Behavioural validation of the ADACOR² Self-organized Holonic Multi-Agent Manufacturing System

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Abstract. Global economy is driving manufacturing companies into a paradigm revolution. Highly customizable products at lower prices and with higher quality are among the most imposed influence factors. To respond properly to these external and internal constraints, such as work absence and machine failures, companies must be in a constant adaptation phase. Several manufacturing control architectures have been proposed throughout the years displaying more or less success to adapt into different manufacturing situations. These architectures follow different design paradigms but recently the decentralization and distribution of the processing power into a set of cooperating and collaborative entities is becoming the trend. Despite of the effort spent, there is still the need to empower those architectures with evolutionary capabilities and self-organization mechanisms to enable the constant adaption to disturbances. This paper presents a behavioural mechanism embed in the ADACOR² holons. A validation procedure for this mechanism is also presented and results extracted. This validation is achieved through the use of a benchmark and results are compared with classical hierarchical and heterarchical architectures as also with the ADACOR.

Keywords: behavioural self-organization, multi-agent systems, reconfigurable manufacturing control

1 Introduction

The current panorama of the world economy is pushing the manufacturing companies to adopt more adaptive and responsive control architectures. Product customization, higher quality and shorter life-cycles are on the epicentre of the requirements imposed to manufacturing companies [1]. Situations of worker absence, resource breakdown and product demand fluctuation are also, at an internal level, a daily concern that require an increase of responsiveness and adaptation from the manufacturing control point of view. A proper manufacturing control architecture is mandatory, required to present

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responsiveness to the imposed disturbances, either at an internal or external level, guaranteeing the highest possible performance level of operation.

Traditionally, manufacturing control architectures relied on hierarchical organization as the mean to design those control systems. This type of organization has the advantage of collecting the information and place the processing and decisional capacity at central nodes that have a wider view of the system state and that are able to achieve high levels of performance optimization. At the other side, a considerable drawback can also be pointed out, related with the fact that the information processing time is high, decreasing dramatically the system responsiveness.

More recently, there's the growing trend of promoting the decentralization of the decision entities, bringing them closer to where they are really needed. This paradigm is also aligned with new research trends, such as the Cyber Physical System [2] and the Industrial Internet [3] paradigms.

Manufacturing control architectures have been proposed throughout the years that already use the decentralization concepts. Notably in the holonic paradigm, two reference architectures can be pointed out, namely the PROSA [4] reference architecture and the ADACOR (ADAptive holonic COntrol aRchitecture for distributed manufacturing systems) [5].

Despite the aforementioned, this new generation of manufacturing control architectures still need to further explore evolutionary theories and bio-inspired mechanisms, such as self-organization. To this part, there are already some propositions, namely the PROSA+ANTS [6] and the P2000+ [7]. The first, extends the PROSA reference architecture with inspiration from the ants food foraging that is used as forecast technique, while on the second one, a buffer type self-organization mechanism is used as the system regulation mechanism.

This paper briefly presents the ADACOR^2 manufacturing control architecture that proposes to enhance its predecessor by acting at two levels: micro level, named behavioural self-organization, and at a macro level, named structural self-organization. The assessment and evaluation of the behavioural component is drawn, starting by depicting a mechanism used during this process and analysing important Key Performance Indicators (KPI).

The rest of the paper is organized as follows: Section 2 makes a brief description of the ADACOR^2 self-organized holonic multi-agent system architecture while Section 3 describes a magnetic based self-organization mechanism used during the validation process. Section 4 describes the validation procedure and results of the behavioural self-organization vector. At last, Section 5 rounds up the paper with the conclusions.

2 A self-organized manufacturing control architecture

ADACOR^2 sets foundation of the well-known holonic manufacturing control architecture, named ADACOR. Therefore, ADACOR^2 makes use of the same set of holons as it have been defined in ADACOR, namely on the Supervisor Holon (SH), Product Holon (PH), Task Holon (TH) and Operational Holon (OH).

Briefly, the SH is responsible to introduce optimized schedules into its holarchy, the PH possesses the knowledge to produce the product that it's responsible for, whereas the TH has the responsibility to manage a product instance that is being produced, taking manufacturing decisions concerning that product. Finally, the OH maps the resources available at the shop-floor, managing its internal agenda, either negating directly with the TH or accepting the schedules from the SH.

