holons in decentralized systems, and the presence of self-organization capabilities associated to ADACOR holons allow the evolution or the re-configurability of the control system, combining the global production optimization with the agile reaction to unpredictable disturbances.

The adaptive production control evolves in time between two alternative states, stationary and transient states. In stationary state the holons are organized in a hierarchical structure, with supervisor holons coordinating several operational and/or supervisor holons. The role of each supervisor holon is to introduce global optimization in the production process. The transient state, triggered with the occurrence of disturbances, is characterized by the re-organization of the holons in a heterarchical-like control architecture, allowing the agile reaction to disturbances. After the disturbance recovery, the system evolves to a new hierarchical control structure, possibly the original one.

3. EXPERIMENTAL CASE STUDY

A pilot installation has been used to validate the ADACOR holonic control system, aiming to address two main objectives: i) validate the concepts and the conformance of the implementation to the specifications, both in normal operation and in presence of disturbances, and ii) evaluate the performance and conclude about the merits of the proposed concepts. The experimental case study used in this work will be described in the next sections.

3.1. PRODUCTION SYSTEM

The pilot installation was a semi-virtual laboratorial platform based on the flexible manufacturing system of CIM Centre of Porto [8], 'extended' with two virtual manufacturing cells, to provide the required hardware/software redundancy and flexibility to allow alternative solutions at the production planning level, as illustrated in Figure 20.

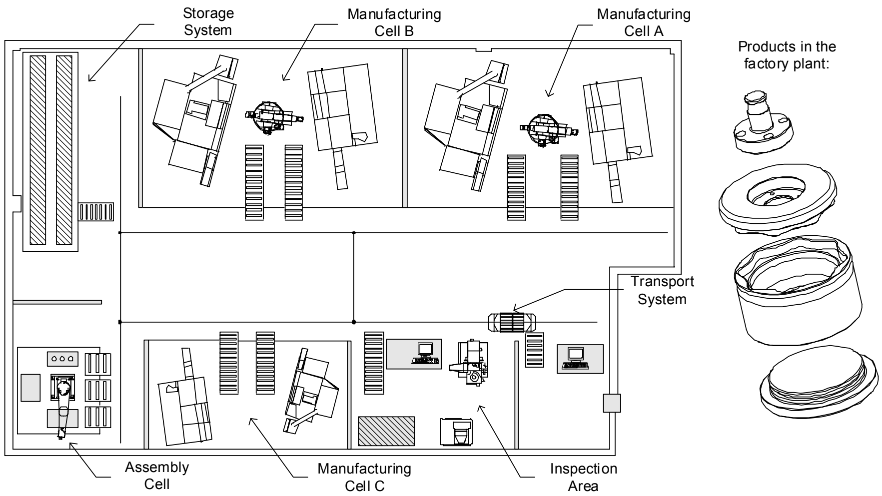

Figure 20: Plant layout of the case study production system

The flexible manufacturing system platform, consisting of three turning machines, two milling machines, one drilling machine, one tool calibration machine, two anthropomorphic handling robots, one SCARA assembly robot, one AS/RS (Automated Storage/Retrieval System) system and one AGV (Auto-Guided Vehicle), is organized as a set of four physical cells: material storage and transportation cell, inspection cell, assembly cell and flexible manufacturing cell. Each machine has a set of tools (such as cutting or inspection tools) that guarantees the capabilities to execute different types of operations. The execution of setups is not considered in this case study, being assumed that the tools are permanently stored in each machine.

The production system contains other types of resources, namely containers and buffers. The AGV transports containers with the material to be processed in the machines or the cells and the pieces produced. Each machine has its input/output buffer, de-coupling its operation from the transport system activity.

In this pilot plant, four different (sub-)products, named Base, Body, Cover and Handle, are produced, as illustrated also in Figure 20. These can create two different final products: Ashtray and Box. The Ashtray product comprises the assembly of the Base and the Body sub-products, and the Box product comprises the assembly of all designed sub-products.

3.2. MANUFACTURING SCENARIOS

The experiment considers two different plant scenarios: i) the first plant scenario considers that no unexpected disturbance occurs, and ii) the second plant scenario considers the occurrence of machine failures, in the turning machine (cell B), with a probability of 25%. In case of failure, the part is destroyed and the machine downtime for the recovery procedures is fixed at 60 seconds.

