Design of a Worldwide Simulation System for Distributed Cyber-Physical Production Networks

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***Abstract*— Modern production infrastructures of globally operating companies usually consist of multiple distributed production sites. While the organization of individual sites consisting of Industry 4.0 components itself is demanding, new questions regarding the organization and allocation of resources emerge considering the total production network. In an attempt to face the challenge of efficient distribution and processing both within and across sites, we aim to provide a hybrid simulation approach as a first step towards optimization. Using hybrid simulation allows us to include real and simulated concepts and thereby benchmark different approaches with reasonable effort. A simulation concept is conceptualized and demonstrated qualitatively using a global multi-site example.**

Keywords*— *production networks, geographical distribution, task realization strategies, Industry 4.0, simulation, evaluation

I. Introduction

Globally distributed production processes involving multiple sites in different countries are common when it involves manufacturing complex products. The need for different resources during production processes and their varying availability across the world has driven the efficient distribution of production sites around the globe. Since production processes require the combination of several kinds of resources, whereas the absence of a single resource could interrupt production progress, resource availability is a key issue in location selection. Here, required resource categories include technology, raw materials as well as personnel. The need for technology is increasingly important in production processes, especially for digital products and for the sake of process efficiency. The need for raw materials of different kinds is inherently important in production as this can be understood as the combination and processing of those. Personnel is required to run the production processes. Closely related thereto is the resource of knowledge which is increasingly important especially for technology-driven production processes.

The emergence of globally distributed production process can be seen across various industries. Due to the prevailing importance, the efficient organization of production networks remains important. The domain of production organization and recently *Industry 4.0* considered aspects that are of importance for the single production site. Aiming at efficient processes within one site, research in this domain focused on aspects for utilizing existing infrastructures to the best possible extent as well as conceptualizing production layouts to do so. Even though many valuable inputs were generated, results achieved primarily focus on single production sites. Research in the domain of *Supply Chain Management (SCM)* considered the organization of different parties involved in the process of producing goods. In this context, aspects that include geographically distributed networks were considered with related questions such as logistics. However, results in this area predominately focused on aspects related to the management and integration of external parties to match the needs of the company's production. In contrast to Industry 4.0 focusing on a single site, SCM considers the total supply chain whereby a focus is set on the integration and coordination of multiple external parties.

Even though insights have been gained by former research, the question how to efficiently distribute and organize globally distributed production sites under control of a single firm in order to achieve production targets remains unexplored. Established concepts of Industry 4.0 and distribution within production sites as well as SCM provide valuable input, they are not suited to deduct guidance for organizing globally distributed production sites. Furthermore, both domains consider structural aspects which are relevant in the design. But those are not sufficient when it comes to dynamic aspects, such as the efficient utilization of existing infrastructures in the case of environmental changes. Given the highly complex and distributed structure of company production networks, this paper aims to contribute to the question of how the advantages of planning and controlling multiple geographically distributed production sites can be realized for production networks. Especially huge companies maintain multiple production sites by their own. We thereby aim to provide a foundation in the form of a simulation model to answer the following research questions:

1. How can a worldwide production network be designed to realize Industry 4.0 advantages on a global level?
2. How can production orders be distributed efficiently among sites?

While the first research question aims to provide insights on how to coordinate a worldwide production network from an

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organizational perspective, the second question aims to provide guidance on distributing production steps within the organizational structure given by question one. The research paper overall aims to consider the dynamic nature and the short-term changes that occur in the domain of production processes and related requirements.

Since the design and implementation costs for research purposes are costly, we aim to approach the research questions by using a hybrid simulation approach combining physical and simulated Industry 4.0 components.

Following Peffers et al. [9], this paper is structured as follows: The second section provides a theoretical foundation and identifies the research gap. The third section designs a concept for worldwide Industry 4.0 production network. Then, the concept is demonstrated and evaluated. The sixth section concludes in how far research questions have been answered. An outlook draws attention to promising future research about worldwide Industry 4.0 production networks.