Precisely at this last point, ADACOR proposed a binary configuration, where when the system is operation under a well-defined situation, the SH introduces optimization issuing an optimized schedule into lower level holons balancing into a more heterarchical organization where THs negotiate directly with the OHs, increasing the responsiveness of the system. This binary state is ADACOR's most strong point, allowing the combination of optimization with responsiveness, but it's also a weak point since it limits the system into two predefined configurations.

$ADACOR^2$ makes use of evolutionary theories and self-organization principles to enable the ADACOR architecture to evolve smoothly as possible and as drastic as necessary, unbounding the system from the two predefined configurations [8].

In $ADACOR^2$, the evolution towards the system re-configuration is supported in two distinct manners:

- A micro-level self-organization, which is related to the self-organization of the behaviour of individual holons, provoking the emergence of a new global behaviour, and in this way a system adaptation. To achieve this, holons have built-in a set of different behaviours and use embedded learning and discover mechanisms to detect new opportunities to evolve and the proper way to reconfigure their behaviours [9].
- A macro-level self-organization, which is related to the re-organization of the interactions among the holons, provoking a new global behaviour based on a new society of holons [10]. To achieve this, holons also possess a set of mechanisms that can be used to detect better structural organization and mechanisms to proceed to its implementation.

The need to act at these two different levels is justified by having different disturbance groups, which impact the system in different levels. Having this in mind, $ADACOR^2$ is enriched with different mechanisms as ways to overcome these constraints levels. The low impact perturbations, being more limited in time and space, can be addressed locally using low impact measures as opposite to high impact perturbation where a deep and long term change in the system can be necessary. Behavioural self-organization is then applied into the micro-level of the system while the structural self-organization is acting on the macro-level allowing the system to evolve into a new configuration (see Figure 1).

Considering that the system is working with a given configuration, C_i, it can either evolve by applying one and/or two of the considered self-organization mechanisms. When a self-organization procedure is applied to either overcome a disturbance or to improve the current holon/system performance, it is said that the system evolves into a new configuration, C_{i+1}, since the current system state has changed.

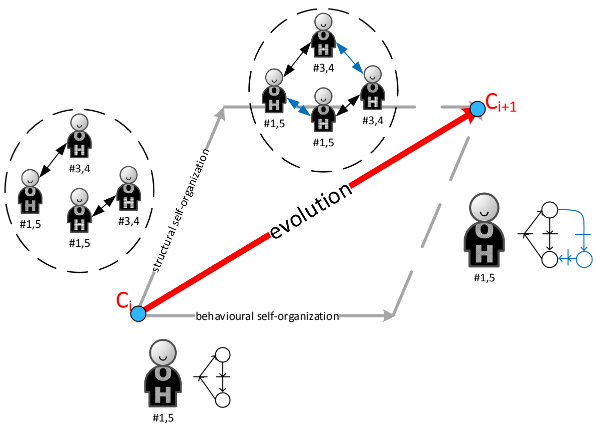


Figure 1 – Evolutionary components in ADACOR²

The behavioural self-organization is observed at micro level, where each individual holon may change its internal behaviour according to the external conditions, resulting in a smooth evolution. The second component, named structural self-organization, is observed at the macro level and drives system to a drastic evolution by changing the relations between the holons. In this way, the system can either evolve using behavioural self-organization and/or structural self-organization, to face the external or internal disturbances.

The holons internal organization must also be re-designed to accommodate these self-organization components and to include a nervousness controller. This controller becomes necessary in this self-organized architectures since entities (and the system) might display instability features due to the entities constant will of adaptation [11].

3 A behavioural self-organized mechanism

Having in mind the two self-organization components, there is still the need to develop and embed into the holons such mechanisms. This section presents, in a simplified manner, one of the used mechanisms that enable the holons, namely the THs, to adapt dynamically their behaviour.

The concept of a Potential Field (PF) is a technique that gets inspiration from the magnetism phenomenon, particularly from the inherent attraction and repulsion forces. This phenomenon can be the inspiration to design dynamic and reactive techniques. These concepts have already been used in several application areas such as in game development [12] robots motion planning [13] and even in manufacturing control [14].

Since this approach is reactive, where the emitted force (or field) is changed as soon a given condition changes, it is a good candidate to be used as a behaviour technique for very reactive environments. In such way, an algorithm based on this concept was developed and deployed in ADACOR² holons.

