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ScienceDirect

Procedia CIRP 118 (2023) 264–269

www.elsevier.com/locate/procedia

16th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '22, Italy

Development of a system for building a cloud-based digital twin as an informational assistance system for context-based dynamic configuration of cyber-physical hybrid production systems

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Abstract

Due to constantly changing conditions, demand, and technologies, companies increasingly seek flexibility. Productivity results from automation, improved working conditions and the focus of people in production in interaction with machines. Unfortunately, the human factor is often not considered to increase flexibility and productivity with new concepts. This work aims to develop a hybrid assistance system that allows a dynamic configuration of cyber-physical production systems considering the current order situation and available resources utilizing simulation. The system also considers human factors in addition to economic factors, which contributes to the extended economic appraisal.

Keywords: Reconfigurable production system; Cyber-physical production system; Simulation-based production; Human-centric production; Digital twin; Human factor in CPPS

1. Introduction

Technological advancements have spurred new approaches to production systems due to the paradigm shift toward flexible and decentralized solutions [1]. The initial stage in creating new production systems based on a cyber-physical production system (CPPS) and IoT technologies focused on basic design and functionality [2]. Due to changes in internal system conditions and changing external environmental conditions, e.g., the need for customization and changes in demand, production systems need to adapt fast and must be able to demonstrate a much higher degree of flexibility [3,4]. New concepts for production systems and technologies result in better solutions for higher flexibility in companies. Reconfigurable hybrid production systems with changing assembly form, which also takes the human factor into account, are much more robust against changing environment included [5].

The need for an assistance system in production becomes apparent when configuring an optimal production system. A calculated optimum through a simulation can be challenging to define beforehand due to the different and constantly changing parameters. The goal is to weigh and compare the parameters. The solution is a decision that only a human can make and not a system alone. A CPPS can be difficult to predict and describe because of the complexity of the processes. A human-oriented solution is previously calculated configurations through a simulation, which has a certain number of degrees of freedom to make a decision. A simulation-based study as a model can describe the behavior of a CPPS. To address a more human-oriented solution the developed assistance system provides previously calculated configurations through a simulation with suggested scenarios, which has a certain number of degrees of freedom to decide on [6].

10.1016/j.procir.2023.06.046

The use of a digital twin leads to a transfer of real production processes into the virtual world. Adding the simulation for describing the behavior of the production system leads to the desired adaptability by simulating different layout forms of the production system in the future [7].

Current solutions that address the lack of human involvement in the production environment do not lead to simulation-based configurable systems and simulation-based reconfigurable production systems' lack of human involvement in the production environment. Using the design science research methodology (in Section 3), a simulation-based system for context-based dynamic configuration of cyber-physical production systems was developed, which considers human-centric and non-monetary criteria in addition to the classical monetary-assessable criteria.

2. Literature Review

2.1. Literature Review Research/Approach

In this work, literature on suitable topics was consulted and analyzed. Among others, on topics such as adaptable/flexible factory and production, digital twins, simulation-based production planning and the human factor in the production environment. Over categorized on topics of the transformable factory and the human factor in production.

Since the term "digital twin" has many implications in the literature, both English and German literature were used for definition. A semi-structured literature search was conducted on the following terms: CPPS, hybrid CPPS, the human factor in the production environment, digital twin and shadow, and simulation-based production planning. Various sources were consulted, such as the Wiso-net database, the Eddi portal, and platforms such as ScienceDirect and Google Scholar.

By using renowned journals and their ratings, current sources on the topics with high quality and relevance could be found. The semi-structured method made it possible to distinguish relevant from non-relevant sources more quickly since this research comprises various interrelated topics. First, the titles were analyzed, and non-relevant was excluded. The next step included the analysis of the abstracts to use only relevant dissertations, articles and books for this work.

2.2. Modeling

The Literature shows that design-science research is a typical engineering research method with a more practical approach. It also focuses on building some kind of artifact that will be useful for a particular stakeholder community. In this case, the evaluation of the designed and built artifact results in how it improves flexibility and efficiency [8].

