An Evolutionary Simulation-Optimization Approach to Product-Driven Manufacturing Control

Mehdi Gaham[1], Brahim Bouzouia[1], and Nouara Achour[2]

[1] Équipe Systèmes Robotisés de Production
Centre de Développement des Technologies Avancées
Baba Hassen, Alger, Algeria 16303
[2] Laboratoire de Robotique Parallélisme Électro-énergétique
USTHB, BP32 El Alia, Bab Ezzouar
Alger, Algeria
mgaham@cdta.dz

Abstract. The presently reported research proposes an adaptive manufacturing scheduling and control framework that exploits the challenging combination of the main capabilities of product-driven control paradigm and online simulation-optimization approaches. Mainly, the proposed approach employs a scheduling rule-based evolutionary simulation-optimization strategy to dynamically select the most appropriate local decision policies to be used by the agentified manufacturing system components. In addition, this approach addresses products and machines agents' local decisional efficiency issues by dynamically adapting their behaviour to the fluctuations of the manufacturing system state. The main motivation of the developed hybrid intelligent system framework is the realization of an effective and efficient distributed dynamic scheduling and control strategy, that enhances manufacturing system reactivity, flexibility and fault-tolerance, as well as maintaining global behavioural stability and optimality. In order to assess the significance of the proposed approach, a proof of proposal prototype implementation is presented and a series of numerical benchmarking experiments are discussed.

Keywords: product-driven control, agent-based manufacturing, holonic systems, simulation-optimization, dynamic scheduling, genetic algorithm.

1 Introduction

Induced by market globalization and pressure, poor demand visibility, shorter product life cycles and adoption of new consumer-driven business practices such as mass customization, are some of the innumerable factors that makes flexibility and agility the key competitiveness issues of nowadays manufacturing enterprise. However, due to their centralized or hierarchically organized planning, scheduling and control structures, legacy manufacturing control frameworks respond weakly to these challenges and behave poorly when the system is subject to internal or external unforeseen disturbances. So, distributed or "heterarchical" control paradigms, aiming to bring manufacturing enterprise more competitiveness by enhancing their ability to dexterously

T. Borangiu et al. (eds.), *Service Orientation in Holonic and Multi-Agent Manufacturing and Robotics*, Studies in Computational Intelligence 544,
DOI: 10.1007/978-3-319-04735-5_19, © Springer International Publishing Switzerland 2014

react to customer orders and changing production environments, have been proposed. Distributed manufacturing control means that each system's component representation in the control software is designed as an autonomous processing unit, which has its own goals and responsibilities and which interacts with other components for constructing overall manufacturing system dynamic behaviour [2]. With the aid of appropriate coordination strategy, decisional distribution is expected to enhance system modularity, flexibility, fault-tolerance, as well as system adaptability and reconfiguration ability. Because multi-agent technology cope efficiently with such complex distributed systems, distributed manufacturing approaches are usually put into practice using the agent paradigm [3, 4, 5, 6].

Within manufacturing dynamic scheduling and control context, full heterarchical bidding-based approaches inspired from the well-known Contract Net Protocol pioneered the usage of multi-agent local decision-making methods [7]. However, because of their inherent decisional myopia, these approaches and some of their variants are increasingly criticized for their inability to cope efficiently with the complexity of real world manufacturing dynamic scheduling and control problems [8, 9]. Actually, efficiency of dynamic scheduling process represents a vital concern for manufacturing organizations evolving within a dynamic and unpredictable environment, and although they enhance agility, adaptability and reconfiguration ability of manufacturing system, agent-based dynamic allocation approaches still incarnate immaturity facing these concerns and penalize seriously industrial adoption of this emerging paradigm. Motivating an important number of research works, hybrid hierarchic/heterarchical multi-agent decisional structures have been also investigated for the improvement of agent-based manufacturing approaches [10]. As a core line of investigation, Holonic Manufacturing Systems (HMSs) represent a major declination of distributed manufacturing dynamic scheduling and control structures where the manufacturing system components (machines, products, AGVs, etc.) feature autonomy and cooperation. Mainly, HMSs focus on decisional efficiency and are characterized by a hybrid decisional structure that combines the desirable characteristics of hierarchic and heterarchical control frameworks, which are behavioural optimality of the former and flexible strategy of the latter. Abundantly documented PROSA and ADACOR architectures exemplify the application of the holonic concept to manufacturing control [11, 12]. Another relevant characteristic of HMSs is that they promote the full integration of the manufacturing products or parts as computational control entities within the manufacturing distributed decisional system. The product becomes an active decisional and communicative entity capable of participating in, or making decisions relevant to its fabrication. Within this context, association of physical product and its informational counterpart is realized by Radio Frequency Identification (RFID)-based product identification technology (Fig. 1).