II. Theoretical Foundation

We use the concept of hybrid simulation to approach the research questions. In the following essential components of the hybrid simulation approach and related characteristics are explained.

A. *Industry 4.0 Production Components*

In accordance to Gronau et al, modern production systems considering Industry 4.0 concepts consist of a collection of CPS, the so called Cyber-Physical Systems [3]. As Fig. 1 shows, these provide four components in order to perceive and interact autonomously with their individual environment.

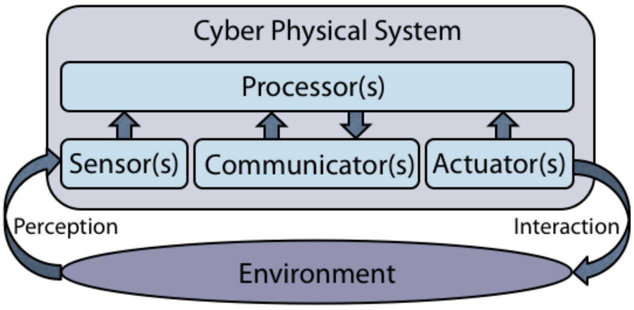

Fig. 1. Schematic structure of cyber-physical systems.

While at least one *sensor* perceives the system's environment and gathers information, which are adequate for the derivation of decisions. This information is augmented on behalf of further information arriving via different communication channels, each considered as *communicator*. For the derivation of decisions different strategies can be carried out. Examples can be found in the use of simple rules, decision heuristics, artificial neuronal networks, etc. On behalf of the actuators, decisions are then made by the system itself in order to manipulate the corresponding environment. Further, the CPS can modify its environment by communicating and interacting with its environment. This enriches the information of other CPSs.

B. *RACI Components*

Building on Lass' concept for hybrid simulations environments, called RACI, the concept presented considers RACI-components as they are visualized in Fig. 2. [7].

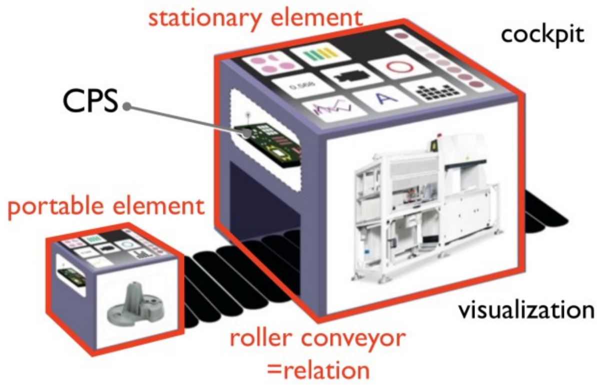

Fig. 2. RACI components.

A differentiation is made between stationary and mobile components in the factory setup. The following two kinds of the RACI-components are stationary and have fix positions within the production environment.

1. **Machines**: ...represent CPS, which produce products. Each machine is surrounded by displays simulating and visualizing its current production state (e.g. a video about a polishing production task). An interactive display on the top serves as cockpit for human workers. In addition to simulated machines, real machines (e.g. robots) are integrated.
2. **Conveyors**: ...represent CPS, which transport products from machine to machine.

Two further kinds of the RACI-components are portable and therefore have variable positions within the production environment.

3. **Workpieces**: ...represent products, which are produced by machines and transported by conveyors. Each workpiece is surrounded by displays visualizing its current production state (e.g. a picture about a product having currently 3 out of 5 parts).
4. **Humans**: ...represent human workers, which are part of the production process. Each human is equipped by further systems such as smartphones that create a digital twin and so integrate humans as CPS.

Altogether, four different kinds of RACI-components are considered as CPS as they fulfill the requirements, which either can be used as hardware components or simulated on base of scripted components.

