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Letters

# Digital twin-based optimiser for self-organised collaborative cyber-physical production systems

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ABSTRACT

The advantages of using collaborative and distributed systems to control and optimise industrial environments have been explored in recent years. However, the self-organised and dynamic approaches that deliver these same advantages bring challenges associated with the long-term unpredictability of these approaches. The proposed work aims to present a framework that integrates a Digital Twin-based Optimiser within these systems to predict the system's evolution and reconfigure it if required. Digital Twins can be an essential advantage in adopting these systems due to the possibility of carrying out simulations at an accelerated speed and reconfiguring the self-organised control system.

## 1. Introduction

Cyber-Physical Production Systems (CPPS) have been highly studied and proposed to deal with the need to develop highly adaptable distributed control systems capable of dealing with disturbances, such as unpredictable demands or malfunctions [1,2]. Most of these solutions are based on self-organised approaches capable of understanding the current situation and how to optimise the system [3,4]. A self-organised system is responsible for changing its behaviour without external interactions. Behaviour change is achieved through emergent behaviours that result from the interactions between the entities that make up the system [5]. Self-organisation has been widely explored in the design of autonomous computing systems [6]. To achieve this autonomy, these systems are often inspired by behaviours found in nature, like bee or ant colonies. In these environments, the entire colony's behaviour results from the interactions between the animals without an entity responsible for coordinating the activities. Hence, the self-organised distributed control systems are commonly implemented using bio-inspired algorithms [7]. This allows more robust and adaptive solutions collaboratively optimising the system without predefined scheduling and tasks allocation, allowing its constant optimisation locally that will bring the optimisation as an entire complex ecosystem [8,9].

In [8], an architecture focused on controlling transporters using the firefly algorithm to identify the best path between two stations is presented. In [9], a solution is proposed to optimise the utilisation of stations. Also, using a self-organised approach, [3] presents a distributed architecture capable of optimising the use of stations and transporters while handling the connection of stations. Although the advantages of these approaches are known, the nature of the entities creates a myopia problem. It is difficult to predict how the system will evolve. This feature is identified as a barrier to adopting these approaches [10]. Both due to forecasting and difficulty of optimise in short and long term.

Hence, Digital Twins (DT) can help to understand their behaviour, even during execution [11,12]. DT focus on modelling the characteristics, behaviours and performance of the physical systems. It is possible to have in real-time cyber high-fidelity representation of the characteristics of the physical world [13]. This virtual model allows the utilisation of simulation to understand the system's evolution. The simulation of different possible configurations enables the CPPS to understand which of the simulated environments will optimise the system in short and long term. The proposed research aims to present an approach com-

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bining the design of self-organised distributed control systems with DT.

## 2. Digital twin based framework for distributed cyber-physical production systems

To integrate a DT based Optimiser capable of receiving the current state of the CPPS and assessing various optimisation possibilities, the framework presented in Fig. 1 is proposed.

The first layer consists of the hardware, and the other three layers represent abstraction layers, where the lower layer provides information to the upper one, and this one responds with generated knowledge.

### 2.1. Collaborative distributed cyber-physical production system

The self-organised distributed control system constitutes this layer. The CPPS comprises entities, like stations or transporters, which, through interactions between them and local control, will create the collaborative dynamics of the system. It is responsible for abstracting the resources on the shop floor, their capacities and the products that will request the execution throughout the process. These systems have a modular nature and are highly dynamic, using self-organising algorithms. Due to the abstraction that makes the shop floor, this layer can make the current state available to the upper layer.

### 2.2. Scenario’s generator and evaluator

This layer aims to generate several possible scenarios that are possible solutions for the system and will evaluate them. The various scenarios are based on the generation of random parameters that are used by cyber-physical entities within the self-organisation algorithm. For example, in some cases, constants are specified that are used to change entities’ reactivity to change. One of the possibilities is to associate different values of this constant to each of the entities. Making small adjustments to parameters makes it possible to change how the system deals with the current state and evolves. As input parameters, the generator and scenario evaluator also receive the production plan and the Key Performance Indicators (KPIs) to be verified in the evaluation.

### 2.3. Simulation engine

For evaluating each scenario, it is then necessary to create a simulation model that executes each of them in a simulated environment. The results are sent to the lower layer to make the ranking of the scenarios and choose the one that best serves the system through the KPIs specified as applicable and priority.