Many different approaches can be found in the literature for either simulation-based reconfigurable and optimized CPPS or only human-centric approaches without using simulation-based assistance systems that provide forecasts for optimum production design [9].

However, this research aims to create a reconfiguration using simulation-based modeling of the CPPS. The complexity of a CPPS can be represented by simulation-based modeling, and its behavior can be imitated [10]. The literature can also find other approaches to a computed optimum using simulations. The research gap is to create a simulation-based reconfigurable production system with a human-centered approach. Simulation is used to predict and evaluate behavior through an extended economic analysis with human involvement in the production environment. In addition to classical economic indicators, factors such as environmental impact and soft factors that take people into account are also included in the evaluation.

2.3. Human factor

According to Westkämper et al. [4], production is understood as a hierarchical socio-technical system that concerns the fitting of the human factor and optimizing the technical aspect.

Different objectives to implement the human factor by improving physical and mental health, motivation and implementation of human-designed work lead to work performance and efficiency. A hybrid production system includes the human factor with automated production in the CPPS [11].

The Institute Frauenhofer already has an approach for reconfigurable factories through simulation within the research project ARENA2036 of the Fraunhofer Institute [5].

The ARENA2036 project addresses transformability, focusing primarily on the technical aspect. Approaches to be found here include the factors of modularity, scalability, mobility and universality. This relates more to the design and technical aspects of CPPS and the integration of people to achieve transformability using new technologies. However, no approach is mentioned to focus on the human factor in the design. The gap here is seen in finding approaches that specifically address the motivation and mental and physical health of the employee with direct feedback.

Other projects addressing adaptability in the production environment are F3-Factory and CoPIRIDE, ModuLOG/Economy of Chain.

The works found in the Literature also address more of a simulation technology-based approach but not a human-centric approach [12].

Other works put in the integration of the human being in CPPS mainly in the work design, ergonomics and in general to increase the well-being of the employee in a CPPS and to equate the indifference of well-being of the human being with the automation, the engineering and technology. However, there is also a gap between predicting the work design for future production scenarios and achieving an optimum, for example, through simulations [9].

This literature review revealed that the gap is that there is no simulation-based configurable cyber-physical production system with a human-centered approach. Simulation-based reconfigurable production systems lack human involvement in the production environment.

3. Structure/Model of an Ontology

To provide the required information for the simulations of the CPPS, a digital twin is implemented. This ensures the transfer of general information of the production system into the simulation tool for the forecasting but also lets data from reported actual production data and additional empiric collected data flow into the developed extension of the used simulation software [7]. The developed extension of the simulation uses empirical data by experiments, which were collected to be used a description model of the non-monetary factors, like mental and physical stress of the employees, for a human-centric approach.

According to Bauernhansl et al. [7], digital shadow transfers the real production processes into the virtual world. A twin uses a simulation to provide a picture as identical to reality as possible.

Nowadays, the higher complexity of production processes is better handled by intelligent systems like hybrid automation systems [3]. Simulation returns different calculated configurations of the factory with a certain number of degrees of freedom to make a decision, and this is more of a human-oriented solution. Out of a variety of simulation methods, module-oriented simulation is used. Module-oriented simulators are common in the field of production and logistics because of their modular structures. They reduce modeling effort and allow their own user-specific modules to create flexible applicable [13].

The extension of the simulation software is developed in Python to consider the following criteria of an extended economic appraisal:

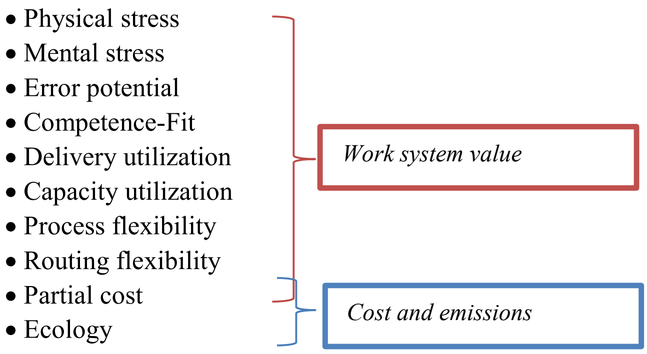


Fig. 1. Criteria for extended economic appraisal.