In this case study, it is considered that no setups are executed, since machines are equipped with the required tools to execute a range of operations. The transport operations are performed by a single AGV and orders are queued by order of arrival. The execution of each transport operation takes the same time, 5 seconds.

Each individual book of orders comprises 6 production orders (involving 17 operations): 2 bodies, 2 bases, 1 handle and 1 cover. The experimental test reported in this paper considers four different levels of plant load, i.e. four different operational scenarios: 6 production orders, 12 production orders, 18 production orders and 24 production orders, i.e. respectively, one, two, three and four books of orders. For example, the scenario comprising 4 individual books of orders, is constituted by 24 production orders, distributed by 8 bodies, 8 bases, 4 handles and 4 covers, amounting to 68 operations. Each operational scenario considers that all the production orders belonging to the same book of orders arrive to the production system at the same time, but different books of orders arrive sequentially to the production system.

4. IMPLEMENTATION OF ADACOR CONTROL SYSTEM

The ADACOR control system prototype was implemented using multi-agent systems, taking advantage of its modularity, decentralization and components re-use. The development of multi-agent systems applications requires the implementation of features usually not supported by programming languages, such as message transport, encoding and parsing, yellow and white pages services, ontology for common understanding and agent life-cycle management services, which increases the programming effort. A set of commercial and academic agent development platforms implementing those features are available, simplifying the development of agent-based applications [12]. The agent development platform chosen to implement the ADACOR prototype was JADE (Java Agent Development Framework) mainly because it provides a set of system services and agents in compliance with the FIPA (Foundation for Intelligent Physical Agents) specifications [9]: naming, yellow pages, message transport and parsing services, and a library of FIPA interaction protocols.

4.1. IMPLEMENTATION OF INDIVIDUAL HOLONS

Each ADACOR holon is a Java class that extends the `Agent` class provided by the JADE framework, inheriting basic functionalities, such as registration services, remote management and sending/receiving ACL messages [10]. These basic functionalities were extended with features that represent the specific behaviour of each ADACOR holon class. The behaviour of each ADACOR holon uses multi-threaded programming, allowing to execute several actions in parallel.

The communication between distributed holons is done over the Ethernet network, using TCP/IP protocol and is asynchronous. The messages exchanged between ADACOR holons are encoded using the FIPA-ACL communication language, the content of the messages being formatted according to the FIPA-SL0 language. The meaning of the message content is standardized according to the ontology defined by the ADACOR architecture [8], translated to Java classes according to the JADE guidelines.

The decision component of each ADACOR holon uses declarative and procedural approaches to represent knowledge and to regulate the holons behaviour [10]. The central element in the decision component is a rule-based system, which applies declarative knowledge, expressed in a set of rules. The rule-based system uses the JESS (Java Expert System Shell) tool, which is a rule oriented programming infrastructure based in the CLIPS (C Language Integrated Production System) language and uses the Rete algorithm as inference engine [11]. ADACOR holons uses also procedural knowledge to represent the holon's knowledge and behaviour. This type of knowledge is embodied in procedures that are triggered as actions by some rules, each one being responsible for the execution of a particular set of actions. The scheduling algorithm is an example of this type of knowledge representation.

The implementation of operational holons that represent physical automation resources requires the development of wrapper interfaces, supporting the integration of those resources. ADACOR introduces the virtual resource concept to make the intra-holon interaction transparent [10]. The development of a virtual resource for each manufacturing device encompasses the implementation of the services at the server side (the real automation resource) which will be invoked on the client side (the operational holon). The client ignores the details of this implementation and each virtual resource can be re-used by other similar resources or holonic control applications.

4.2. ADACOR CONTROLSYSTEM PLATFORM

The developed ADACOR-based control system for the described flexible manufacturing system is illustrated in Figure 21. It shows that the several holons presented in the system are distributed by several different personal computers, running different operating systems, in this case Windows XP®, Windows 2000® and Linux, demonstrating that ADACOR supports the heterogeneity present in industrial automation environments. It also illustrates the graphical user interface of an operational and a supervisor holons during their operation.

The characteristics of each manufacturing holon are configured using a XML (eXtensible Markup Language)-based configuration file. These characteristics are the product data model and the process plan for the product holon, the resource model for the operational holon and the organizational structure of the factory plant, and they are loaded and interpreted by the holon behaviour during its start-up.