Hence, intelligent product driven manufacturing control emerges as a promising declination of multi-agent HMSs, and is actually defined by Pannequin [13] as a specialization of holonic agent-based distributed control paradigm where agent technology brings forward new fundamental insights on decentralized coordination and auto-organization, enabling new manufacturing decision-making policies and on-the-fly reconfiguration capabilities and infotronics technologies address the issue of synchronization between physical objects and their informational representation. Beside, Trentesaux and Thomas [14] arguing that product-driven control is based on the assumption that the product is the core object in the design, manufacturing, logistic and services systems, define this paradigm as "*a way to optimize the whole product life cycle by dealing with products whose informational content is permanently bound to their virtual or material content and, thus, are able to influence decisions made about them and participating actively to different control processes in which they are involved throughout their life cycle*".

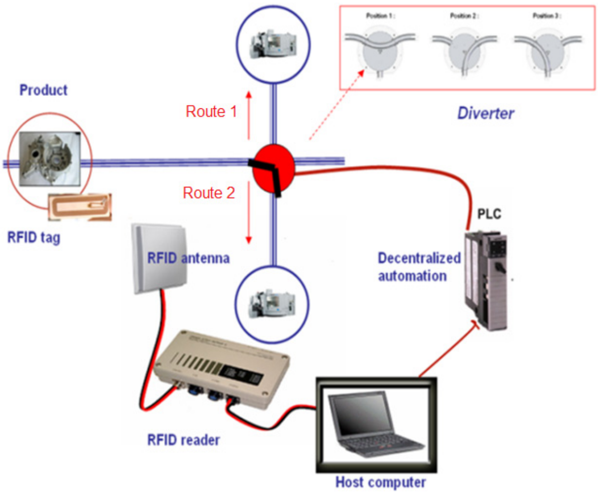

Fig. 1. Product-driven manufacturing control technological issues related to industrial implementation

Focusing on decisional efficiency, the reported research proposes an adaptive manufacturing dynamic scheduling and control framework that explores the challenging combination of main capabilities of this emerging control paradigm and simulation-optimization approaches. Relevant expected contribution of the proposed approach to multi-agent product-driven control is that it exploits a genetic algorithm simulation-optimization approach to dynamically select the most appropriate local decision policies to be used by the agentified manufacturing system components. Exactly, it addresses products and machines agents' local decisional efficiency issues by adapting dynamically their behaviour to the fluctuations of the manufacturing system state. Beside, expected to maintain the correct balance between hierarchical and heterarchical behaviour, the proposed hybrid decisional framework is mostly intended to introduce some level of optimization capabilities within product-driven manufacturing control paradigm by dynamically tuning the used local operational policies.

The rest of this paper is organized in the following way: in section 2, the adopted multi-agent control architecture is succinctly presented, section 3 is dedicated to the presentation of the genetic algorithm simulation-optimization adaptive scheduling approach, prototype implementation and results discussion are presented in section 4 and section 5 concludes the paper.

