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► **To cite this version:**

Marie-Pierre Pacaux-Lemoine, Frank Flemisch. Human-Cyber-Physical System Integration (HSI) in Industry 4.0: design and evaluation methods. IEEE International Symposium on Industrial Electronics, Jun 2021, Kyoto, Japan, Japan. hal-03960399

HAL Id: hal-03960399

<https://uphf.hal.science/hal-03960399v1>

Submitted on 27 Jan 2023

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Human-Cyber-Physical System Integration (HSI) in Industry 4.0: design and evaluation methods

Marie-Pierre Pacaux-Lemoine
Université Polytechnique Hauts-de-France
UMR CNRS 8201 LAMIH
Valenciennes, France
marie-pierre.lemoine@uphf.fr

Frank Flemisch
Institute of Industrial Engineering and Ergonomics,
RWTH Aachen University, Aachen, Germany
Fraunhofer Institute for Communication, Information
Processing and Ergonomics,
Wachtberg, Germany
f.flemisch@iaw.rwth-aachen.de

Abstract—This overview article describes the design and use space of integrating humans and cyber-physical systems in Industry 4.0, with special regards to the interplay of analysis, design and evaluation methods and phases. Starting with an introduction into the challenges of Industry 4.0 and an overview on existing methods of system design, the design and use space of method models is described and exemplified with examples from Industry 4.0. An extended U-Method of iterative analysis, design and evaluation is derived, described in theory and exemplified with practical examples. An outlook identifies potential roadmaps of future design and evaluation methods especially for industry 4.0.

Keywords—human-machine cooperation; design and evaluation methods; cyber-physical systems; industry 4.0

I. INTRODUCTION

Industry 4.0 promises the next level of industrial revolution with a higher level of integration and productivity for industrial production, but also imposes a couple of challenges to politics and R&D, to employers and employees (e.g. [1], [2]).

Using appropriate concepts and methods can make the essential difference between managing an industrial project successfully or unsuccessfully. This choice is not trivial, especially in times of severe changes like in Industry 4.0. In science, the challenge arises to develop appropriate and scientifically sound methods in time, which provide essential and useful guidelines to manage those projects successfully, from the formulation of objectives, the definition of hypothesis to the analysis of data and results about hypothesis, and more. Deep data analysis may lead system designers and engineers to identify the justifications of the results or new directions that could be taken.

Before we look into new directions, let us take a look at what is already around. Several user-centered design methods have been published with the aim to increase the ergonomics of systems. They provide knowledge about the design and evaluation of interfaces, e.g. usability and models of human-machine interaction based on cognitive behavior. Nielsen defines the usability as a sub-part of acceptability, which is the extent to which a product matches customers' expectations [3]. Gould and Lewis describe usability engineering as a general approach with three strategies: taking into account of users and their tasks early on, empirical measures and iterated design [4].

This approach includes user aspects in most of steps of project management and defines several norms. Nevertheless, other methods exist, originating from different domains, such as the method presented in social acceptability. Brangier *et al.* propose a comparison between social and ergonomic approaches [5]. The authors underline the interest in exploiting their complementarities. This is also the method proposed by Millot, the so-called method in “U” [6]. This method takes the V-cycle by [7] or V-model [8][9] as a starting point, but aims to propose an easier way to design and evaluate systems. V-cycle, stemming from systems engineering, bases the method on the different stages of the cascade model. Nevertheless, it is very difficult to use this model for complex environments, such as dynamic environments, the main application of our research. Moreover, it does not take into account humans and their interactions with assistance systems. The method in “U” has this objective, as well as balancing human involvement with machine involvement in the control of the process in a cooperative manner.