C. *Research Gap*

Different aspects of distributed production controlling and monitoring were discussed in previous literature. Even though many aspects have been considered, there integration in one holistic concept is missing. In the following, related work is classified according to the different dimensions to highlight the research gap.

The criterion *Industry 4.0 infrastructure* refers to the consideration of CPS-based infrastructures where the system components match the requirements of a CPS. The criterion *CPS autonomy* is fulfilled if single CPS-based entities of the production system are able to take decisions autonomously which is important for decentralized decisions. *Symbiotic planning* refers to the integration of other planning systems (e.g. enterprise resource planning systems) in the planning process.

TABLE I. CATEGORIZATION OF RELATED WORK.

Contributions	Industry 4.0 infrastructure	CPS autonomy	Symbiotic planning	Hybrid simulation	Dynamic simulations	Multiple production sites	Geographical distribution
Lima et al. (2016)	-	-	*X*	-	-	*X*	*(X)*
Colombo et al. (2004)	*X*	-	-	-	*X*	*X*	-
Timpe and Kallrath (2000)	-	-	*(X)*	-	-	*X*	*X*
Trentesaux (1998)	*X*	*(X)*	-	-	*X*	*X*	-
Tjahjono and Jang (2015)	-	-	*X*	-	*X*	-	*X*
Lass (2017)	*X*	*X*	-	*X*	-	-	-
Grum et al. (2018)	*X*	*X*	-	-	*X*	*(X)*	*(X)*

X – considered, (X) – partly considered

The term *hybrid simulation* refers to the combined consideration of entities that are of real physical and virtual nature. This allows, for example, for the use of human machine interactions or the combination of simulated elements with real physical production machines. The aspect of *dynamic simulation* refers to the adoption of changed environmental states during production execution. The adoption of the current situation is important due to the complex nature of production and the many interruptions or changes that can occur (e.g. machine breakdown). The aspect of *multiple production sites* refers to the consideration of different production sites that are organized individually. In addition to that, the *geographical distribution* refers to the spread of the sites over wider areas. This is important since different aspects with regard to the exchange of physical products are to be considered that influence planning and control mechanisms. The results of the classification are presented in Table 1.

While different contributions considered some of the aspects individually, none of them considered the aspects in combination. Even though the input of former research is valuable, the combination of the aspects is a new field of research, which possesses own research questions and targets, to be explored. This paper aims to consider the different aspects related to the efficient utilization of geographically distributed network of Industry 4.0 production sites, while incorporating physical as well as simulated elements in a hybrid approach. The simulation design is conceptualized as a first step to explore how an efficient distribution of resources can be achieved.

III. RACI AS WORLDWIDE INDUSTRY 4.0 PRODUCTION NETWORK

This section provides a concept for worldwide production networks considering Industry 4.0 concepts. According to Peffers [9], requirements are defined before a solution for a certain research problem is designed. Then, a concept for production environments is drawn, before task realization strategies are discussed. The evaluation of corresponding simulation runs is conceptualized in a last subsection. Altogether, a design is presented, which specifies a RACI standard for production sites.

A. Requirements

The worldwide production network needs to fulfill the following requirements:

1. **One company**: The network considers the perspective of one company. So, the realization of production tasks can be characterized as internal or external.
2. **Minimum # of production sites**: the network consists of at least two production sites, so that geographically optimized production setups can be simulated.
3. **Minimum # of processing units**: each production site consists of at least four processing units, so that a simple transfer of the workpiece (1st CPS) from machine (2nd CPS) to machine (3rd CPS) via conveyor (4th CPS) can be realized.
4. **Real and simulated units**: each production site consists of at least four real CPS, so that a simple transfer of the workpiece from machine to machine via conveyor can be realized and human interactions are enabled. Further units can be simulated.
5. **Task types**: production orders need at least two kinds of tasks, so that the choice of production routes can be evaluated.
6. **Hardware characteristics**: must match task types, the production sites provide at least two different kinds of CPS components, so that different kinds of task type realizations can be evaluated.
7. **Redundant capabilities**: at least two processing units of the production network need to provide redundant capabilities so that alternative production units can be identified and different process flows can be compared (including transportation).
8. **Transportation routes**: the production network provides at least one transport route so that two sites can be integrated. Furthermore, none of the sites considered is in isolation (not connected to other sites).
9. **Human machine interactions**: each production site needs to provide at least one human work place, so that human machine interactions can be conducted.
10. **Simulation Engine**: each production site needs to provide an individual simulation component, so that site-specific task realizations can be conducted and integrated by a worldwide simulation clock.