Those extended criteria can be categorized into the work system value part, a cost and emissions part and are chosen in cooperation with Sonnenberg, Manuel [14]. The order situation of the production is generated manually; a simulation tool simulates the orders according to priority and gives the utilization of the factory precisely like the sequence and time course of the orders. This is the basis for the system developed in the Python environment, which uses this data to calculate a score with the previously defined criteria (See Fig. 1). The system runs through each possible scenario upon the given resources and rates them regarding the extended economic appraisal calculations. Every combination with the provided resources is simulated, and every employee is simulated at every possible workstation. The preference of the desired workplace and the employee's qualifications from a qualification matrix are also considered.

Results of the individual scenarios are stored separately in Comma-separated Values (CSV) format. The developed system provides a comparison and supports the decision-maker with a pre-selection in which, for example, the three best scenarios with the highest score in work system value, the lowest value in total costs and the lowest CO_2 consumption. By using Matplotlib, the results of the proposed scenarios are visually displayed to give the decision-maker the freedom to weigh these three parameters according to preference.

The assistance system acts as an extension of the classic production simulation, adding human-centered factors such as stress and physical strain as well as environmental impact based on the CO_2 footprint to the lead time, costs and sequence due to "Industry 4.0" and the rapid change in technology [15]. Automation and the exchange of information between machines and products are increasingly in focus. In this context, the human factor in the production environment plays a major role in achieving flexibility [16].

To take the human factor into account in this work and to integrate it into the evaluation of the possible scenarios, humans were modeled for the forecasts. Here, the focus was placed on the employee's well-being and on the desires and qualifications regarding his or her work arrangement. Each employee has a different heart frequency on different stress levels, depending on the work he is executing and in which scenario. Tracking and measuring heart rate and blood oxygen saturation as well as work duration serve as indicators of each employee's stress level.

A forecast of the future stress levels is provided by comparing empiric data of similar scenarios with forecasted scenarios and what mental and physical stress of each employee leads to. Continuous tracking with a sensor keeps data updated in order to get forecasts as accurate as possible [17]. (See Fig. 2.)

By accumulating enough data, the machine learning approach can optimize this process. The constant flow back of the tracked data of the fitness trackers of the employees as CSV of the real current scenario ensures sufficient data. Design-science research builds an artifact by evaluating the artifact used by the learning factory Werk150 in Reutlingen.

4. Application in the UseCase (Werk150)

4.1. Development with Learning Factory Werk150

At the same time, the application and limitation of this work is the development of the system with the specifications of the learning factory Werk150 of the university in Reutlingen.