It is then possible to say that the simulation-based DT optimiser is composed of the top two layers. Possible scenarios are generated in the first layer, and these scenarios are then simulated in the top layer and then evaluated again in the scenario generation layer. An overview of the framework’s execution is presented in Fig. 2.

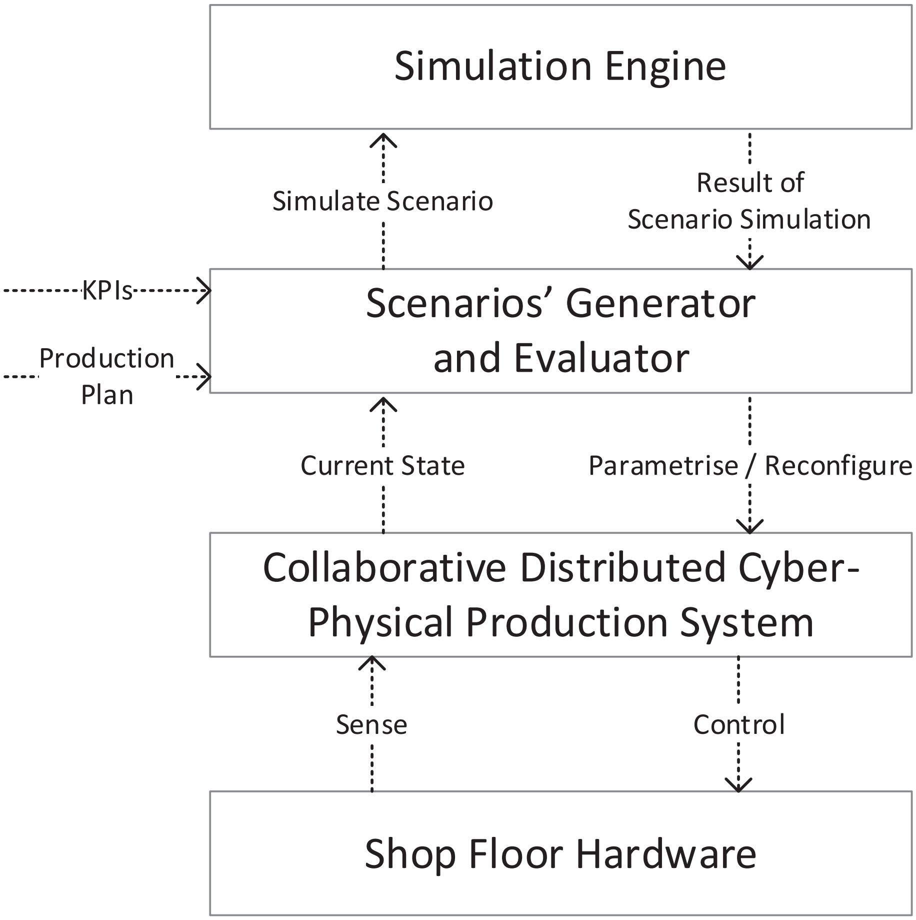

**Fig. 1.** Digital Twin-based framework overview.

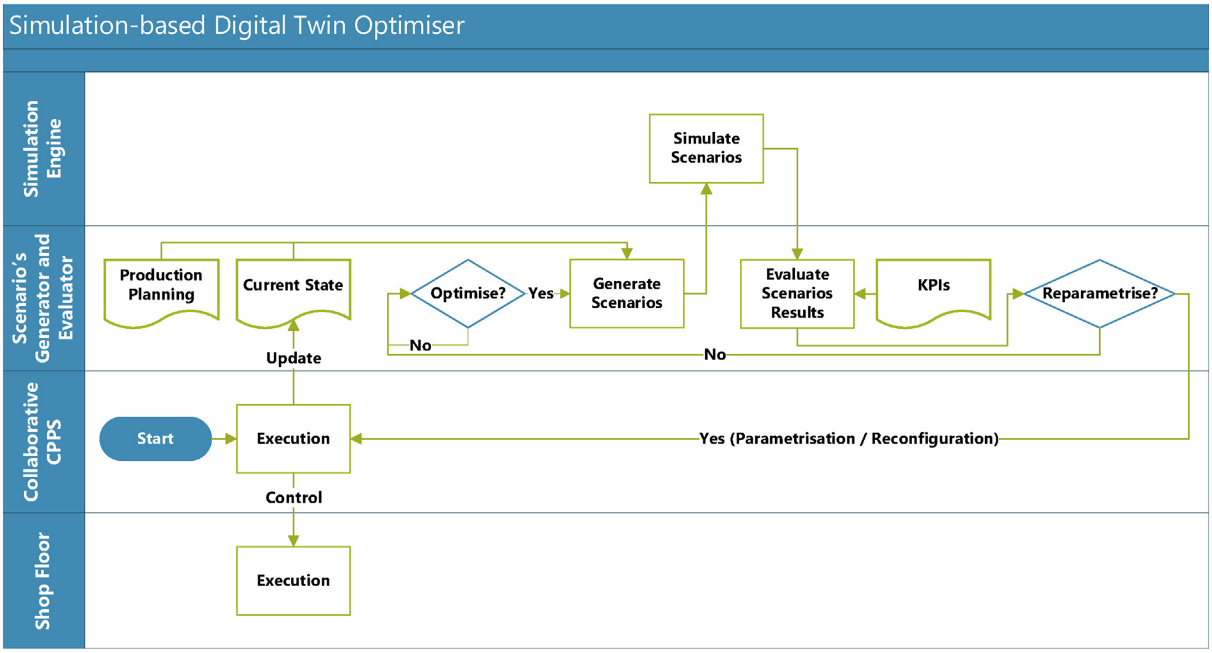

**Fig. 2.** Digital Twin based framework execution.

## 3. Application scenario

In Fig. 3 is presented an application scenario of the proposed framework. The CPPS used as the basis for the work was designed in [4], where each conveyor is abstracted by a Transport Entity Agent (TEA) and each production resource by a Resource Agent (RA).

This work presents a collaborative and self-organised system controlled by agents that dynamically control products' flow along a network of conveyor belts. This system is optimised using an algorithm that calculates the cost of carrying the product from the point where it is to the destination using the sum of the cost of crossing each conveyor, divided by the number of conveyors crossed. The cost of crossing each conveyor is given by the division between the conveyor's capacity and the conveyor's speed. The cost of crossing each conveyor is not constantly updated. An equation is used to identify the cost's variation. If that variation is above a maximum or below a minimum threshold, then the cost is recalculated. The definition of these thresholds will define the level of reactivity.

Three databases are necessary, where the KPIs, the production plan and the current state of the system are stored. For the presented case, two possible KPIs to evaluate performance are Cycle Time [18] and Throughput [19]. Regarding the production plan, this should contain the following products to enter the line and the process of each one of them. Finally, the system status has the products travelling on each conveyor and the order in which they are on