2 Presentation of the Multi-Agent Product-Driven Control System

Manufacturing facilities organized in flexible job shop production structures are the main focus of the proposed multi-agent control architecture. According to specific implementation issues related to project development perspective, the architecture is separated in two distinct and independent parts: high-level decisional and low-level system emulation part. Each agent in the multi-agent emulation part is a representation of manufacturing component - either a physical resource, a RFID reader or a product. The sited agents are mainly intended to emulate the operational and informational activities of the manufacturing facility. Informational activities such as contract-net real-time information gathering are also encapsulated in this part. Within decisional part, machine and product agents counterparts are implemented as independent agents (Decision Machine (D_Machine) and Decision Product Agents (D_Product)) encapsulating decisional capabilities of product and machine agents. According to overall system design, common manufacturing machine selection rules and job dispatching rules are used by D_Product and D_Machine agents as local decision policies. According to machine related real-time information, machines selection rules are heuristics used by D_Product agent for the selection of the next processing resource to be visited by product agent. Heuristic job dispatching rules are used by D_Machine agents to select from waiting products which one to process next. As an integral component of the decisional part of the multi-agent architecture, Operational Policies Optimization Agent (OPOA_Agent) is responsible of the online tuning of the decisional capabilities of D_Product and D_Machine agents. Instead of using a fixed decisional policy along manufacturing system operational horizon, an optimized set of decision rules is assigned to decisional agents at each occurrence of a perturbation that can affect system' stability. The architecture is shown in Fig. 2.

3 Scheduling Rules-Based Genetic Algorithm Simulation-Optimization

Although they play a significant role within practical manufacturing dynamic scheduling context, one of the commonly identified shortcomings of dispatching rules is that their relative performance depends upon the system attributes, and no single rule is dominant across all possible manufacturing system states. Addressing this issue, simulation is usually used to empirically assess the performances of various dispatching rules and to determine the best rule to be used according to the configuration of the manufacturing system. However, these approaches don't propose a clear

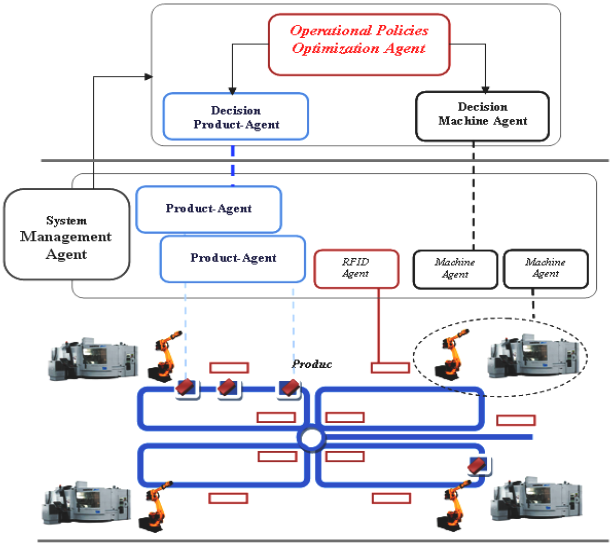

Fig. 2. Product-driven manufacturing control multi-agent architecture

optimization strategy that can guarantee the calculation of an optimal set of rules. By providing a unified integrated framework, simulation-based optimization or simply "simulation-optimization" approaches overcome this limitation. Indeed, as an increasingly investigated research topic, online scheduling rules-based simulation-optimization has been identified as offering a real efficiency perspective to practical manufacturing dynamic scheduling approaches. Within this context, optimization is used to orchestrate the simulation of a system configurations sequence (each configuration corresponds to particular settings of the decision variables) so that a system configuration, that provides an optimal or near optimal solution, is eventually obtained [15]. Decision variables correspond to the set of machines selection and jobs dispatching rules, and simulation is carried out by a simulation model that reproduces the stochastic behaviour of the modelled system.

Hence, scheduling rules-based simulation-optimization is a well suited adaptive dynamic scheduling approach as it makes possible a real-time tuning of used local operational policies according to the manufacturing system state. Moreover, scheduling rules-based simulation-optimization has been successfully applied to a number of real industrial operational management problems. Recently, in [16] a Genetic Algorithm-simulation approach to solving multi-attributes combinatorial dispatching decision (MACD) problem in a flow shop with a multiple processors (FSMP) environment is presented. This approach illustrates the effectiveness and the efficiency of that kind of methodology compared to several common industrial practices. However, as stressed by the authors, although the MACD decision is effective for a practical application, it adds complexity to the shop-floor control problem and its implementation requires supports for a sophisticated shop-floor control system that can perform the dispatching algorithms and control. This shortcoming is well addressed by the *product-driven multi-agent integration* and technological framework adopted in this research.