The interplay of requirements presented allows for the realistic simulation of worldwide production networks and is essential for a coherent result analysis.

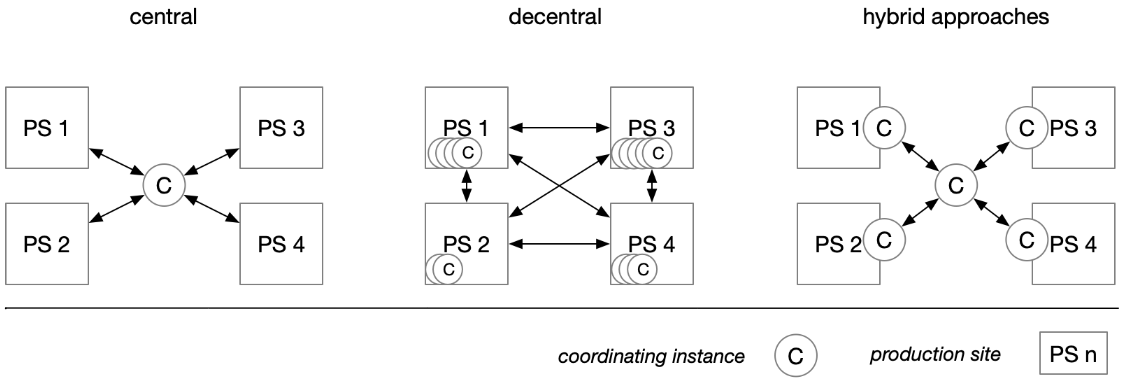

Fig. 3. Organization principles for production networks

B. Distribution and Processing Strategies

As a foundation for optimizing a given production network, organizational principles need to be set in order to design the approaches and mechanisms accordingly. The organization of worldwide production scenarios allows the application of different organizational principles. To demonstrate potential organization approaches, Fig. 3 shows three scenarios having four production sites. A production site refers to a business location in that production steps are conducted. In addition to the sites, coordination instances are mechanisms to control production with regard to the aspired targets. In the *central* approach, one central coordination unit controls all machines in all sites. Each CPS in every production site receives tasks from the central unit as well as sends information to the central coordination unit. In the *decentral* approach, no overarching coordinating instance is involved since all CPS are directly interacting with each other within and across production sites. The combination of both approaches – *the hybrid approach* – is a multilayer concept following the divide and conquer idea. CPS are aggregated in different groups, i.e. production sites and each is controlled by a single coordination instance. On the next level, the coordination of the coordination instances (sites) is realized by a central coordination instance.

Following [6], a task realization consists of two steps that are task distribution and task processing. While the first focuses on the transfer of tasks among task processing units, such as production systems realizing production tasks or analytic systems for analytical tasks, the latter focuses on the sequence of tasks being processed at each processing unit [6]. The *distribution of tasks* can be organized using the organizational principles described above. While different approaches have their advantages and disadvantages, using the possibilities of connected Industry 4.0 infrastructures allows all the approaches to be realized. Exemplarily, the heuristic approach of [1] can be used to decide for task distribution within networked infrastructures.

