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► To cite this version:

Ali Attajer, Saber Darmoul, Sondès Chaabane, Yves Sallez, Fouad Riane. Design and development of a distributed and knowledge-based control architecture to achieve operational resilience in cyber-physical production systems. 7ème Journée Régionale des Doctorants en Automatique, Nov 2021, Compiègne, France. <hal-03845298>

HAL Id: hal-03845298

<https://hal.science/hal-03845298v1>

Submitted on 9 Nov 2022

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Design and development of a distributed and knowledge-based control architecture to achieve operational resilience in cyber-physical production systems

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Introduction

Context

Nowadays, production systems are subject to different types of challenges, related to fast technological evolution, unpredictable markets, changes, disruptions and operational risks [1]. Accordingly, numerous research projects have developed so-called "cyber-physical production systems (CPMS)" (Figure 1). These systems implement new concepts related to technologies that allow the construction of the factories of the future, which can adapt rapidly to unexpected changes, while maintaining or even improving their competitiveness [2]. In the context of a CPMS, resilience refers to the ability of a system to withstand disruptions by maintaining system functions and structures, reducing the magnitude and duration of disrupted states, and/or responding to disruptive events/situations [3].

Problem statement

With Industry 4.0 technologies, CPMSs can now take advantage of the opportunities for information distribution, and decentralization of decision-making processes that the Industry 4.0 revolution offers [3]. Despite the emergence of distributed/decentralized control paradigms and architectures, such as multi-agent, holonic, and bionic systems [4], the management of operational disruptions and risks is still governed by predominantly centralized or hierarchical organizational modes, information systems, and control architectures that do not take advantage of the full potential and flexibility of Industry 4.0 technologies [5]. In the literature [6], [7], [8], only a limited number of articles focus on the development of distributed architectures, where intelligent products play an active role in the control, management and organization processes of production [9]. Moreover, these references consider only limited types of disturbances and do not propose generic mechanisms, allowing to face several types of disturbances and risks in an autonomous, adaptive and resilient way [10], [11]. To the best of our knowledge, no work has been reported that analyzes the contribution of smart and active products in the operational resilience of the production system in which they are manufactured. Accordingly, the development of distributed control architectures, where smart products are able to cope with different types of disturbances and risks and help decision makers to react in an agile, flexible and resilient manner, remains an open, complex and challenging problem.

Objective

This project main contribution is the design and development of a distributed and knowledge-based control architecture exploiting product intelligence to achieve resilience, and thus be able to effectively manage disruptions and operational risks in CPMS.