The system's online simulation-optimization capabilities are encapsulated in the OPOA_Agent. Triggered by the System Management Agent (SM_Agent) at each occurrence of an internal or external disturbance (product arrival, machine breakdown), the OPOA_Agent uses simulation-optimization (Optimization and Simulation modules) for the calculation of the new set of decisional policies (scheduling rules) to be dispatched to the decisional agents of the system (via the communication module). The optimization is carried out using a Genetic Algorithm (GAs) as shown in Fig. 2.

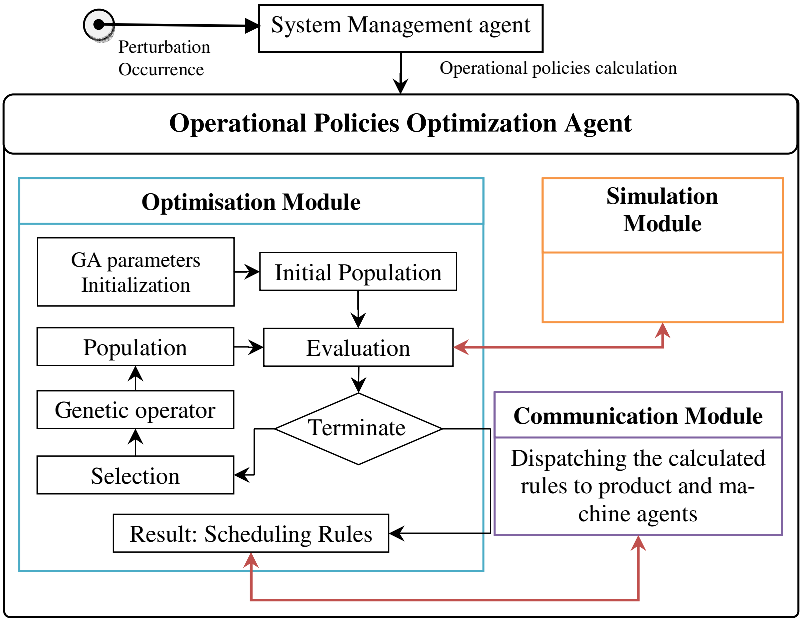

Fig. 3. Internal architecture of the Operational Policies Optimization Agent

In GAs, individuals within a population reproduce according to their fitness in an environment (optimization space). Using stochastic recombination operators, the population of individuals combines to perform an efficient domain-independent search strategy. During each generation, a new population of individuals is created from the old one via the application of genetic recombination operators (crossover, mutation), and evaluated as solutions to a given problem (the environment). Due to selective pressure (Selection operator), the population adapts to the environment over the generations, evolving better solutions. Our approach uses a real coded genetic algorithm (an individual codes a sequence of scheduling rules that equals the number of machines and products in the system) combined to classical crossover and mutation and selection operators.