the conveyor as well as the available stations and if they are operating. This information will allow the optimiser to start the simulation with the current state of the physical system. Every time the optimisation is triggered, the optimiser queries the current state and the desired production plan. With this information, the optimiser should generate possible parameterisation scenarios for the CPPS (in this case, the possible scenarios are described as different maximum and minimum threshold values for each conveyor). Then each of these scenarios is simulated, using a simulation model that mimics the execution of the real system but with the new parameterisation. For the generation of scenario, a solution based on Artificial Immune Systems (AIS) is proposed. These algorithms are widely known for their ability to be used in systems optimisation, as presented in [14–16]. In the literature, it is possible to find several AIS algorithms, like Negative Selection, Clonal selection or Network Model [17]. These algorithms aim to mimic the functioning of human body's immune system. In [17], a performance study of these algorithms is performed. Considering that the optimiser must run in parallel with the system execution, it is convenient to choose the algorithm with the best performance in generating possible solutions. The algorithm that obtained the best result was the Network Model. This algorithm assumes that the immune system maintains a network of B cells connected to facilitate the detection of the antigen. The connection between two cells is proportional to their affinity. Each of these B cells generated by the AIS algorithm is simulated to verify the execution of each scenario at a higher speed. Subsequently, the optimiser evaluates each of the simulations, checking the values of Throughput and Cycle Time. Hence, the optimiser will rank the scenarios according to the selected KPI. The parameters used for each conveyor (maximum and minimum threshold) during the simulation are then pushed to the CPPS to reparametrise each conveyor.