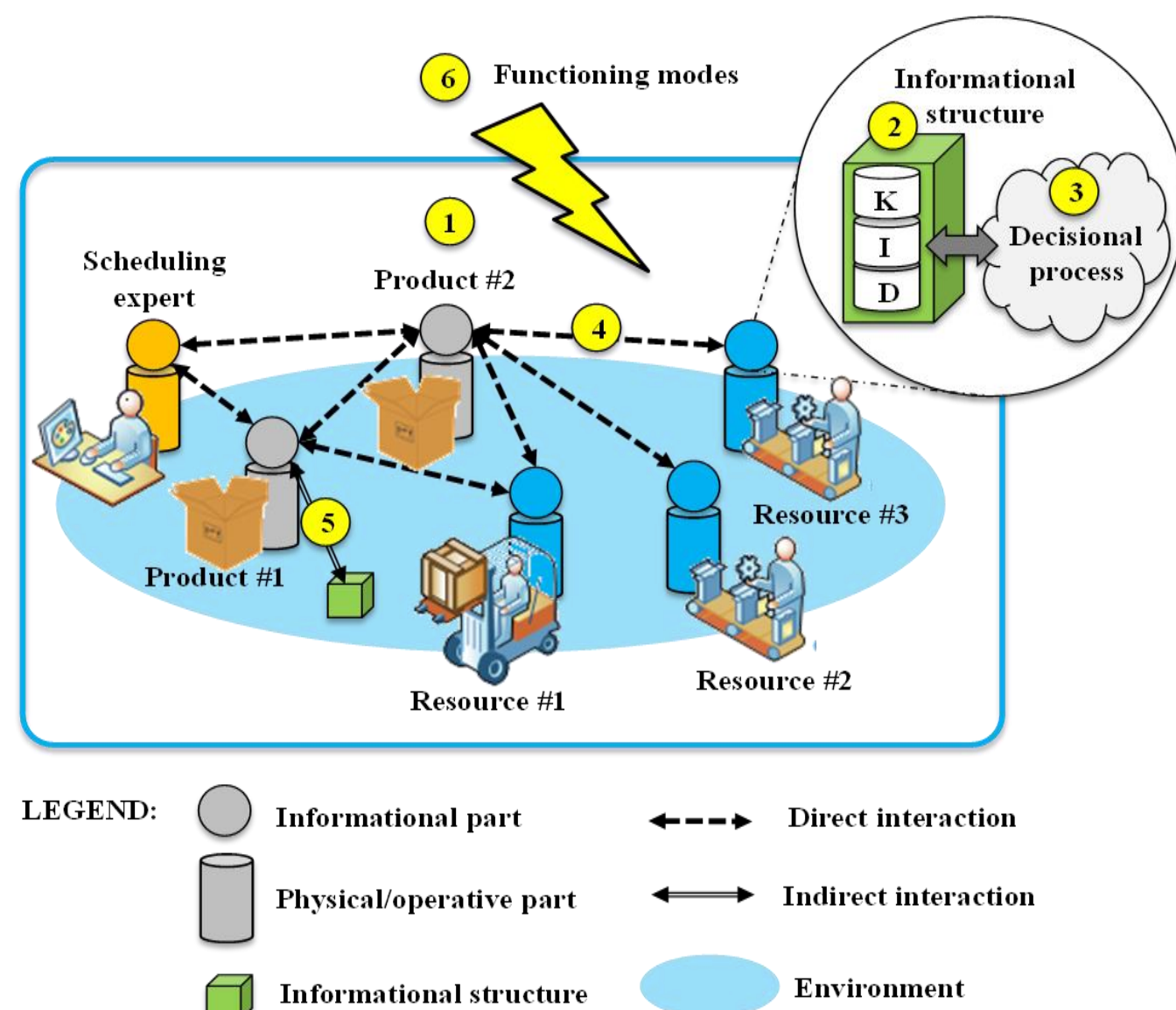


Figure 1. An illustration of cyber-physical system [12]

Main contribution

In this project, we highlight that distributed decision-making, augmented with white box artificial intelligence, more particularly explicit knowledge representation, captures, stores, uses/reuses, and contributes to confer operational resilience to CPMS. We demonstrate that biological immunity offers a design pattern to develop knowledge-based systems and knowledge management processes, which guarantee embedding operational resilience within CPMS control architectures. Main limitations with respect to the relevant literature, this research project brings answers to are shown in Figure 2.