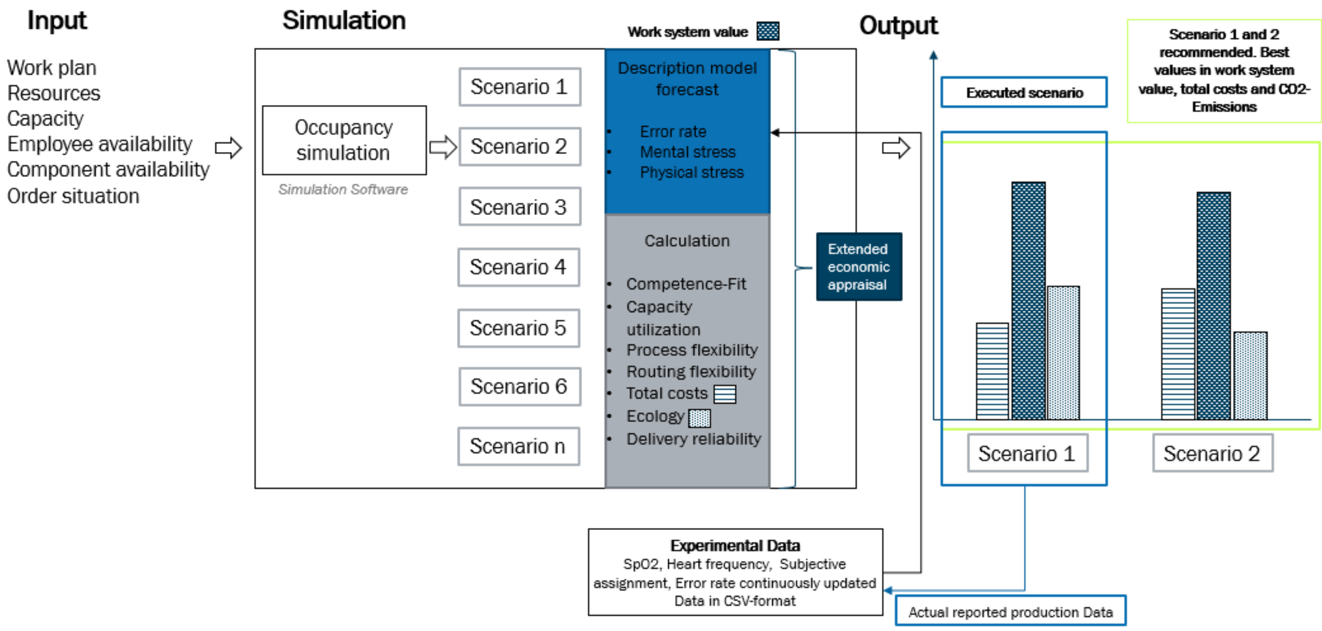


Fig. 2. Assistance system for context-based dynamic configuration of CPPS.

The learning factory offers a variety of applicable technologies, resources and the possibility to evaluate the model simultaneously. The Werk150 functions as a reference model for any further application of this research. Production types used in Werk150 as assembly organizations are flow production and individual workstations. These two options were used for the different configuration scenario setups in the Werk150. The production output was two different scooters: The Flex Blue (FB) scooter and the Beewatec Silver (BS) scooter. The work plan was already pre-defined with the production sequence of line assembly (Table 2). These are described in the concept as basic scenarios. Line assembly for scooter assembly for the FB is divided into four work stations and for the BS into three work stations.

Possible allocation options result from the qualification of the employees, which are shown in the following qualification matrix in Fig. 3. This contains information about which workplaces can be carried out by which people. A cross symbolizes that the employee can fill the workplace. With the help of the experiments, all possible combinations of employee and workplace were tested.

Since the influencing factors: people and workplaces are categories that cannot be continuously subdivided into levels but are described mathematically as vectors in different dimensions, as shown in Fig. 4, the choice of the experimental design fell on the full factorial design, in which all possible combinations are tested directly.

4.2. Experiment

To predict the stress levels of employees in future scenarios, the experiment was conducted to get empiric values to serve as indicators for future situations. The experiment consisted of 5 workers for each working station, and they all were equipped with a fitness tracker to collect data. Each employee has gone through each working step over four shifts, as illustrated in Table 1.

	P1	P2	P3	P4	P5
FB_order picking		x	x	x	x
FB_assembly base	x	x	x		x
FB_assembly stem	x	x		x	x
FB_wedding	x	x	x		x
FB_individual wp	x	x	x	x	x
BS_assembly base	x		x	x	x
BS_assembly stem	x		x	x	x
BS_wedding	x		x	x	x
BS_individual wp	x	x			

Fig. 3. Qualification matrix.

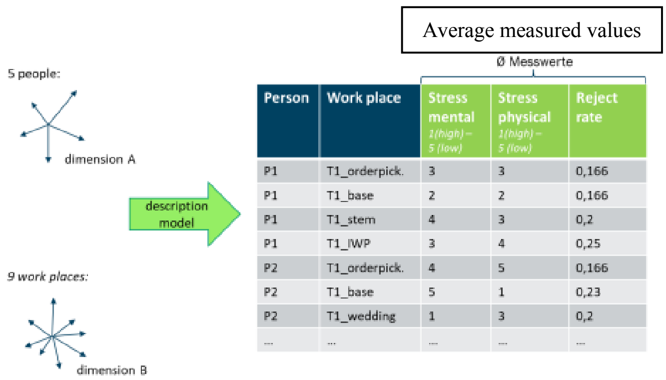


Fig. 4. Collected data of small batch production of scooters in learning factory Werk150.