With regard to the *task processing*, different approaches emerged in production literature. Simplistic approaches such as first-in-first-out approaches assure task processing in the order tasks arrived at the operating unit. Priority-based approaches ensure task processing according to the priorities given. Further, the "time" aspect, when the product is needed, can be used for prioritization.

For efficient utilization of a given production network, an approach should combine distribution and task prioritization to their full extent. Even though the principles for realization could be generic, their adoption and configuration to the individual needs and targets is important.

C. Production Environment

According to the concept of Grum et al., the task realization of production orders is realized on behalf of three levels [6]: the CPS level, a local level and a public level. These are visualized in Fig. n and explained thereafter.

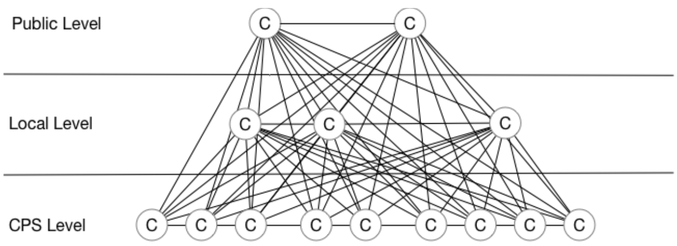

Fig. 4. Production infrastructures.

The *CPS level* refers to the shop floor level and is at the very bottom. Following Gronau et al., components are variations of CPS, vary in hardware characteristics and take part at value creating production processes [3].

The *local level* is situated above the CPS level. Here more powerful CPS can be found, which can realize production orders faster, but tend to be more cost-intensive. Typically, these components are part of the enterprise infrastructure.

The *public level* is the top architectural level, which brings production tasks beyond internal production sites. Since systems at this level can obtain the most powerful but costy processing units, they are the first choice for ad hoc tasks, high workloads or sudden changes in availability.

Within this hierarchical production network, four different allocation options exist, which are visualized in Table 2 and explained thereafter:

TABLE II. ALLOCATION OPTIONS

Option / Level	Vertical-upward	Vertical-downwards	Horizontal	Local
CPS level	*X*	-	*X*	*X*
Local level	*X*	*X*	*X*	*X*
Public level	-	*X*	*(X)*	*X*

Firstly, production tasks are realized *locally* for each level, i.e. at which level they occur. This includes e.g. a mapping of planning systems.

Secondly, tasks are escalated vertically, which either considers an *upward escalation* or a *downward escalation.*

While the first refers to a transfer of jobs to higher and probably more efficient units (exceptional is the top unit), the latter refers to transfers of jobs to lower levels, which cannot be applied at the very bottom layer.

Thirdly, tasks are realized on neighboring systems (horizontal). This means, that system on the CPS-level can send their production tasks to neighboring CPS, local sites consider neighboring local sites, and public send task to public sites as well.

D. Global Evaluation

In order to assess the improvement achieved by coordinating different production sites in the networks as well as to compare different strategies with regard to their performance, an evaluation measure is needed. In accordance to Grum et al., task realization strategies are to be evaluated from a system-specific perspective as well as a global, system-wide viewpoint [4]. For a worldwide production network, therefore, a common objective function needs to address the following aspects each illustrated by an example:

- **Task-specific criteria**: task importance, remaining time per task, required capabilities, etc.
- **System-specific criteria**: cost per CPS, production capacity, production duration, etc.
- **Distribution-specific criteria**: transfer costs, taxes, time needed for transfers, geographic specific staff costs, etc.
- **Scenario-specific criteria**: CPS workload over time, number of realized jobs, etc.
- **Global criteria**: accumulated costs per production site, average number of waiting tasks, average waiting time, etc.

Based on a common objective function using the above mentioned criteria, different task realization strategies can be compared as benchmark in simulation runs and best strategies can be derived.

IV. Demonstration

This section exemplarily demonstrates the designed system and demonstrates its suitability as solution for the research problem presented.