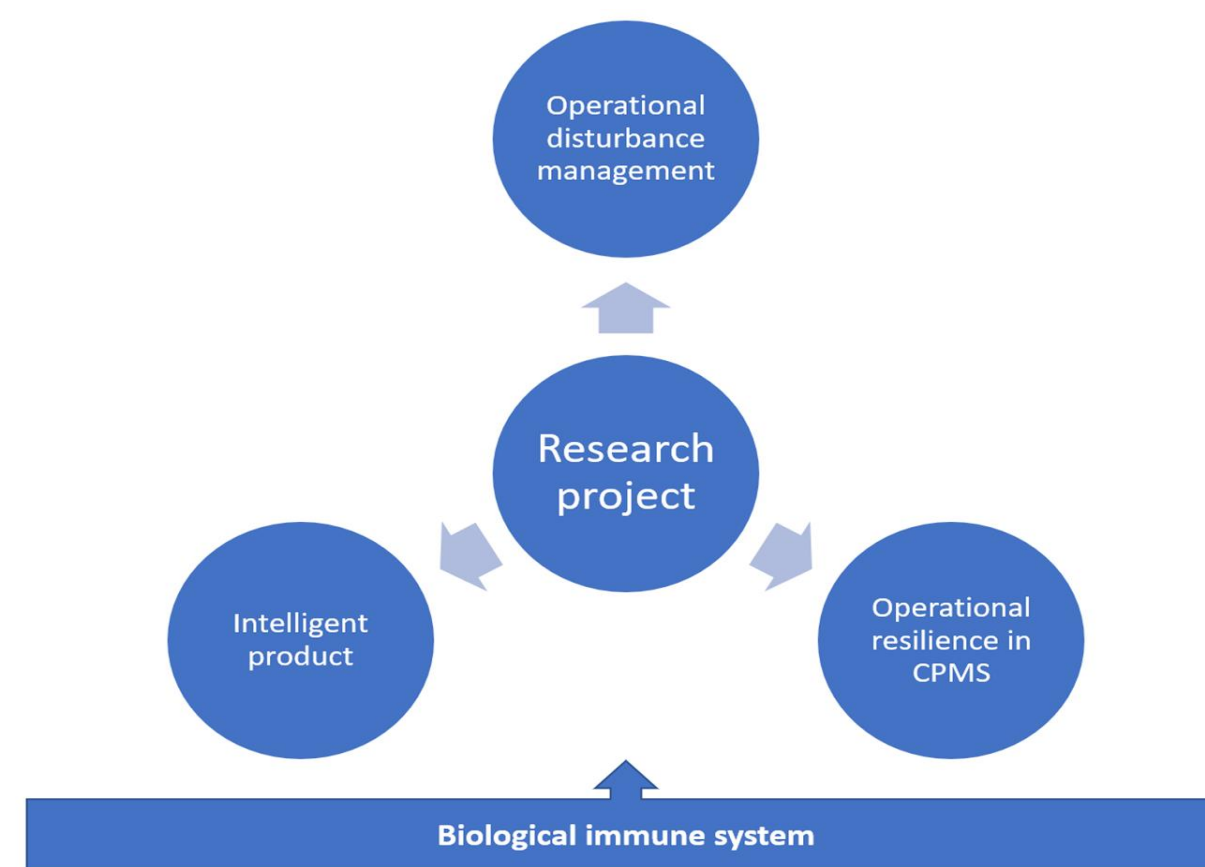


Figure 2. Position and contributions of the research project

Methods and materials

This work is based on a fundamental assumption, which consists in stipulating that the human Biological Immune System can guide the design of a knowledge-based distributed control architecture to enhance the resilience of operations management and production planning and control in cyber-physical manufacturing systems (Figure 3).