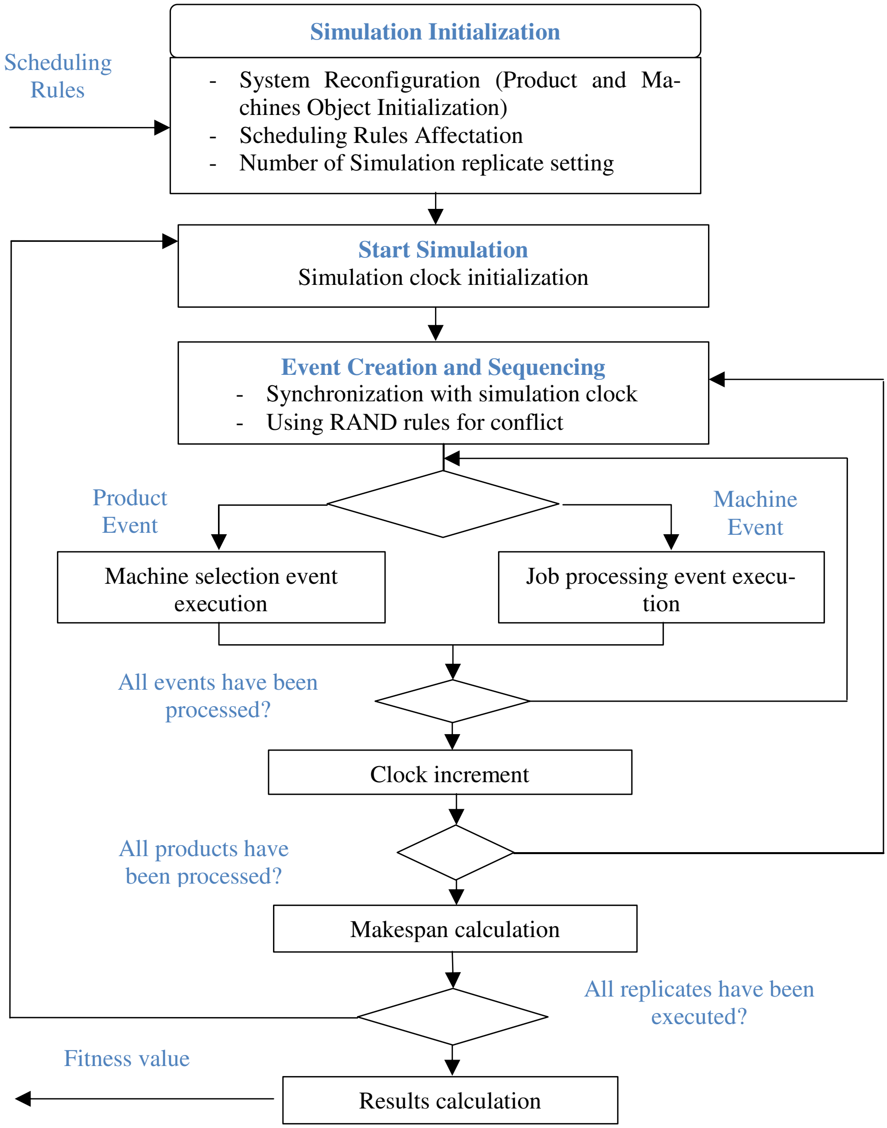

Fig. 4. Flowchart of the object oriented discrete event simulation module

Evaluation of each individual is carried out using a predefined number of simulation replicates that assesses the performances of the set of scheduling rules according to the stochastic nature of the adopted multi-agent manufacturing control framework. In charge of the simulation execution, the independent simulation module is implemented as an object oriented discrete-time simulation framework. For each simulation replicate, the simulation framework, guided by the simulation clock evolution, constructs a schedule using the manufacturing system real-time status and the set of machine selection and job dispatching rules. Stochastic transportation times and randomized synchronization of decisional time conflicts are integrated within the schedule construction and evaluation for each simulation replicate. Schedule evaluation is done using the makespan criterion. Fig. 4 illustrates the functional operation of the simulation module.

4 Prototype Development and Approach Validation

As depicted in Fig. 5, Open source NetBeans IDE and JADE (Java Agent Development Environment), have been used for the development of the prototype emulation and control system.