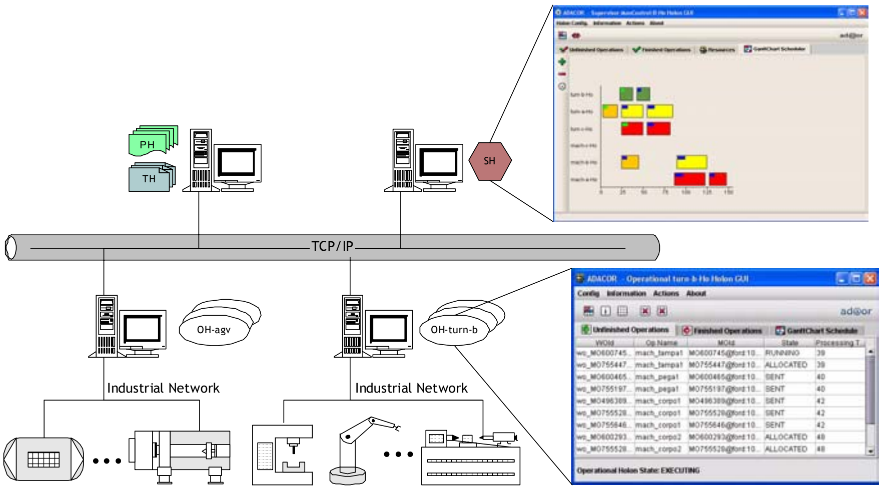

Figure 21: Platform of the prototype ADACOR control system

The graphical user interface for the operational holons allows to visualize the local schedule using a Gantt chart to show the work orders executed by the resource, to configure some operational holon parameters, and to display statistical information related to the resource performance, such as the degree of utilization and the number of delayed work orders. The graphical user interface for the supervisor holon allows to visualize the global schedule, i.e. the work orders allocated to each lower-level resource, to display the resources under its coordination domain and their characteristics, and to configure some holon parameters.

5. EXPERIMENTAL RESULTS

The first result is that the ADACOR control system works as specified, either in normal operation or in presence of disturbances. The test also showed the prototype re-configurability, i.e. the system response to the introduction, removal or modification of manufacturing component. The use of the plug and produce concept, allows each ADACOR holon to work autonomously, not requiring the need for additional re-design, re-program and re-start of other components. This feature helps the re-configurability of the manufacturing control system, essential to support different production systems or different books of products.

The experimental tests also allowed to evaluate the performance of the ADACOR control system. The experimental results will be presented and discussed in the next sections. It must be emphasized that all the three control approaches uses the same prototype platform: i) in the hierarchical-like control approach, the holons are organized in a hierarchical control structure, the supervisor holon acting as the shop floor controller, ii) in heterarchical-like control approach, the holons run on a completely decentralized control structure, without supervisor holons, and iii) in the ADACOR holonic control approach, the holons are organized in a hierarchical control structure, the supervisor holon acting as shop floor controller during normal operation, and enabling the self-organization capability of each operational holon.

5.1. QUANTITATIVE INDICATORS

The analysis of the performance of a manufacturing control system, using quantitative measures, is based on the statistical treatment of different production performance indicators, such as manufacturing lead time, tardiness and throughput. This experimental analyzes the manufacturing lead time indicator and also the correlation between the manufacturing load of the system and the manufacturing control performance in terms of lead time.

Manufacturing Lead Time

The manufacturing lead time is the total time required to process a given product (or part) through the factory plant, and comprises the setup time, the no-operation time (e.g. handling, intermediate storage, inspection and transport), the idle time and the processing time. The lead time reflects the production optimization level and affects the factory plant productivity.

The statistical results of the manufacturing lead time for the four values of manufacturing load, and using the three different control approaches, are summarized in the Figure 22. Analyzing the overall experimental results it is possible to verify that the manufacturing lead time increases with the increase of the manufacturing system load, and that the stable scenario and the disturbance scenario present similar patterns, the variation of the lead time with the manufacturing load being probably linear; although this rule is highly dependent of the scheduling algorithm.