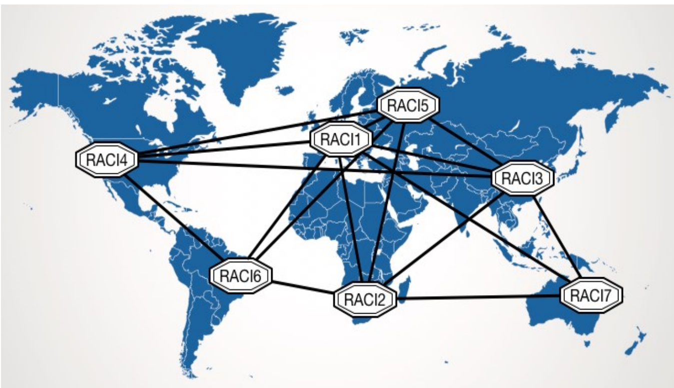

Fig. 5. Exemplary WW production network.

As Fig. 5 shows, the worldwide production network considers the interplay of seven production sites following the RACI standard. Transportation connections between two sites are visualized by black relations. Numbers of RACI conform production sites are considered in regard to the planned system roll-outs. As required, even more than two sites have been connected in the long run. A first version of a worldwide production network is achieved when at least a second production site is integrated. For the sake of simplicity, we will initially focus on this simple version. The following system includes production sites in Germany and South Africa matching the hybrid simulation standard. Although a fully meshed transportation network would be plausible reference, limitations have been considered exemplary. This first version is visualized in Fig. 6.

Here one can see the current German version realizing a hybrid simulation environment consisting of Industry 4.0 elements. Detailed descriptions can be found at Grum and Gronau [5] as well as Lass [7]. Since the second production site is not realized yet, the view of the South African production network is schematic and a description follows: A conveyor is realized on behalf of *CPS2*. It connects the two machines *CPS1* and *CPS3*. Further, it transports the workpiece *CPS4* between these two machines, so that a human worker *H1* can be part of interactive production steps.

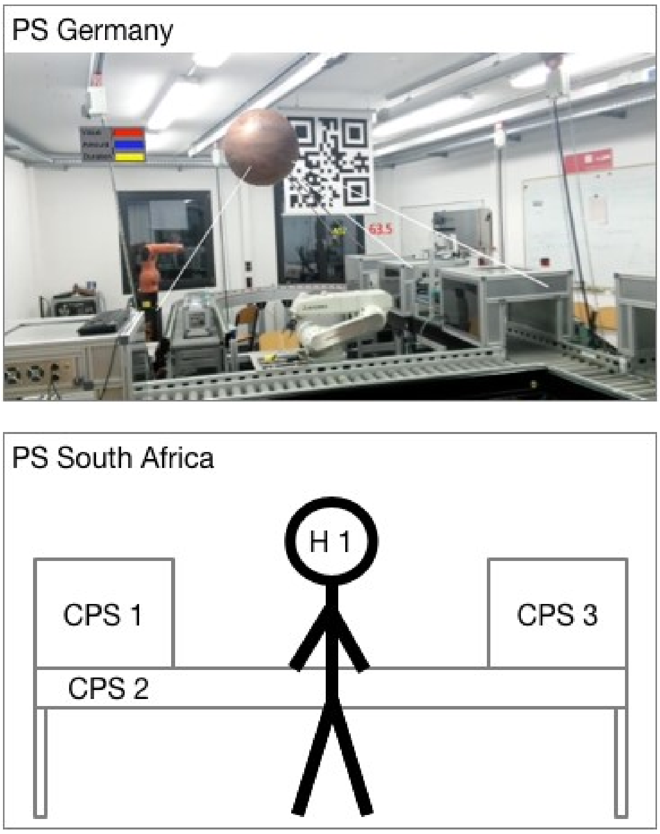

Fig. 6. Local sites of Germany and South Africa.