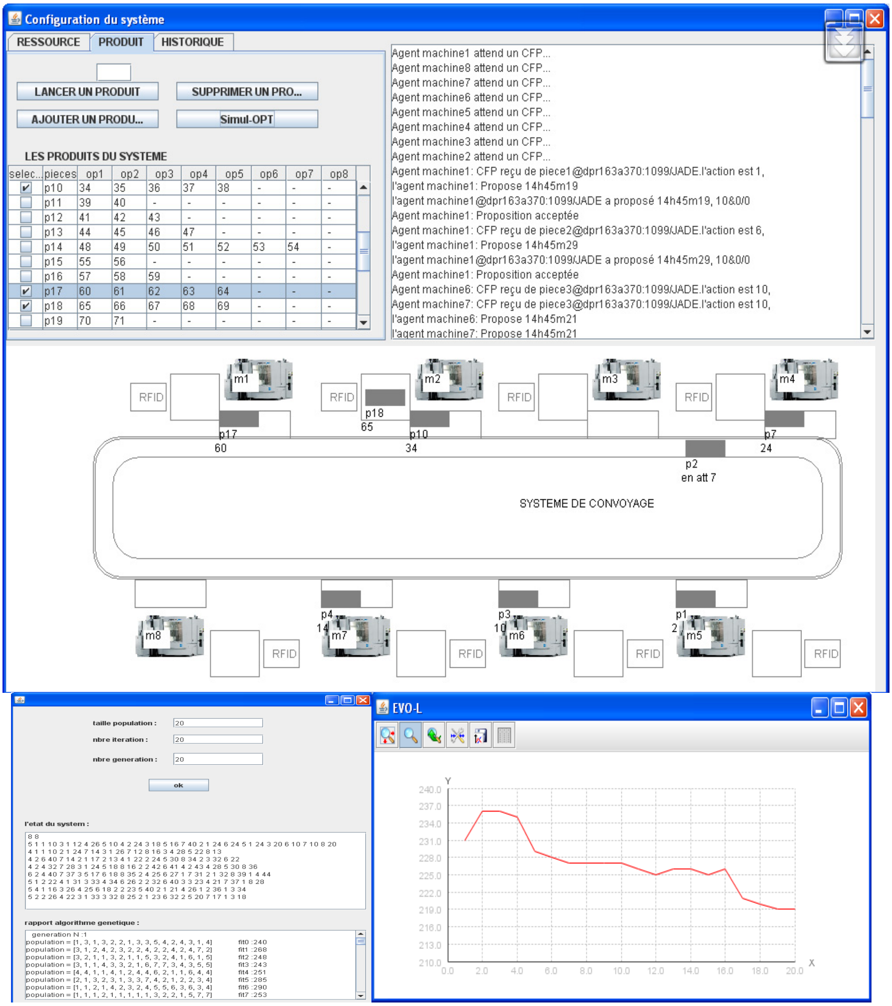

Fig. 5. Snapshots of the JADE-Based Prototype Implementation

JADE is an open source platform [14] that provides basic middleware-layer functionalities which simplify the realization of distributed applications that exploit the agent's software abstraction [15]. A multi-agent system based on Jade has amongst others the following features: fully distributed, compliant with the FIPA specifications, efficient transport of asynchronous messages, provides a library of interaction protocols. JADE also provide a runtime environment and a set of graphical tools to support programmers when debugging and monitoring applications.

In order to evaluate the pertinence of the dynamic scheduling approach in terms of solution quality and computational effort, several tests have been carried out using an instance problem of 8 machines and 15 products. Different machine selection and job dispatching rules have been used. Table 1 summarizes the set of rule.

Table 1. The set of scheduling and dispatching rules used as local decisional policies by the product and machine agent

	Rules	**Description**	
	Pr1	LRW	Least remaining work
PRODUCTS	Pr2	LRPT	Least Remaining processing time
	Pr3	LPT	Longest processing time
	Pr4	SPT	Smallest processing time
	Mr1	SPT	Smallest processing time
	Mr2	LPT	Longest processing time
MACHINES	Mr3	EDD	Earlier due date
	Mr4	LRW	Least remaining work
	Mr5	FIFO	First in first out
	Mr6	LIFO	Last in first out
	Mr7	RANDO	Random selection

The evolution of the fitness value for the conducted experiments is illustrated in Fig. 6. The GA parameters have been respectively set to 20 and 10 respectively for the population size and number of generation. The number of replicate has been empirically assessed and has been set to 10. The conducted experiments showed the effectiveness of the approach for the minimization of the makespan. Thus, simulation-optimization seems to be a well suited approach for the online determination of dynamic scheduling operational local policies, but it is still highly sensitive to the number of replicates. In fact, the dynamic nature of the simulation-based optimization problem makes this parameter a critical one. Fig. 7 shows the influence of this parameter for the conducted test problem. In this figure, the dotted curve corresponds to the evolution of solution for a number of replicates equals to 1. It can be seen that the variance of the values is clearly superior to the values variance of the other curve that correspond to a number of replicates equal to 20.