In a parallel research stream in Germany focused on cooperative systems and iterative, participative design methods, a paradigm of human-systems exploration was developed and iteratively refined in a couple of research projects (e.g. [10]). Central idea is that in contrast to a V- or U-shaped approach, in this “exploration turbine” more than one iteration is needed to explore the multitude of combinations of design- and use space, combining actions for designing and engineering with actions for estimating or measuring effects. Another central idea of the exploration turbine is that based on first ideas, it first opens up to explore the field of possibilities, and then narrows again to condense the options to concrete design, prototypes and results (e.g. [11]).

II. ITERATIVE DESIGN, DEVELOPMENT & TEST

Over a decade of fruitful scientific discussion, the two models were fused to explain the different phases of Human-Cyber-Physical System Integration (HCPS). Fig. 1 presents an iterative procedure based on four main characteristics: the design phase, the evaluation phase, the field of possibilities and the number of iterations. The spiral refinement brings attention to the long design and evaluation phases at the start of Human-Cyber-Physical System (HCPS) design due to the high number of possible systems that could fit the objectives. Nevertheless, the more explorers and experimenters iterate the procedure, the more they reduce the number of possible systems and the shorter the iteration phases become.

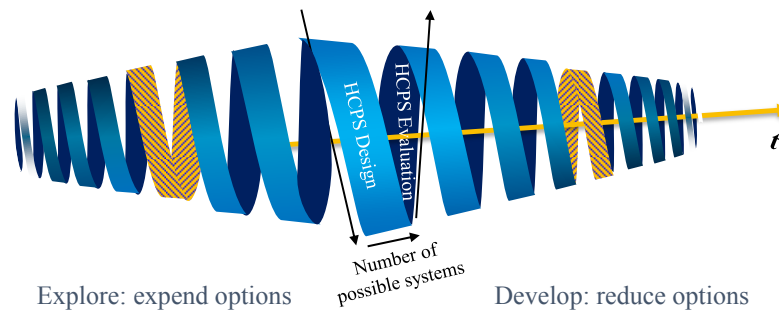


Fig. 1. Iterative procedure with spiral refinement [12]

III. EXTENSION OF THE METHOD IN U

Initially used in telerobotic domain [13], other domains like automotive domain applied this method as well [14]. Fig. 2 presents a new version of the method. Indeed, details about human and machine representations through the tasks description, their interactions through the Common Work Space, and the multi-level aspects of cooperation enrich the previous version. In this method, a descending phase designs HCPS and an ascending phase evaluates it. All the steps of the descending phase use the models of cooperative agents, levels and layers of cooperation as well as the notion of Common Work Space defined some years ago with works dealing with Human-Machine System design. For detailed presentation the reader can refer to next documents [15], [16], [17] ; however those definitions are briefly presented and explained throughout the description of the method explaining their usefulness with a focus on industry.

At the first stage, designers should understand and identify the objectives of the human-cyber-physical system they have to design (cf. Fig. 2-1). Objectives usually describe the increase of performance, but performance is a general word that hides many things. It could be the increase of the number of planes air traffic controllers can manage, the decrease of deaths on the road with driving assistance systems, the increase of the number of products generated by manufacturing systems. However, performance can also mean better comfort or more capacities for humans in their activities, such as systems to augment physical or cognitive capacity or to compensate weakness or disability. It is already a request from industry in the context of Industry 4.0, how to adapt CPS to human operators' competences regarding their expertise, skills regarding their experience, ordinary or temporal mental and physical capacity for current or specific process state. Therefore, system designers must correctly identify and understand objectives in discussions with managers and experts, but most of the time it is also useful to have discussions with the future end users, especially for the next step of the method regarding the analysis of the process (cf. Fig. 2-2).

