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Conducive Design as an Iterative Process for Engineering CPPS

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ABSTRACT

To leverage the full potential of cyber-physical production systems (CPPS) in terms of flexibility and adaptability, the development of such systems must go beyond digitization and modularization. During the engineering and operation of CPPS, humans are essential enablers for the system's changeability. In this paper, we propose a model of an iterative conducive design process that incorporates perspectives and competencies from several research disciplines such as process control, industrial engineering, computer science, and instructional and cognitive psychology. The goal of this approach is to enhance human-machine interaction and to realize efficient functioning of the system via a combination of the unique potentials provided by humans and the system. The proposed iterative approach is exemplified on a practical level in the engineering of a demonstration plant that tests safety systems for modular plants.

Keywords: Adaptable systems, Conducive design, Cyber-physical production system, Human-machine interaction

INTRODUCTION

The demand for individualized products in smaller batch sizes increases in various domains (e.g., pharma industry). To meet this demand, higher efficiency and shorter development periods are required (Huber 2018). Consequently, the principle of economy of scale is reaching its limits and adaptable production systems need to be developed (DECHEMA e.V. 2016). An answer to this are highly automated cyber-physical production systems (CPPS) that consist of a combination of digital (cyber) and physical system components. These components are connected via information networks and thus enabling high levels of automation. Further, the systems comprise modularized process units (modules) that can be combined flexibly and hence allow for system changes on relatively short time scales compared to conventional plants (Lasi et al. 2014). The flexibility of CPPS will result in major changes of human-machine interaction. In order to leverage the full potential of CPPS, the new requirements of human-machine interaction need to be taken into account throughout the design process. Several research disciplines can offer their specific perspectives and approaches to optimize the design of human-machine interaction. While different disciplines can contribute important aspects each, any single one alone is incapable of addressing all relevant dimensions. Therefore conducive design (e.g., Ziegler and Urbas 2015) is only achieved by combining perspectives from various disciplines. Building on previous research on conducive design, this paper illustrates the interdisciplinary scientific approach of bridging disciplines as diverse as ergonomics, psychology, computer science, and engineering by describing an iterative design process of a scenario from the process industry. To this end, we present a model of an iterative design process that embeds the four different levels of conduciveness (competencies, health, changeability, trust) proposed by Ziegler and Urbas (2015).

CONCEPTUALIZATION OF CONDUCIVE DESIGN

The design of any system traditionally has been a technology-driven, linear process that aims at developing a set-up to transform inputs to outputs and meeting pre-defined goals (Czaja and Nair 2012). In this process, humans were considered rather late, e.g., in user interface engineering (Czaja and Nair 2012). As the non-accounting of human factors in earlier design stages can lead to unsatisfactory quality of human-machine interaction (Zühlke 2012), considering human factors increases (Czaja and Nair 2012). Conducive design aims at overcoming the disregard of humans in system design by active involvement. According to Ziegler and Urbas (2015), the concept of conducive design considers four distinct, but interrelated levels of conducive design. These are (1) competencies, (2) health, (3) changeability, and (4) trust.

Due to the high levels of automation, tasks performed by human operators in CPPS will shift to a more dispositive nature (Hirsch-Kreinsen 2014). According to the *Ironies of Automation* (Bainbridge 1983) or the *Out of the Loop-Unfamiliarity* (Endsley and Kiris 1995), resulting problems may be the loss of competencies or the human inability to take over control of highly automated systems. Therefore, whenever levels of complexity rise, countermeasures must be established in order to ensure that the system remains manageable and comprehensible for humans and to put them back into the loop (GMA 2013). An advantage of CPPS over former traditional systems is that comprehensive information on the processes and system states exist and can be disclosed to the human. Systems designed to be conducive to competencies can utilize this information and support human reasoning and problem solving by providing contextual information (Müller et al. 2021) as well as increasing the motivation to learn and expand competencies (Dostert and Müller 2021). These cognitive and physical human states can be incorporated into a human model, which can constantly be improved and updated through real operation. This allows to control the fit between demands and resources (e.g., task allocation or presentation according to expertise) in order to achieve conduciveness to health (Schmidt and Luczak 2017). Moreover, changeability is enabled through the consideration of system as well as human states. Not only CPPS are changeable in terms of different configurations