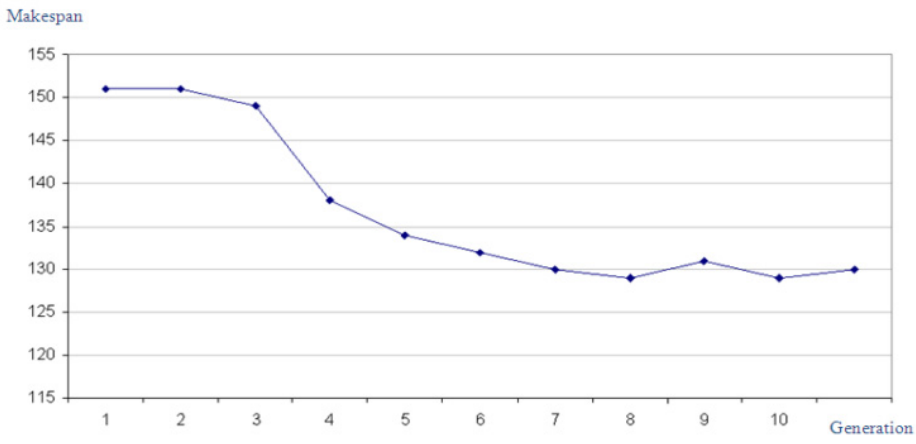

Fig. 6. Genetic algorithm Fitness Evolution

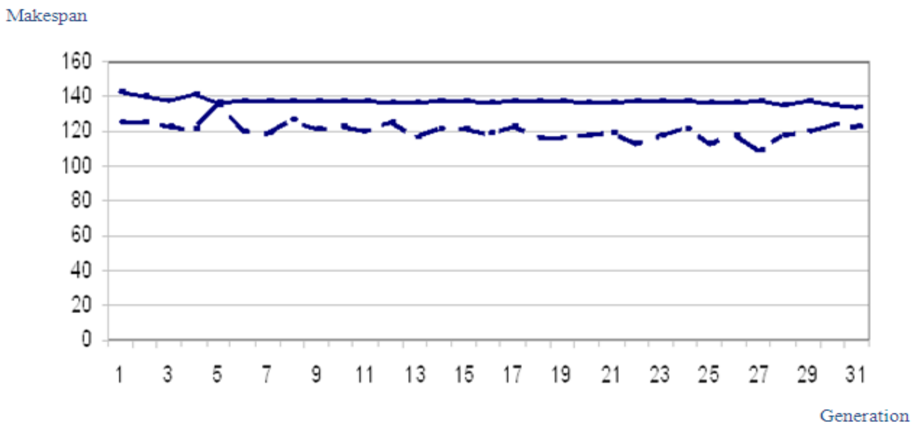

Fig. 7. Number of simulation replicates influence

4.1 Computational Results

The computational tests were conducted using flexible job shop benchmark problems (Brandimarte [17]). Six test problems have been chosen. As the problems are static, ones with no transportation time defined and with no due date, the system has been adapted according to those facts. The computational tests compare the genetic algorithm based simulation-optimization approach with some of most relevant combination of scheduling and dispatching rules. To handle stochastic nature of the system, ten realization were conducted for each rules combination and average makespan (completion time for all the tasks) are given as indicator. Genetic algorithm parameters are as follow: Population=100, Generation=50, Crossover probability=0.9, Mutation probability=0.02, Number of simulation replicates=10.

Table 2. Comparative results of the simulation approach and rules combination

	Num. of products	Num. of machines	Best rules value	Rule combination	Brandimarte values	GA values
MK 01	10	6	54	Pr 1+ Mr 1	42	47
MK 02	10	6	42	Pr 1+ Mr 1	32	38
MK 03	15	8	234	Pr 1+ Mr 5	211	222
MK 04	15	8	81	Pr 1+ Mr 1	81	77
MK 05	15	4	197	Pr 1+ Mr 5	186	188
MK 07	20	5	217	Pr 3+ Mr 1	157	168

The conducted experiments validate the proposed approach in term of computational efficiency. In fact, for that specific set of benchmark problem the approach is superior to simple combination of scheduling and dispatching rules. The approach, also, gives a very interesting results compared to those of Brandimarte, for example for the of mk04 problem.