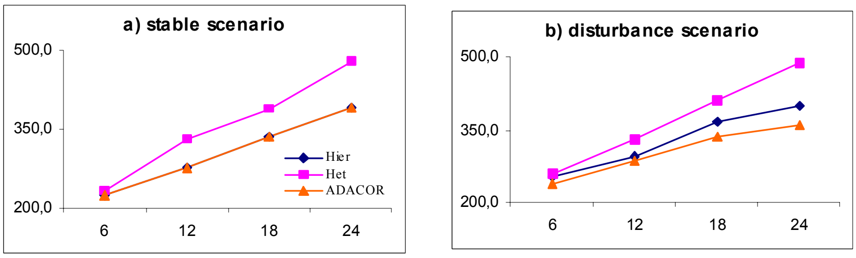

Figure 22: Evolution of manufacturing lead time over the manufacturing load

In stable scenarios, i.e. without the presence of unexpected disturbances, the system operates in a predictable context. The analysis of the results from this scenario shows that ADACOR and hierarchical-like control approaches present identical experimental values, since for stable scenarios the holons of the ADACOR control approach are organized in a hierarchical structure. These values are also smaller than for the heterarchical-like control approach. The better performance presented by those approaches results directly from the better production planning achieved by the centralized entity, i.e. the supervisor holon that elaborates optimized production plans.

Analyzing the linear regression values obtained for this scenario (ADACOR and hierarchical: *165,9+9,4t*; heterarchical: *160,2+13,2t*), it is verified that the hierarchical-like and ADACOR control approaches present higher initial values and smaller slope than the heterarchical-like control approach. One could then guess that the higher the manufacturing load the better will be the performance of the hierarchical-like and ADACOR control approaches, in terms of manufacturing lead time.

The second scenario considers the occurrence of unexpected disturbances, which increases the entropy and unpredictability of the control system, according to the disturbance model described previously. The first conclusion extracted from the experimental results of this scenario is the degradation of performance in the presence of disturbances. The ADACOR is the control approach that presents the better performance in terms of lead time. It is also possible to verify that the hierarchical-like control approach still presents better performance than the heterarchical-like control approach. However, it is also possible to verify that the difference of performance between hierarchical-like and heterarchical-like control approaches has been reduced (reduction of approximately 8,7%).

Analyzing the linear regression values associated to the disturbance scenario (ADACOR: 202,9+6,9t; hierarchical: *201,9+8,4t*; heterarchical: *181,6+12,7t*), it is verified that all control approaches have higher initial values and slightly smaller slopes than those presented in stable scenarios. This observation allows concluding that any control approach will present worse lead time in disturbance scenarios than in stable scenarios. The ADACOR control approach presents also smaller slope than the hierarchical-like and heterarchical-like control approaches implying that the higher the manufacturing load the better will be the performance of ADACOR control approach.

Throughput

The throughput is a real indicator about the productivity of a manufacturing system. In the context of this work the throughput of each experience is equal to the ratio between the number of parts produced in the experience and the batch time spent to execute the experience. The throughput of an experimental scenario is given by the mean value of all throughput values obtained for all the experiences that constitute the scenario.

The statistical results of the throughput for the four manufacturing loads, and for the three control approaches, are graphically summarized in the Figure 23. The analysis of the experimental results shows that the throughput increases slightly with the manufacturing load, presenting a similar pattern to the manufacturing lead time.

The analysis of the linear regression results for the stable scenarios (ADACOR and hierarchical: *40,5+0,47t*; heterarchical: *35,3+0,57t*) show that the hierarchical-like and ADACOR control approaches present higher initial values of throughput and smaller slope values than the heterarchical-like control approach, leading to the conclusion that in stable scenarios, the hierarchical-like and ADACOR control approaches will present better performance, in terms of throughput, than the heterarchical-like control approach.

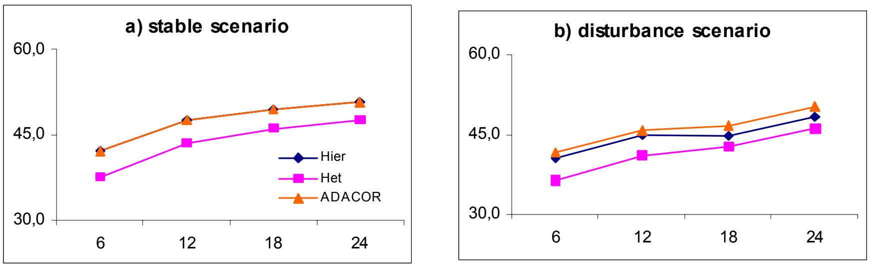

Figure 23: Evolution of throughput over the manufacturing load

Analyzing the linear regression values obtained for the disturbance scenario (ADACOR: *39,5+0,44t*; hierarchical: *38,8+0,39t*; heterarchical: *34,0+0,51t*), it is possible to verify that the ADACOR control approach presents the highest initial value and the ADACOR and heterarchical-like control approaches present quite similar slope values, but higher than the slope presented by the hierarchical-like control approach. This observation allows concluding that the ADACOR control approach will present better performance in disturbance scenarios with higher manufacturing loads.