Process and human activity dealing with the control of this process are usually not new; they already exist in industry. Therefore, models of current organization, models of prescribed tasks and functions, and detailed description of current process might inform designers (cf. Fig. 2-0). Less

often, only human activity exists and designers have to imagine and create systems to automate parts of human tasks. Therefore, designers must identify the limits of their intervention, defined by a set of human tasks and sub-tasks they have the agreement for modification from managers. However, it could be also interesting to have the agreement from future end users to improve their acceptability of the new system, especially regarding what could be their future tasks. Today, only safety and security criteria usually define such limits, but other values like human operator workload or motivation or ethical risks must be considered [18]. Then, designers study human and technical resources (cf. Fig. 2-3), and may conduct an analysis of the current process with points of view that are sometimes different from the point of view of managers (cf. Fig. 2-2). The objective here is not to avoid the influence of managers, but to have a neutral approach to offer novel and original perspectives. Ergonomic and social fields help analyze human resources, extracting cognitive and physical constraints linked to activities, as well as constraints from the social organization.

The method highlights the interest in extracting the levels of activity and layers of cooperation from the organization (cf. Fig. 2-4). The designer has then to identify tasks and sub-tasks of humans and CPS at each level (e.g. operational, tactical, strategic), as well as tasks or information transferred from one level to another (cf. Fig. 2-5). At each level, the designer suggests modifications of current tasks or creations of new tasks for humans and for CPS (cf. Fig. 2-6). It is an iterative procedure analyzing activity level by level, as well as complementarity between levels (cf. Fig. 2-7). Tasks or functions deal with individual and cooperative activities. Based on the models of Human-Machine Cooperation: the Know-How(-to-operate) functions tackle the control of the process according to four main sub-functions: Information gathering, information analysis, decision making, action. The Know-How-to-Cooperate functions address the cooperative interaction according to four other main sub-functions: — information gathering on other agents, — detection of interferences between cooperative agents' situation awareness and decisions/actions, — management of those interferences, — the allocation of authority, but also responsibility to control the process (e.g. [19] Know-How (-to-operate) and Know-How-to-Cooperate functions may be analyzed through a grid to identify and define tasks and sub-tasks [20].