5 Conclusions and Future Works

This paper investigates an innovative hybrid framework combining holonic product-driven manufacturing control and scheduling rules-based genetic algorithm simulation-optimization approaches for real-time adaptive dynamic scheduling of real world stochastic manufacturing systems. Both design and implementation issues related to the adopted multi-agent system have been presented, and as a core component of the overall framework, a scheduling rules-based genetic algorithm simulation-optimization approach has been described and evaluated. The applicability and effectiveness of the proposed hybrid framework has been demonstrated by the developed prototype and the conducted and succinctly presented tests.

Future research direction will deal with the investigation of a more formal approach for the determination of algorithm parameters, and particularly the number of simulation replicates.

References

1. Duffie, N.A., Piper, R.S.: Non-hierarchical control of a flexible manufacturing cell. Robotics & Computer-Integrated Manufacturing 3, 175–179 (1987)
2. Trentesaux, D.: Distributed control of production systems. Engineering Applications of Artificial Intelligence 22, 971–978 (2009)

3. Marik, V., Lazansky, J.: Industrial applications of agent technologies. Control Engineering Practice 15, 1364–1380 (2007)
4. Shen, W., Norrie, D.H.: Agent-based systems for intelligent manufacturing: a state-of-the-art survey. KAIS 1, 129–156 (1999)
5. Shen, W., Hao, Q., Yoon, H.G., Norrie, D.H.: Applications of agent-based systems in intelligent manufacturing: An updated review. Advanced Engineering Informatics 20, 415–431 (2006)
6. Deen, S.M. (ed.): Agent-based manufacturing Advances in the holonic approach. Springer (2003) ISBN 3-540-44069-0
7. Parunak, H.V.D.: Manufacturing experience with the contract net. In: Huhns, M.N. (ed.) Distributed Artificial Intelligence, pp. 285–310. Pitman (1987)
8. Maione, G., Naso, D.: A Genetic Approach for Adaptive Multiagent Control in Heterarchical Manufacturing Systems. IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans 33 (2003)
9. Zambrano Rey, G., Pach, C., Aissani, N., Bekrar, A., Berger, T., Trentesaux, D.: The control of myopic behaviour in semi-heterarchical production systems: A holonic framework. Engineering Applications of Artificial Intelligence 26, 800–817 (2012)
10. Heragu, S.S., Graves, R.J., Kim, B., Onge, A.: Intelligent Agent Based Framework for Manufacturing Systems Control. IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans 32, 560–572 (2002)
11. Van Brussel, H., Wyns, J., Valckenaers, P., Bongaerts, L., Peeters, P.: Reference architecture for holonic manufacturing systems: PROSA. Computers in Industry 37, 255–274 (1998)
12. Leitão, P., Colombo, A.W., Restivo, F.: A formal specification approach for holonic control systems: the ADACOR case. IJMTM 8, 37–57 (2006)
13. Pannequin, R., Morel, G., Thomas, A.: The performance of product-driven manufacturing control: An emulation-based benchmarking study. Computers in Industry 60(3), 195–203 (2009)
14. Trentesaux, D., Thomas, A.: Product-Driven Control: Concept, Literature Review and Future Trends. In: Borangiu, T., Thomas, A., Trentesaux, D. (eds.) Service Orientation in Holonic and Multi agent, SCI, vol. 472, pp. 135–150. Springer, Heidelberg (2013)
15. Law, A.M., McComas, M.G.: Simulation-based optimization. In: Proceedings of the 2000 Winter Simulation Conference (2000)
16. Yang, T., Kuo, Y., Cho, C.: A genetic algorithms simulation approach for the multi-attribute combinatorial dispatching decision problem. European Journal of Operational Research 176, 1859–1873 (2007)
17. Brandimarte, P.: Routing and scheduling in a flexible job shop by tabu search. Annals of Operational Research 41, 157–183 (1993)