## 4. Conclusion

The application of DTs to create time machines to predict the execution of devices and systems in industrial environments has been explored [12]. In the case of self-organised control systems, it can make an important contribution due to their nature. The authors believe that the proposed framework may increase the use of these systems capable of dealing with disturbances since the proposed approach allows to adapt the system to comply to specified KPIs and production desire.

It is crucial to specify design principles that guide implementing this type of systems. Subsequently, those design principles must be used to design and implement multiple scenarios in the laboratory and industrial environment to assess their performance.

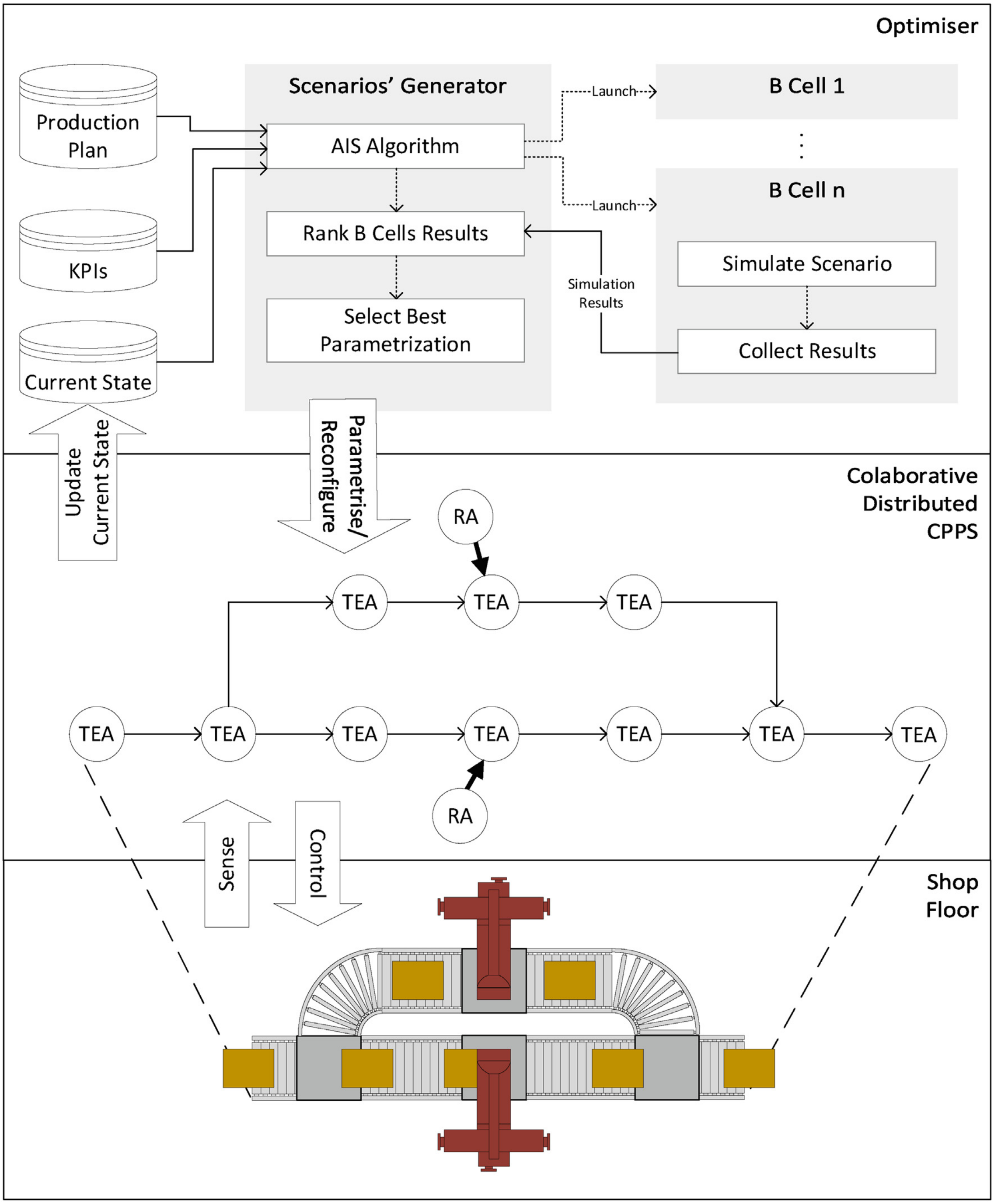

**Fig. 3.** Application scenario.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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