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(Lasi et al. 2014), but also human performance can improve with, e.g., increasing expertise (Feltovich et al. 2006). Accordingly, a constant reconciliation between the human and the system is necessary and the system must not only be able to adapt to technical boundaries, but also to the human. For example, the information provided may differ in accordance to the users' level of expertise. If a user is inexperienced with a task or perhaps has not performed it in a long time, they may benefit from such additional support. However, humans who are adept at solving the problem at hand may experience detrimental effects by additional support such as warning hints, additional information, or tutorial advice (Kalyuga et al. 2003). Adapting to human states can also enhance trust, e.g., in automation. For example, whenever the human is required to intervene during operation, the system should reduce interfering stimuli to facilitate the allocation of attention to the task (Parasuraman and Manzey 2010). For the successful implementation of such a conducive CPPS, cognitive and instructional psychology can provide frameworks and theories to determine which information is useful in a given context. Computer science focuses on the digital representation of the system, the data processing, and presentation of data in an adequate format. Disciplines from engineering accompany this process in order to ensure system operability and efficiency while complying with underlying regulations. In conclusion, the human operator is considered as a positive and essential part of the system rather than a "problem".

CONDUCIVE DESIGN APPROACH

Within the life cycle of CPPS, conducive design affects two phases: engineering and operation. The engineering phase generally defines system characteristics. The conducive design approach goes beyond that and also takes human capabilities and requirements into account when defining system characteristics. In respect thereof, the human-machine interaction can be considered as a central aspect: This fosters as early as the engineering phase to consider future use of the system and anticipate what challenges may arise for humans during operation.

This creates two cyclic dependencies: (1) The engineering anticipates the operation, which is in turn influenced by the design resulting from the engineering phase. (2) The adaptation of the system in accordance with the individual characteristics of the user during operation. In former systems, the human had to interact and work with the system by adapting to system requirements. In contrast, a conducive designed system is able to adapt to human capabilities. In Figure 1, we depict the described dependencies within the general life cycle of a human-centered CPPS. It further illustrates that conduciveness can be achieved by either collecting, evaluating, and using scenarios and experiences with an existing system and using this information to derive improved design of the apparatus. At the engineering stage, attributes that need to be taken into account for an individualized operation mode are integrated into a universal human model. During the operation phase, the attributes are instantiated according to the individual characteristics of the specific human operator working with the system. Thus allowing

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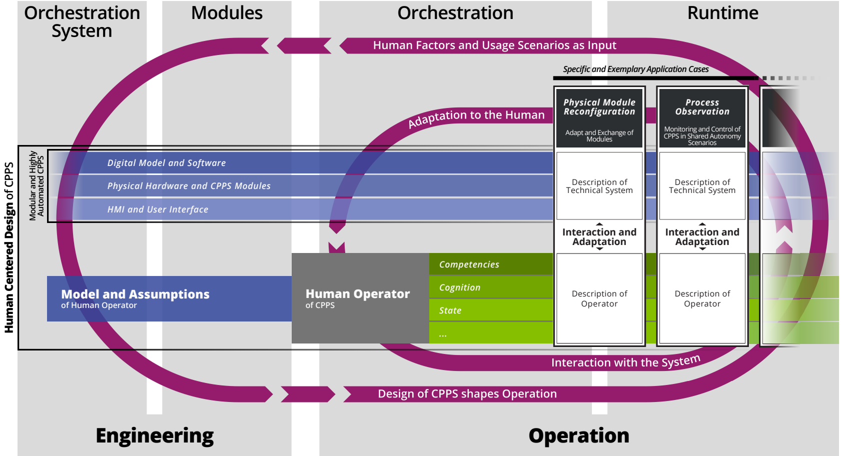

Figure 1: Representation of conducive design of CPPS as an iterative process.

for the best possible fit between human and machine on an individual level.

Engineering

CPPS are made up of individual modules in the form of adaptable process units that cover functional portions of a superior production process. These modules can be interconnected and organized in an orchestration system to implement a production process (Bloch et al. 2017). Further, the orchestration system is used for module management, production planning, and monitoring during operation. The way the modules and the orchestration system are designed, affects the quality of the human-machine interaction during the operation phase. The engineering does not target the production of a single product anymore; it rather aims at enabling flexible production. Therefore, assumptions of human-machine interaction as well as lessons learned in the form of feedback from the operation phase have to be considered and accounted for during engineering. For that, either real data from prior processes or models of human behavior can be used (e.g., human states or competency levels).

Operation

The operation of CPPS encompasses the orchestration and the runtime. Orchestration refers to configuring a system for automated production which involves module adaptations and exchanges, programming, scheduling, and optimization activities. The runtime is the production phase itself and requires the human mainly to monitor the system. However, severe incidents (e.g., malfunctions of modules) may occur that require human intervention. Challenges for humans arise from increasing complexity and automation (Kluge 2014). But also due to the frequently changing system configurations that make it impossible to build up adequate mental models by experience of working with the system. In order to counteract these effects, conducive design considers human states for individual system configurations.