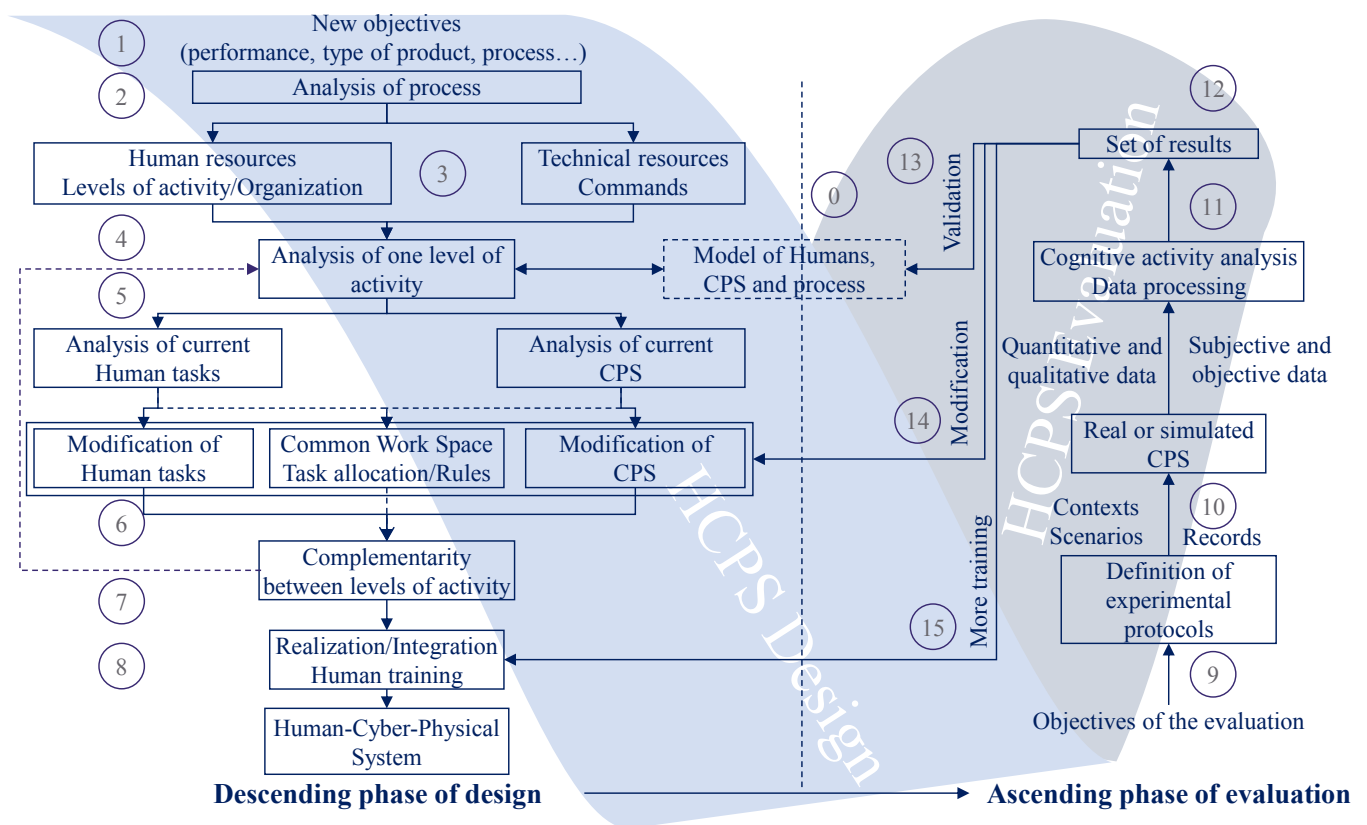


Fig. 2. Extended U method [17]

After checking complementarities between levels, the designer can proceed to the programming part, except if he/she is in the exploratory part of the method in which the functions can be simulated (cf. end of the paper). If he/she is in the implementation part of the method the designer can start to program CPS functions, the programming of the interface (visual, auditive, haptic) and the training of future users (cf. Fig. 2-8). Definition and organization of human and CPS functions are important in the design of HCPS. However, the interface, the external representation of the Common Work Space, support of the cooperative activity, is another crucial part in the success of such a system. Nevertheless, we will not focus on this aspect, but use dedicated literature and especially that which aims to choose or mix different sensory perceptions (*e.g.* [21]) and several articles deal with such an aspect for Industry 4.0. At the end of the descending phase, the ascending phase takes over the work to evaluate the new HCPS.

In the engineering approach, which usually relates (wrongly) to the “implementation” of the method, the ascending phase usually starts when the HCPS has a minimum number of functions to be implemented, at least at one level of activity of the industrial process. The objectives of the evaluation must answer the questions raised by the stated hypothesis. What do we want to highlight with the evaluations? How can the proposed new HCPS be assessed and prove its usefulness? Experimental procedures and protocols answer such questions (cf. Fig. 2-9). Experimenters define contexts and scenarios. Context deals with whole or part of the process in

which the HCPS takes part. A starting state of the process and objectives define a global shape of user activities. Scenarios aim to encourage users to complete some tasks by asking them (and the assistance systems/automation) to reach goals despite triggering unexpected events. The experimental protocol may involve building several scenarios to allow experimenters to compare different experimental conditions, *i.e.* different configurations or propositions of HCPS, like the comparison of several levels of automation [22].

Scenarios must be different to prevent users from recognizing a situation, from making the same decisions and from interacting with the assistance system in the same way; however, scenarios require similar tasks to make the data comparable. The duration of scenario depends on the tasks and can last a few minutes for the control of a robot at the operational level, to several hours when the objective is to evaluate industrial process supervision. Scenarios and experimental conditions are, most of the time, counterbalanced using a Graeco-Latin square experimental design to reduce order and learning effects. Such an organization of experiments defines the experimental design, which aims to reduce the impact of evaluating one type of assistance system before another one, and the specificity of a scenario according to the type of assistance system. As a control condition, a condition without new assistance systems is defined. It makes it possible to evaluate potential benefits of the new HCPS. Experimental design involves defining experimental procedures, *i.e.* the various steps experimenters interact with participants taking

part in experiments. Firstly, experimenters present scientific objectives and then the experimental platform. Secondly, participants may have to learn the process if they are novices on the task. They may have to identify context and types of scenario (requested tasks), usually without using new assistance systems. Therefore, they may have to learn how the assistance or automation system functions with a formal presentation, and then use it in a dedicated scenario to train themselves. Training scenarios are different from experimental scenarios, but with similar difficulty.