Since many further production components can be considered by scripted components, greater production environments can be simulated in South Africa. Based on the possibility of using machines and workpieces to visualize any production component, a great collection of different production scenarios can be simulated. Therefore, the following focuses on the production of artificial knees [7] at the *PS Germany*. At the *PS South Africa* the same setup is replicated, but only a *grinding machine* (CPS1) and a *laser robot* (CPS3) are considered by the hardware. All other machines, conveyors, work pieces and workers are scripted components.

V. Evaluation

In accordance to Peffers, this section evaluates how far the requirements stated have been fulfilled by the demonstration presented. For this, requirements are considered by its number.

The first requirement can be satisfied, as long as the production scenario either considers the *PS Germany* and the *PS South Africa* to be part of one company or one of the sites is considered as external company on the public level which is controlled by the same company.

The second and third requirement can be satisfied since the two production sites provide more than two processing units each. While the *PS Germany* consists of more than 60 units, the *PS South Africa* consists of five real units, which refer to four CPS and one human worker, the fourth requirement is satisfied. Since human machine interactions can be realized using the real components only, the ninth requirement can be satisfied, too. Further, the eigth requirement can be met because both production sites are accessible via a transportation route.

The fifth requirement is satisfied since different versions of artificial knees are produced in the scenario presented. While some demand for polishing, and packaging, other require for individual laser manipulations [5] and collection by customer. Each is considered a separate task type.

The sixth requirement is satisfied, as the artificial knee production scenario contains CPS having different capabilities e.g. some CPS provide actuators in the shape of arms (robots), others provide actuators in the form of conveyor roles. Since the entire artificial knee production of the German production site is replicated, each production component provided by the scenario is redundant and accessible for the other production site as alternative component.

As a worldwide hybrid, symbiotic simulation builds on the simulation of two production sites, production site-specific simulations can be carried out by separate simulation components. So, human-based interactions can be considered aside scripted workers easily, and the tenth requirement is satisfied conceptually.

VI. Conclusion

Modern production infrastructures of globally acting companies involve distributed production sites across the world. Optimizing given infrastructures among the globe challenges traditional planning approaches. In the context of Industry 4.0 environments, organizing production is still a major question in research. However, organizing total production networks consisting of Industry 4.0 infrastructures proposes new challenges for companies which are not reflected by research so far. Having focused on the first research question (How can a worldwide production network be designed to realize Industry 4.0 advantages on a global level?), we provided an abstract design for self-optimizing, globally distributed Industry 4.0 production infrastructures and its examination by proposing a hybrid simulation model concept. Using hybrid simulation allows to include real and simulated concepts and thereby benchmark different approaches with reasonable effort. The simulation model is designed using existing concepts of Industry 4.0 infrastructures.

Besides the design, the second research question (How can production orders be distributed efficiently among sites?) has been focused and a concept for the autonomous CPS-specific organization has been proposed: Our concept is a first approach to demonstrate important issues in dynamically managing globally distributed production networks. Major limitations include the use of a single simulation concept for Industry 4.0 infrastructures. Even though being flexible, specific needs of individual industries and resulting complexity might not be covered yet. With regard to the demonstration, our concept is yet to be realized and validated using real execution data. Furthermore, the suitability of the different optimization criteria is yet to be validated in a real example.

Even though the hybrid simulation is in a conceptual state currently, it can serve as a first attempt to address the efficient organization of global production networks. Results are limited with regard to their practical validity. Therefore, consecutive research needs to address the following: First, concepts have to be realized in a practical environment. Second, simulation runs have to be carried out and should be benchmarked. Third, their superiority with regard to existing approaches needs to be assessed. Fourth, the production network should be grown so that more production sites can be considered. While this increases the complexity of the network, this raises the execution flexibility as well. Taken together, even though still being a theoretical concept, valuable input for practical realization is given. Concerning the setup for further simulation environments, first steps are taken.

Acknowledgements

The work of Prof. Attahiru Alfa is supported by the SARChI Chair Program of the NRF.

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