Additionally, a subjective assessment was conducted to get the most accurate results out of the small batch production that has been tested. A meaningful way to find out about stress is to ask people concerned about their subjective perceptions [18]. Subjective assessment of the stress and requested as the ordinal scale of 1-5 (high stress - low stress) experience matrix with mean values from previous shifts for each possible combination of employee and workplace.

Post-hoc lists for combinations of employees and workplaces and the experience values of the respective physical and mental stress serve as a basis for the assessment of stress. For this purpose, the sum of the products of employee stress at the workplace and employee time at the workplace is divided by the sum of the work durations.

Table 1. Working shifts in the learning factory Werk150.

Work Place (WP)	Shift 1	Shift 2	Shift 3	Shift 4
FB-Individual WP	Person 3	Person 6	Person 2	Person 1
BS-Assembly Stream	Person 1	Person 3	Person 5	Person 2
BS-Assembly Bases	Person 2	Person 1	Person 3	Person 4
BS-Wedding, Quality, Packaging	Person 5	Person 2	Person 1	Person 3

A fitness tracker that measures the oxygen saturation in the blood (SPO_2) and the heart rate (1/s) at 4-second intervals during the entire shift and saved them in a CSV file.

4.3. Assistance system

The monetary and non-monetary criteria of the work system for evaluation and pre-selection are calculated in the Python environment, and different production scenarios are compared with subsequent recommendations. This recommendation includes CO_2 impact, Total costs and total calculated extended work system value factors.

The database consists of general information about the Learning Factory Werk150 and additional experimentally collected data, which is used in a description model. This model is used to estimate missing information for future production scenarios. In the scenarios, the error rate for each workstation and employee was documented as well as the times. After the four scheduled shifts in production, the employees were asked about their subjective perception of the physical and mental stress. Subjective assessment of the stress and requested as the ordinal scale of 1-5 (high stress - low stress) experience matrix with mean values from previous shifts for each possible combination of employee and workplace. In addition, each employee was equipped with a fitness tracker that measures blood oxygen saturation SpO2 and heart rate during shifts. The delta in oxygen saturation, as well as heart rate, can be used as an indicator of stress. The mean value of the individual employees and work combinations are used in a post-hoc approach as empirical values for future scenarios [19].

The data stored by the employees are saved in CSV format and can be continuously expanded. The design artifact developed in the Werk150 can be extended and adapted for general use in different production environments. Further conceivable is the constant extension of the employee data, leading to a more precise prediction through a machine learning approach.

The systems perform an automatic calculation of the configured scenarios and evaluate them by the extended economic rating system. The extended economic rating system takes into account classical monetary-assessable criteria as well as non-monetary ones, which is summarized as work system value. The system automatically compares all foreseen and possible scenarios and makes a preselection based on the calculated score as shown in Fig. 5. out of the scenarios of the Werk150. This preselection is then saved separately as a CSV and is also provided visually to the user. A graphical representation of the results with a recommendation can visually support the decision process to weigh between costs, CO_2 and working system value (See Fig. 6).

```
mental stress in %: 60.276505250503185
physical stress in %: 72.80503465423183
error potential in %: 72.635
competence fit in %:  85.51076230636156
delivery reliability in %:  100.0
routing flexibility in %:  83.33333333333334
process flexibility in %:  58.333333333333336
total costs [€] (including changeover):  1305.4180033333332
total co2 [kg]:  13.5949
work system value in %:  76.12770983968048
```

Fig. 5. Result score of a Werk150 scenario.