Another conclusion extracted from these experimental results is that the heterarchical-like control approach will present similar values of throughput to ADACOR control approach, for both evaluated scenarios, for higher manufacturing loads.

5.2. Quantitative Indicators - Analysis of Agility

The qualitative measures reflect properties of the manufacturing control solution, such as the agility and flexibility, which cannot be directly obtained from the production data and are of a more subjective nature than the quantitative indicators. In this section, the ADACOR holonic control system is evaluated by analyzing a single qualitative performance parameter, the agility.

The agility of a control system can be defined as the capability to react in a short period of time to the occurrence of unexpected disturbances, more exactly, the time needed by the system to recover properly from the occurrence of a disturbance [8]. In this experimental test, the agility parameter is evaluated by running *n* experimental tests and analyzing the loss of productivity in presence of disturbance scenarios. For that purpose, it is necessary to know in first place the time required to produce a specific amount of items with no disturbances. Then, it is measured the time required to execute the same products, under a disturbance scenario. Having these two values, it is possible to calculate the throughput in each case, and the percentage of reduction of throughput, which is the loss of productivity. The smaller the loss of productivity value is the higher the agility of the system will be.

Figure 24 illustrates the comparison of the loss of productivity for the scenario of 18 production orders and considering the disturbance model previously described. It is possible to verify that the ADACOR control approach presents even better values to those exhibited by heterarchical-like control approach. As expected, the hierarchical-like control approach presents the higher loss of productivity in case of disturbances. Since the agility can be inducted by analyzing the loss of productivity, the experimental results show that the ADACOR control approach presents the same levels of agility to those presented by the heterarchical-like control approach. In more drastic scenarios it is expected that the levels of agility presented by the several control approaches are reduced.

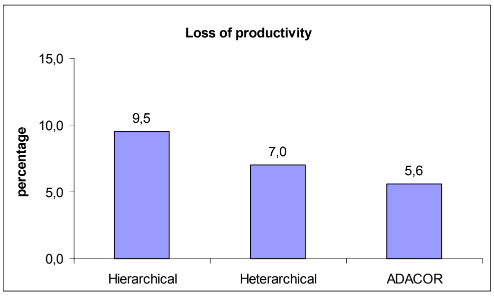

Figure 24: Loss of productivity of the evaluated control approaches

The results obtained reveal that the ADACOR holonic control system presents promising performance results, since it shows better response to the disturbance scenario, illustrated by smaller value of manufacturing lead time and higher values of throughput. The experimental results confirm also that the ADACOR holonic control system combines the hierarchical and heterarchical best features, presenting similar values of agility to the heterarchical approach, but better production optimization.

6. SUMMARY

ADACOR holonic control systems address the re-configurability and the agile reaction to the occurrence of unexpected disturbances at shop floor level, by introducing an adaptive production control approach, that evolves dynamically through different control approaches supported by the self-organization capability associated to each holon presented in the system.

The validation of the ADACOR concepts, to analyze their correctness, applicability and merits, requires their implementation and experimental test in a prototype. For that purpose a prototype was implemented, applying the ADACOR concepts to develop a manufacturing control system for a flexible manufacturing system, using the JADE framework. The experimental tests allow verifying that the ADACOR holonic control system works as specified, which was one of the major objectives of the experimental validation. The re-configurability of the ADACOR holonic control system was proven, since the system responds correctly to the introduction, removal and modification of manufacturing components, being not necessary additional re-design, re-program and re-start of other components.

The experimental results reported in this paper, which are preliminary due to the immature stage of the prototype implementation and to the limited number of experiences and scenarios, shows that the ADACOR control system presents the better performance in comparison to heterarchical-like and hierarchical-like approaches, represented by high values of agility (evaluated through the analysis of the loss of productivity parameter), combined with high values of production optimization (illustrated by the manufacturing lead time and throughput indicators).

Future research work will comprise the experimental validation of the ADACOR concepts considering more test cases, experiences and scenarios, and also the improvement of the prototype implementation, in order to reach a more sustainable conclusion about the ADACOR merits.

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