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However, requirements put on the human differ due to system characteristics and resulting tasks.

Interaction

Within conducive design, engineering and operation phases interact in order to achieve the best possible outcome for human-machine interaction. Information from real operation or from simulations of exemplary scenarios is fed back to the engineering phase. This allows for improvements in the system through re-design. For humans, this consequently facilitates operation. Another interaction can be found during operation as CPPS can assess human states (e.g., fatigue or competency levels), while they work with the system. By continuously taking these into account, the human-machine interaction is improved through adaptations and, e.g., the provision of information can be carried out more precisely considering human and system states.

PUTTING INTO PRACTICE: SAFETY DEMONSTRATION PLANT

In order to exemplify our proposed theoretical approach, we describe the iterative process of conducive design in the engineering of a demonstration plant that tests safety systems for modular plants (Pelzer, Klose, et al. 2021). We investigated the adaptation and exchange of modules by the operator from a safety perspective. Therein, we focus on conducive design driven by practical insights regarding changeability and health. In order to maintain systems changeability, safety systems must be designed to be modifiable by operators, which leads to fundamental changes in the safety engineering lifecycle (Pelzer, Pannasch, et al. 2021).

Since changeable plant-wide safety systems were implemented in modular plants for the first time, no practical insights from operation existed beforehand (Pelzer et al. 2020). The starting point of investigation were the theoretical models of system behavior derived from the guideline VDI 2776 (VDI e.V. 2020) and human operators derived from the description of a chemical worker according to the German training standard (BGBl. I 19 2005). Accordingly, operators are skilled in basic chemical processes, electrics and control, and instrumentation technical operations. However, they are not familiar with the safety engineering approach specified in the standard IEC 61511 (IEC 2016). Based on these models, we designed two CPPS modules. Observing operators interacting with these modules showed that the results of the first design iteration were only partly conducive to operators. Bottlenecks arose from system engineers' incomplete knowledge about system operation, particularly of tasks during adaptation and exchange of the modules. In analyzing operators performing the tasks, we identified the following exemplary weaknesses: power connections of modules were not reverse polarity protected, live parts were accessible due to the plug connections used, and signal cables could be interchanged. As a consequence, the initial design that was intended to implement system changeability, ultimately led to new risks for operators (e.g., electric shock dangers from high voltage live parts or injuries from heavy equipment handling) as well as for the plant.

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Design weaknesses and the resulting foreseeable misuse of systems by operators can lead to malfunctioning of safety systems and therefore does not serve the goal of mitigating risks. These early insights into plant operation were valuable for the next iteration step and provide a useful contribution to the implementation of conducive design. In order to facilitate the safety reconfigurations without imposing additional risks to the operator, cable design was adapted, e.g., the use of interference-proofed plug connections. Furthermore, the wiring of different module configurations was realized in the same style that operators were familiar with plugs and locations of connections. In conventional plants, this task could have been handled only by trained control and instrumentation technicians, since new connections would have to be created and changes on the implementation of the plant would be needed. Future research should focus on feeding back practical insights to the engineering phase, which helps to improve the design that in turn facilitates meeting the requirements operators face in CPPS.

CONCLUSION

CPPS combine high levels of automation and an architecture that enables changeability (Lasi et al. 2014). These advancements will thoroughly alter the requirements for human operators. Therefore, it is likely that without any counteractions, advanced operations will exceed human capabilities. Conducive design puts the human at center stage within system design, as humans not only remain an important factor for safe and efficient operation, but are considered as an essential part of CPPS (Ziegler and Urbas 2015). The aim is to enable flexible socio-technical systems by accounting for human capabilities and states at the engineering stage. This paper presents an approach for an iterative conducive design process with two cyclic dependencies: (1) Considering the human during the engineering phase, analyzing human machine interaction during real life operation, and then feeding back the insights to the engineering phase. (2) Further interaction can be found during operation as CPPS are capable of assessing human states and competencies, adapt to them, and even foster human development (e.g., increasing competency levels) through these adaptations. To gain understanding of the interaction between engineering and operation phase, a demonstration plant with special emphasis on safety systems was built. Insights from adapt and exchange scenarios based on the demonstration plant underline our notion of the need for considering the human characteristics and capabilities at the engineering stage. However, this is just a first step in achieving a design conducive to health, competencies, changeability, and trust. Further research, e.g., regarding the real-time adaptations of CPPS according to human states, is required. In order to implement conducive design comprehensively, it will be inevitable to bring together perspectives from different fields of research.

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