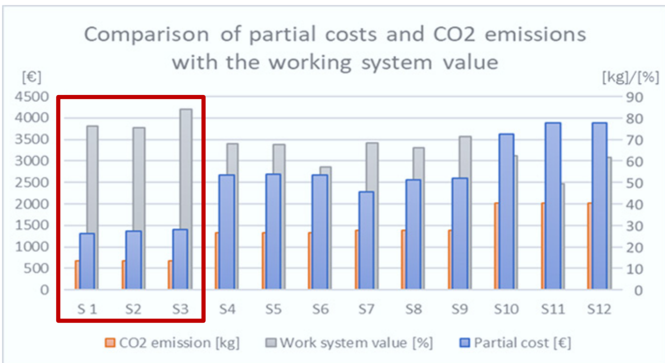
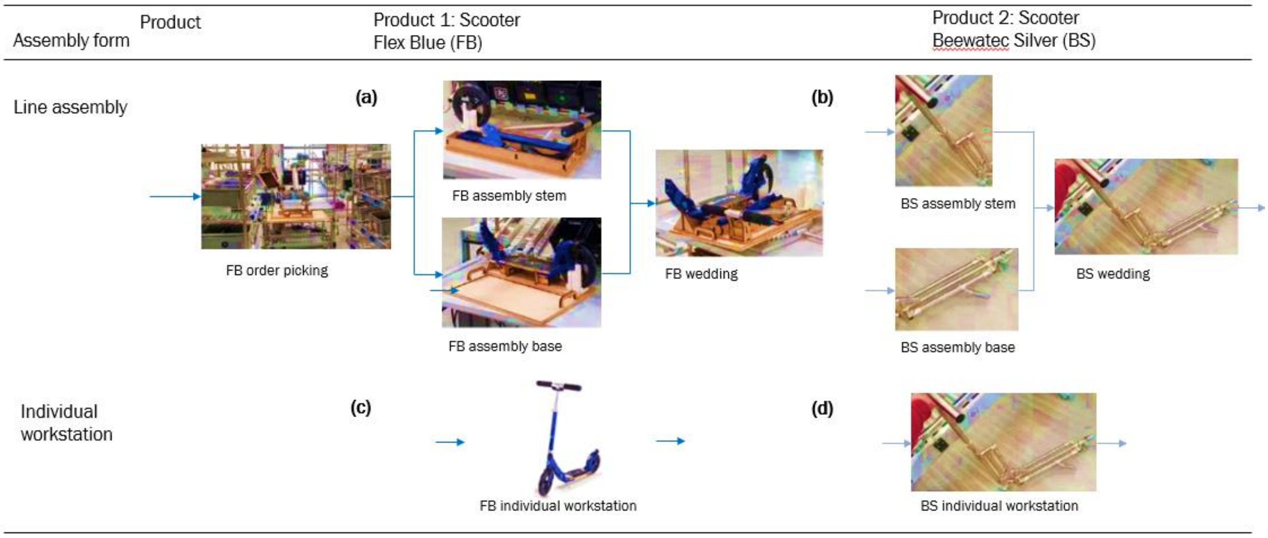


Fig. 6. The output of the three most optimal scenarios is suggested from twelve possible scenarios in the Werk150 scenarios.

5. Conclusion

A continuation and further development of this work could include the data information flow in real-time, which consists of production data but also data from the employees in the production environment.

Table 2. Activity Sequencing in Werk150 Scooter Production for line assembly of FB (a) and BS (b) and the individual workstation for FB (c) and BS (d).



This constant flow of data from, for example, the tracking rings for heart rate and oxygen blood content in real-time and constantly improves the data situation for the forecasts. This can lead to better recommendations from the system through machine learning. The focus is primarily on the human as the final decision maker for the desired scenario. A multi-criteria decision system can be extended and given different weights depending on the application. The pre-selection can thus be made more application-specific by the system with the corresponding desired weighting of the respective user.

Furthermore, it was a big challenge to simulate the stress factor with limited data in this work. Therefore, the subjective perception of the employees based on a survey was also used. The context-based and configurable CPPS with assistance systems is currently limited to the plant150 and can be adapted and extended for further applications. A larger amount of data can also improve the accuracy of the prediction for the stress level of the employees and provide better recommendations on a larger basis.

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