Real environment or simulators may support HCPS studies (cf. Fig. 2-10). The level of realism of the simulator can range from very low level of realism, where participants have only to perform very simple tasks but usually with many repetitions, to high level of realism where simulation only concerns the environment but command and control systems are real ones. The more advanced simulators can mix between simulation and reality of environment and/or control and command systems. A simulated environment proves to be a very useful tool for experimenters to control experiments. Nevertheless, participants may sometimes display unnatural behavior, since they are aware their activities are being recorded and do their best to meet experimenters' expectations. For each stage of the experiments, designers and experimenters prepare data records. Data can be objective, subjective, qualitative, quantitative, raw, interpreted, and coded, depending on experimental design and experimental platform. Data record definition and control are an important step for experimenters since it is a necessary condition for obtaining useable data to generate relevant results. The next section deals with this step.

Data is a more frequently cited word nowadays, as in, for example, big data, database, data mining, data cloud, but experimenters must find the right compromise between recording many data and spending a lot of time cleaning, selecting and analyzing data, or selecting the most appropriate data regarding objectives and the way to analyze them. Online data records and their analysis are at the core of the understanding of HCPS activities. (cf. Fig. 2-11). Designers can program data records directly on the experimental platform. All commands sent through human-CPS interfaces and information updates in the Common Work Space constitute precious information for experimenters to understand process situations and agents' decision making regarding such situations. Precoding data during execution of simulation and experiments may support analysis. Spontaneous verbal reports and video outputs of user workstations provide other types of data. Spontaneous verbal reports are especially interesting when two humans work together during experiments. However, online verbal reports are sometimes not easy to understand for experimenters. Therefore, in addition to these reports, experimenters use self-observation reports. After task execution, participants watch video records of their activities and provide comments to explain (but not justify) their decision-making.

Like in spontaneous verbal reports, simulated environments give experimenters the opportunity to record other kinds of subjective viewpoints, *e.g.* online participants' workload and situation awareness. Experimenters evaluate online workload assessment by asking to participants to regularly answer questions requesting information about their workload.

Questions are verbal or posed by the way of a scale drawn on a display. Even though it is an additional task for participants, this question can be part of a cooperative task, especially if participants have to evaluate their own workload to decide to allocate tasks to a partner. Designers and experimenters may compare the evaluation of workload done by participants to calculated assessment performed by the system using different technics. The evaluation of situation awareness is also a useful tool to state how participants perceive and understand a process or an environment, and come to a decision. Several methods exist. Endsley proposed a method associated with her three-level model of SA [23]. The method, known as SAGAT (Situation Awareness Global Assessment Technique) [24], used in simulated environments, consists in freezing the situation randomly, blanking the displays and asking participants relevant questions on their understanding of the current situation. SAGAT has acquired a status as a reference method. However, its main limitation lies in the freezing of the simulation, which prevents its use in real applications.

Simulated environments allow testing assistance systems in safe and controlled conditions. Such experiments are required before conducted tests in real world. Nevertheless, real world tests involve many constraints. Indeed, experiments conducted in the real world are much more complex and much less controllable than in simulated environments, especially when the focus is on human-CPS cooperation. Moreover, unlike controlled simulated environments, technical problems occurred like communication disturbances or interruptions. Even if such problems can also occur during real missions, these uncontrolled events prevented repetitive scenarios from being conducted to extract statistically significant results.