Each OH emits a set of PFs based on the offered services, as shown in Figure 2. Briefly, Figure 2 is built by 3 OHs, mapping resources, namely OH_1 and OH_2 offer the service *yellow* (non-negative values) while OH_3 offers *red* and *purple*. The PF must be propagated accordingly with the transportation routes that are mapped in the figure by the thick straight arrow, e.g., it is possible to route from OH_1 to OH_2. In such way, OH_2 back-propagates the *yellow* PF value to OH_1, which then calculates its value reflected on it. The value on the final OH is calculated considering the distance to the emitting source OH, i.e. has farther the OH, the lower the PF is. Notice also that in this case, a propagation of the OH_2 PF value is also relayed back since it is possible to convey from OH_3 to OH_1.

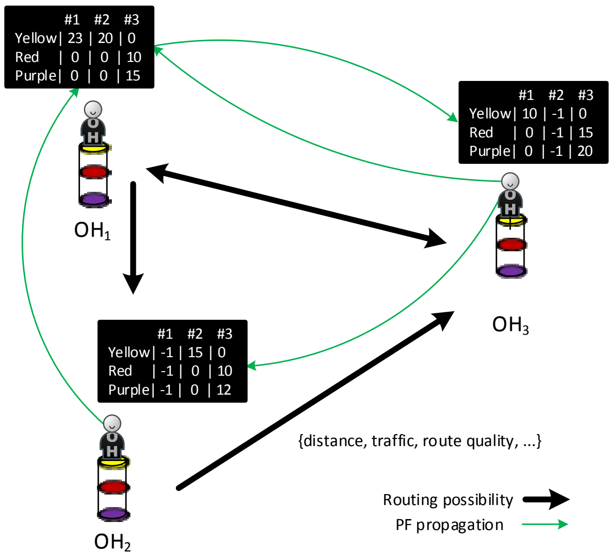


Figure 2 – Potential Field concept

The PF values are stored in the OHs using a blackboard system [15], represented as the black rectangles in Figure 2, being accessible to the holons that need to use them, e.g., THs searching for a processing resource. Additionally, the back-propagation of the PF value ends when the calculated value on the OH is lower than a pre-defined threshold. On the other side, the holons that require the execution of a given service, e.g., a TH that needs a processing task, will check in the current OH for the attractive fields of the next desired service. The selection of the OH that will perform the necessary service is selected by simply, chose the highest emitting field for the service.

Several resource parameters can be used to calculate the strength of each PF, namely the resource workload, the service processing times, the service quality and a scheduled maintenance.

$$OH_i^{PF_{pf}} = \sum W_P \times P_P$$

where,

- W_P is the weight given to parameter P.
- P_P is the value of the parameter P.

In this way, every time a given considered parameter changes, the correspondent OH is responsible to re-calculate the strength of the PF, and to propagate it to its adjacent nodes (i.e. to its adjacent OHs).

Having this information spread over a set of OHs, the THs must then select the most appropriate OH. In this decisional phase, the TH will follow the maximum emitting PF value.

Although being a very simple, reliable and fast mechanism, the PF approach has a major drawback to be considered and that is related to its myopia. Note that from the point of view of the TH, it is only worthy to select the next processing task since if more tasks are allocated, the allocation assumptions for the subsequent tasks will dynamically change and are not therefore guaranteed in the processing execution moment.

As seen previously, two holons from the architecture are considered in the development of this mechanism, namely the OH and TH. These holons have well defined and independent roles in the process, where the OH is responsible for the generation and spread of the system conditions, whereas the TH is only concerned on monitoring and taking decisional actions, abstracting itself from the underlying process.

4 Validation of the behavioural self-organization

This section describes the use case used to validate the behavioural self-organization vector, particularly the system organization, the resources skills and the products catalogue. Additionally, the tests assumptions and results are also described.

4.1 The AIP-PRIMECA cell description

The FMS, depicted in Figure 3, is composed by 7 machines connected using a conveyor system. The rack conveyor system allows the parts needing processing operations to reach the desired machine using a transport shuttle.