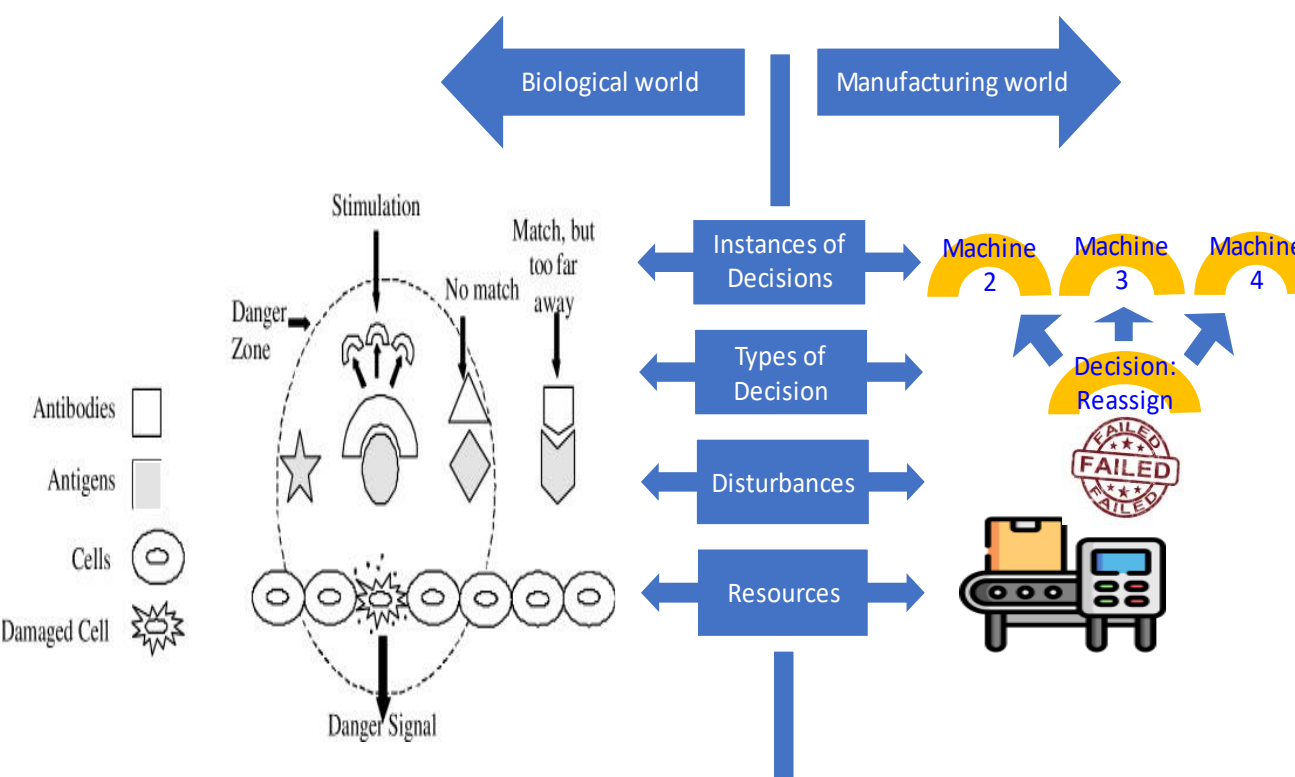


Figure 3. Analogies between the biological and manufacturing worlds

The assessment of this assumption is achieved through a knowledge-based decision-making and decentralization of decision mechanisms on intelligent products. The knowledge-based decision-making is achieved through the development of decision mechanisms, which are based on an innovative combination of Case Based Reasoning (CBR) with an Analytic Hierarchy Process (AHP) augmented with Expert Rules. These decision mechanisms are embedded within Intelligent Products in a decentralized way to enable them learn how to deal with disturbances and operational risks related to resource unavailability and unreliability. It is worth noting that, to the authors' best knowledge, CBR has not yet been implemented as a reaction-based mechanism embedded within Intelligent Products to cope with disturbances in a decentralized way. The suggested architecture is implemented and validated using an ANYLOGIC multi-agent system simulation of an industrial scale learning factory. The estimation of resilience indicators show competitive results and provide interesting research openings.

Simulation results

A series of simulations scenarios are generated to evaluate the operational resilience using an ANYLOGIC multi-agent system simulation of an industrial scale learning factory: S.mart platform of LAMIH, Valenciennes. For instance, Figure 4 provides radar charts for a set of scenarios. In each radar chart, 3 performance indicators are displayed for three reaction strategies: (1) the average throughput time of products; (2) the average production cost; (3) the average products throughput per hour. Results highlight that the augmented AHP outperforms as the product fully takes advantages of the system's flexibilities.