Evaluating workload and situation awareness in a real environment is of course more problematic than on a simulator, unless evaluating their workload and awareness are part of participants' tasks. Concerning workload assessment, Durso et al. proposed an over-the-shoulder subjective assessment by a subject matter expert (SME)[25]. They also used a query technique that did not have a memory component, SPAM (Situation Present Assessment Method). The measurement consists in experimenters' detecting participants' errors concerning specific events integrated into the scenarios. Regarding situation awareness assessment in real situations, Jones and Endsley proposed the "real time probes" method. It consists in asking a series of periodic questions related to the three SA levels (but without blanking the displays) and using participants' response time to the questions as a complementary index of the SA quality. They partly validated the method by making comparisons with SAGAT. Online records provide objective and subjective data that reflect human and technical agents' activities. Focusing on their tasks, humans normally had no time to reconstruct their understanding of situation, or to imagine more than what they actually remembered doing during the experiments. However, they prevent experimenters from going deeper into the analysis to understand reasons for participants' behavior. Offline records can mitigate such shortfalls, and various methods help aggregate online and offline data. The following sections detail these capabilities.

After the end of each experimental session, experimenters can again assess workload and situation awareness; however, questionnaires constitute the main tool for the offline records.

One of the main methods to evaluate participants' workload is NASA TLX (Task Load indexX). This method poses questions to participants in two phases [26]. After each experimental session or each experimental condition, experimenters ask participants to give their feelings about six descriptors by drawing a cross on a 10cm line. Descriptors are mental demand, physical demand, temporal demand, own performance, effort and frustration level. This questionnaire could be useful with participants who are professional human operators, like in industry. Indeed, they give a good representation of their work and tasks, and they are used to evaluating themselves with similar questions, especially when they perform risky tasks. Questionnaires remain the main tool to evaluate the quality of the interaction between participants and assistance systems, and a generic questionnaire dealing with human-CPS cooperation has been proposed and is based on the model of a cooperative agent [17]. Other questionnaires may also evaluate how participants perceive experiments, the experimental environment, procedures and evaluations.

The 12th step of the method (cf. Fig. 2-12) is the result of all the previous steps. Experimenters may describe the experimental HMS results. Three main feedbacks aim to update boxes of the design phase. The first round of feedback (cf. Fig. 2-13) validates the HMS and updates current models of human operators, assistance systems and processes according to new achievements. The second round of feedback (cf. Fig. 2-14) highlights unsuitable aspects in the design of the HMS. Therefore, designers must modify such aspects that may deal with new human tasks, or new assistance tasks, or new Common Work Space, or new organizations. The data processing stage and the proposed tools provide precise information about unsuitable aspects, so designers know precisely where modifications need to be made. The third round of feedback (cf. Fig. 2-15) underlines the necessity for participants to have more training with their new tasks, regarding their cooperation with assistance systems, or with the process.