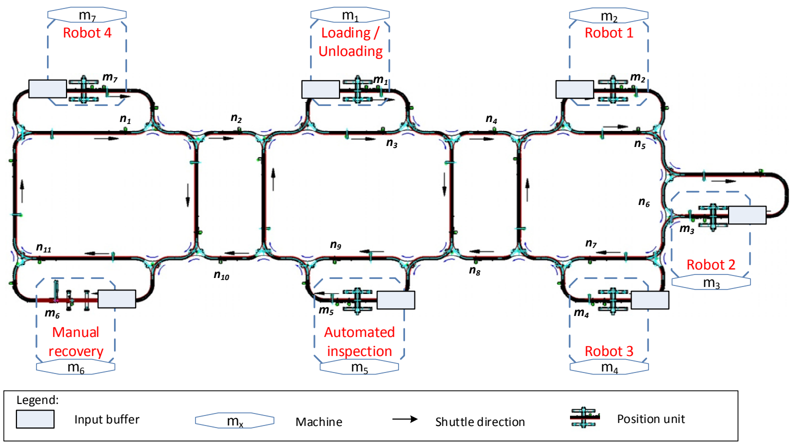


Figure 3 – The AIP-PRIMECA cell layout

Each machine (from M_1 to M_7) offers a set of skills, needing a defined amount of time to complete the processing task, and the shuttles need to convey for different transportation times depending on the start and destination nodes [16].

The system offers a catalogue of products, namely the BELT, AIP and LATE, that are composed by the appropriated set of sub-products, particularly the letters b, e, l, t, a, i and p. A visual perspective of the sub-products is given in Figure 4.

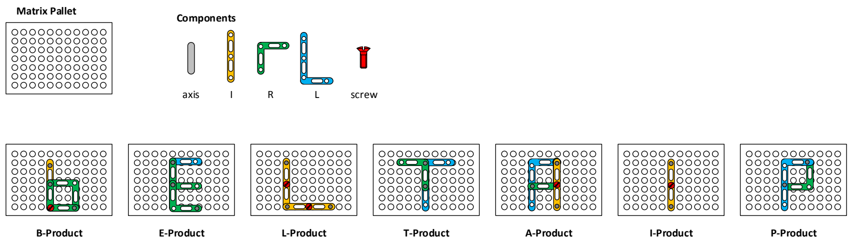


Figure 4 – Sub-products representation

To realize each sub-product, an assembly process must be followed, see Table 1. As an example, to produce the sub-product i, the assembly base plate must be loaded into the shuttle, followed by two axis components, one I and one Screw, followed by an inspection and ending with an unloading procedure.

Table 1 – Products processing sequence

Oper	*B*	*E*	*L*	*T*	*A*	*I*	*P*
#1	Loading	Loading	Loading	Loading	Loading	Loading	Loading
#2	Axis	Axis	Axis	Axis	Axis	Axis	Axis
#3	Axis	Axis	Axis	Axis	Axis	Axis	Axis
#4	Axis	Axis	Axis	Rcomp	Axis	Icomp	Rcomp
#5	Rcomp	Rcomp	Icomp	Lcomp	Rcomp	Screw	Lcomp
#6	Rcomp	Rcomp	Icomp	Inspection	Lcomp	Inspection	Inspection
#7	Icomp	Lcomp	Screw	Unloading	Icomp	Unloading	Unloading
#8	Screw	Inspection	Screw		Screw		
#9	Inspection	Unloading	Inspection		Inspection		
#10	Unloading		Unloading		Unloading		

The decisional choices are then concerned with the appropriate machine selection, routing selection and product release order.

4.2 Validation scenarios

Several scenarios from the Bench4Star benchmark are used, namely those ranging from A0 to E0 [16], allowing the test of different batch combinations, varying the batch products and number. In this work, all the scenarios have real transportations times and non-infinite transportation shuttles (note that these are neglected for some scenarios). Scenarios without and with disturbances are also considered, namely the #PS12 [16] that introduces a 60s breakdown in M_2 at the end of processing of every 4 jobs.

Table 2 – Production scenarios (adapted from [16])

	Number of shuttles	Transportation times	Order #	Products		
				BELT	AIP	LATE
A0	10	Real	#1	1	-	-
			#2	-	1	-
B0	10	Real	#1	-	2	-
C0	4	Real	#1	1	-	-
			#2	-	1	-
D0	10	Real	#1	1	-	-
			#2	2	1	-
E0	10	Real	#1	2	1	-
			#2	-	2	1
			#3	-	-	2

Four manufacturing control architectures are compared in both situations, namely a fully hierarchical architecture, where a high level entity is always providing optimized schedule, a heterarchical architecture where entities are completely autonomous, and finally the ADACOR and ADACOR^2 approaches. Particularly, in the ADACOR^2 tests, the entities are allowed to switch between two different behaviours, namely between a market-based, following a Contract Net Protocol approach, and the Potential Field [9].