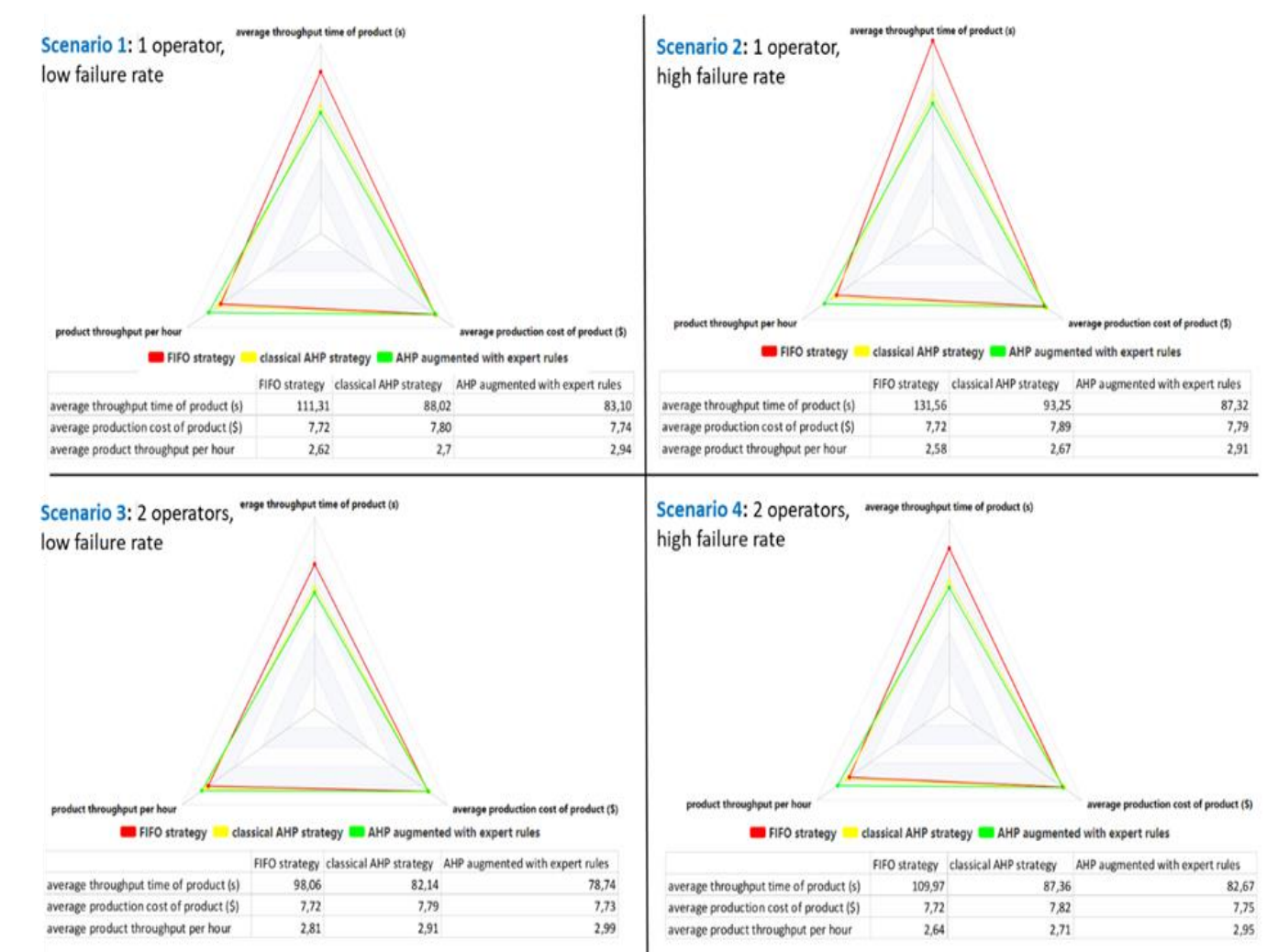


Figure 4. Results of simulations

Conclusion

The research project is based on Biological Immune System to guide the design of a knowledge-based distributed control architecture that enhances the resilience of operations management and production planning and control in CPMS. It suggests an immune inspired distributed product-driven control architecture to cope with operational disturbances using two novel decision mechanisms, which are an innovative combination of Case Based Reasoning (CBR) with an adaptive version of the Analytic Hierarchy Process (AHP) augmented Expert Rules. Methodological and numerical results are presented, and promising perspectives are highlighted.

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