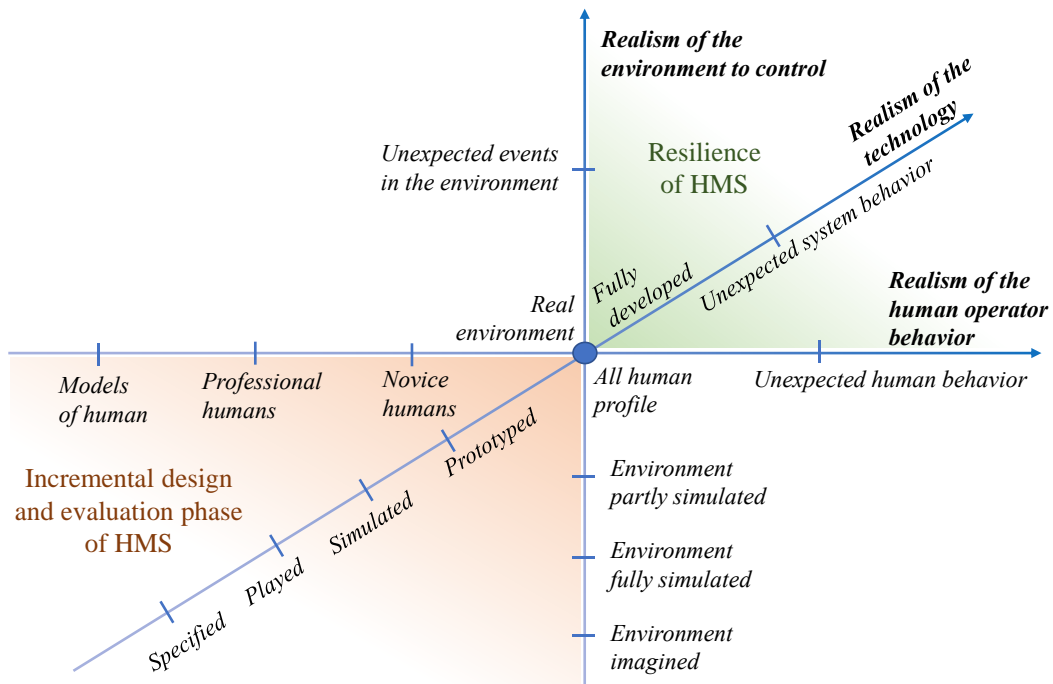


Fig. 3. Three dimensions for experimental design and evaluation (adapted from [12])

IV. EXPERIMENTAL DIMENSIONS

As a conclusion for this part on methodological aspects, we provide a synthesis of all the types of experiments we conducted with a presentation using three dimensions. The first one comprises of the experimental conditions, described according to the realism of the situation, which is the human activity context and type of process. The second dimension deals with the realism of human behavior that evolves from small samples of humans, who are more or less aware of the process, and the use of new systems, to huge samples equivalent to all end-users. The third dimension is the realism of new system and, above all, its maturity. These three

dimensions may help to define the right number of experiments and the right steps from one experiment to the next to be sure of the relevance of these experiments (cf. Fig. 3).

Each dimension shows examples of states, but more states in between might exist. Fig. 3 presents the central point at the intersection of the three axes highlights what we could consider as an end to experiments. However, before achieving this point, several other points describing several types of experiments may exist, and experimenters have to explain and justify how they go from one point to another one in order to be sure of improvements on each axis, as well as the consistency of the successive results.

The next step should be the implementation of new systems as well as the training of human operators. Nevertheless, when implementation of the HMS is complete, the humans involved in the management or in the use of such HMS must make sure that it functions appropriately. Many characteristics of HMS may change and destabilize its proper functioning. Indeed, as made clear by the arrows of the three dimensions, they point toward an “unknown world” in which many unexpected events, good or bad, could occur. How to address this “unknown world” systematically in the adaption of HMS will hopefully be studied in a new future.

V. CONCLUSIONS AND PERSPECTIVES

Starting point of the discussion were the challenges of Industry 4.0 especially regarding the integration of humans, technology and organization into meaning- and successful human-CPS systems. Human and CPS are complementary actors cooperating to reach common goals. Design and engineering methods are crucial for this challenge. The proposed method builds a bridge to well established V- and U-Model, and identifies where iterative phases can and should happen. The method also builds a bridge between exploratory, engineering and experimental approaches by combining them in different phases. In particular, the method provides tools to identify and specify human and CPS individual and cooperative functions, and to support their cooperation with a Common Work Space. The bridging method was build and tested in a couple of research projects, and is now ready for being iteratively tested and refined in real world projects.

ACKNOWLEDGMENTS

The authors acknowledge the French National Research Agency, which supports and funds the Humanism Project (ANR-17-CE10-0009) and the current research work. On the German side, the research was supported by the DFG-Cluster of Excellence “Internet of Production”.

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