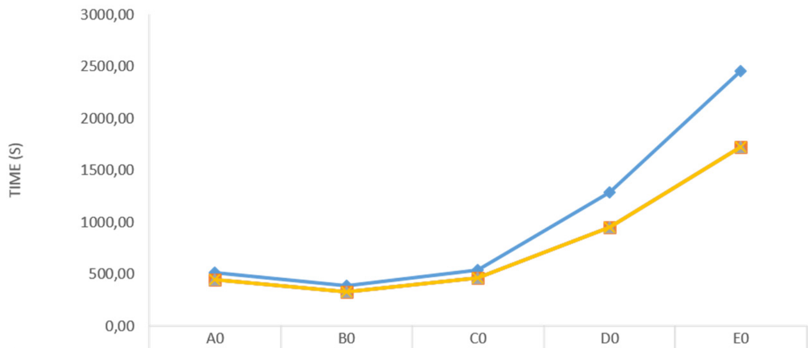
4.3 Behavioural self-organization assessment

In order to provide a proper validation, each of the aforementioned architectures were simulated, considering each production scenarios, 30 times. Several KPIs, e.g., the C_{max}, throughput and predictability, were extracted, providing a number of results that, after analysed, allow the assessment and validation of the control architectures. With the simulation results, statistical analysis was performed, namely average values and standard deviation were made.

One of the most used KPI in manufacturing control is the C_{max} that is a direct measure of the total time needed for the manufacturing control to produce a given amount of products. In such, and for simplicity reasons, this KPI will be used for the assessment of the behavioural part.

The first batch of simulations were conducted for scenarios where all parameters are well known and controlled, i.e. a system without disturbances. Experimental results for all the non-disturbance situations are shown in Figure 5.

As it can be seen, the hierarchical approach alongside with ADACOR and ADACOR^2 present the most optimized solution. This is explained by the fact that in these approaches, the SH is constantly introducing optimization schedules to the OHs, since everything is predictable and under control. The heterarchical approach presents the worst results since the THs are directly interacting with the OHs and in this way, myopic phenomena may appear.

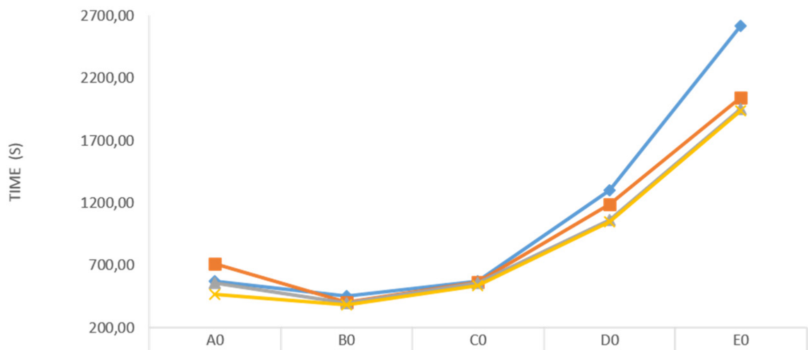


	A0	B0	C0	D0	E0
heterarchical	512,30	392,37	543,47	1286,70	2453,13
hierarchical	445,87	333,73	463,50	951,70	1721,57
ADACOR	445,87	333,73	463,50	951,70	1721,57
ADACOR2	445,87	333,73	463,50	951,70	1721,57

Figure 5 – Cmax for non-disturbance scenarios

A system without disturbances is not realistic and not expected nowadays and so any manufacturing control architecture must be tested within these disturbance working conditions in order to assess its viability. In this way, the #PS12 scenario, as defined in [16], is used. This disturbance scenario introduces a 60s malfunction in M_2 at every 4^{th} processing operation. The experimental results for the C_{max} KPI are shown in Figure 6.

After analysing the graph, it is possible to observe that under these conditions, $ADACOR^2$ is the one that achieves a better performance, allowing to produce the same amount of work in less time, i.e. providing a lower C_{max}. Additionally, and as already shown in [5] the ADACOR control architecture surpasses the hierarchical and heterarchical control solutions.

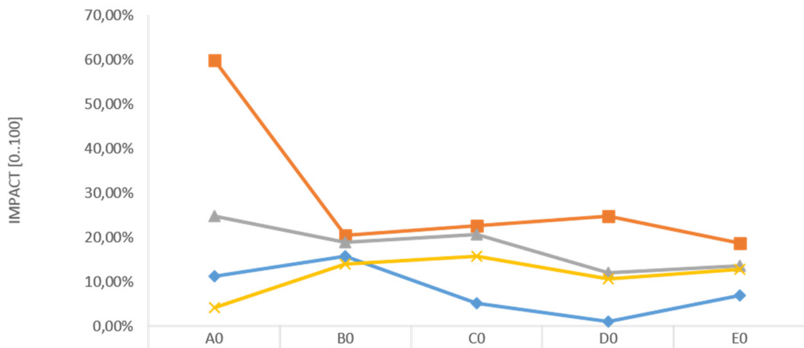


	A0	B0	C0	D0	E0
heterarchical	569,60	453,67	571,07	1299,17	2622,37
hierarchical	712,70	402,07	567,73	1186,70	2042,13
ADACOR	555,92	396,67	558,77	1066,50	1956,13
ADACOR2	464,67	380,53	535,83	1052,53	1941,07

Figure 6 - Cmax for disturbance scenarios

Quantitatively, the $ADACOR^2$ control architecture is able to reduce, on average, the C_{max} by 91s for the production scenario A0, 23s for C0 and 15s for E0. The apparent margin improvement decrease, as the batch size increases, seems counterproductive and is explained by the behavioural parameter adjustment. It is expected that with a proper selection and fine-tune of the selected behaviour parameters will improve these KPIs. It is worthy to note that a parameter adjustment was not performed during the simulation tests, despite the change of the working conditions for the different scenarios, e.g., the number of shuttles being able to transport the. Additionally, the AIP-PRIMECA FMS cell configuration may have harder freedom limits when a high congestion production appears, decreasing the improvement rate.

An impact assessment can be conducted, see Figure 7, foreseeing the performance degradation of the manufacturing control strategies when disturbances are introduced.



	A0	B0	C0	D0	E0
heterarchical	11,18%	15,62%	5,08%	0,97%	6,90%
hierarchical	59,85%	20,48%	22,49%	24,69%	18,62%
ADACOR	24,68%	18,86%	20,55%	12,06%	13,63%
ADACOR2	4,22%	14,02%	15,61%	10,60%	12,75%

Figure 7 – Impact of the disturbance occurrence

Expectably, the heterarchical approach is the one that suffers less impact due to the disturbance introduction. As commonly known, in completely heterarchical structures, the entities react locally to the disturbances, making them more responsiveness. On the opposite side, the hierarchical approach, due to the higher amount of time that the superior entity needs to re-compute an optimal plan, has the worst performance impact. ADACOR and ADACOR^2 suffer impact levels between those bounds and have good impact performance indexes. ADACOR^2 has a gain over ADACOR, meaning that the dynamic selection of behaviour, in reaction to disturbances, helped to a decrease of the overall system impact.

Globally, and as it is possible to conclude, the ADACOR^2 manufacturing control architecture is the one that best perform under the full range of production scenarios.

5 Conclusions

The current manufacturing world is demanding for innovative control architectures that are able to constantly adapt to the daily constraints. To achieve this, holonic principles implemented using agent technology is a good candidate to address those constraints. Despite of the good results, there is still the need to further enhance those architectures, particularly allowing them to evolve alongside with the disturbances.

The ADACOR^2 manufacturing architecture combines the holonic design principles, it uses the agent based technology and empowers this combination with bio-inspired mechanism, namely self-organization principles. In fact, ADACOR^2 proposes to act at two distinct levels as the way to address different disturbances that may appear.

This paper addresses the behavioural vector, acting at the holons internal level, and assess and validates this approach by means of use of a benchmark. Results have shown that using these principles, ADACOR^2 is able to achieve better results than a hierarchical, heterarchical and the ADACOR control architecture.

Future work, related to this, will be devoted to the development of different behavioural mechanisms and the test in different production system configurations.

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