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Using Cognitive Work Analysis to deploy collaborative digital twins : application to predictive maintenance

Naomi Kamoise

Lab-STICC, University of South Brittany, France. E-mail: naomi.kamoise@univ-ubs.fr

Clément Guérin

Lab-STICC, University of South Brittany, France. E-mail: clement.guerin@univ-ubs.fr

Mohammed Hamzaoui

Lab-STICC, University of South Brittany, France. E-mail: mohammed.hamzaoui@univ-ubs.fr

Nathalie Julien

Lab-STICC, University of South Brittany, France. E-mail: nathalie.julien@univ-ubs.fr

The digital twin is a technology that expands the possibilities of manufacturers thanks to its various applications, particularly for the application of predictive maintenance. In the context of Industry 4.0, technical agents such as digital twins tend towards more autonomy. Indeed, one of its characteristics lies in its partial or total capacity to act on its physical counterpart. Therefore, it is necessary to consider the digital twin and the human agent as cooperating agents. Under this perspective, decision loops between the digital twin and human agent is necessary in the deployment of the digital twin. The JUPITER project aims to develop the digital twin for predictive maintenance of the SCAP platform, a manufacturing line. The objective of this paper is to show how Cognitive Work Analysis (CWA) could contribute to the definition of the allocation of the decision making activity between the digital twin and the human. Two CWA analysis were applied: the Work Domain Analysis (WDA) and the Social Organization and Cooperation Analysis with his tool Contextual Template Activity (SOCA-CAT). The functions identified by the WDA highlighted the allocation decision between the cooperative agents and the SOCA-CAT provided a contextualization of this allocation. The allocation of the decision making activity was considered in terms of the level of automation between the digital twin and the human agent.

Keywords: Cognitive Work Analysis, Digital Twin Deployment, Human-System Cooperation, Predictive maintenance, Smart Manufacturing, Activity allocation

1. Introduction

1.1. Digital Twin applied to predictive maintenance

The current context of digital transition and the new technologies it implies have led to the fourth industrial revolution, allowing the improvement of productivity and flexibility of manufacturing operations. The digital twin is one of the pillars of Industry 4.0, particularly because of the range of possibilities it offers to manufacturers. This technology represents a growing topic of study among academics and manufacturers (Julien & Martin, 2021). The many definitions of the digital

twin vary around a common notion of a link between a physical object with a virtual entity that represents it, through a data flow (Silva, Azevedo et Soares, 2021). Then we consider the digital twin as a dynamic virtual representation of a physical counterpart, a product, a system or a process. First developed within the aerospace domain, it was in 2014 that Grieves, the precursor of the term digital twin, extended it to industrial applications such as maintenance.

The main objective of maintenance is to provide high levels of availability of production equipment by ensuring its reliability. According

to NF-EN 13306:V2018, there are different maintenance strategies grouped into two main categories: corrective maintenance, in which interventions are carried out after failures have occurred, and preventive maintenance, which aims to anticipate them. Within this last category, known as proactive maintenance, we distinguish between systematic maintenance (interventions at predetermined time intervals), condition-based maintenance (interventions depending on reaching a degradation threshold) and predictive maintenance (interventions based on forecasts made from historical and current data analysis). In contrast to other types of proactive maintenance, predictive maintenance allows interventions to be initiated only when it is needed. Indeed, systematic and condition-based maintenance may lead to unnecessary actions, leading to an increase in the operating costs (Carvalo, Soares, Roberto, Basto & Alcala, 2019). Predictive maintenance is the most studied in the framework of Industry 4.0 (Zeniseks, Wolfartsberger, Sievi et Affenzeller, 2019), notably because of the reduction of operating costs possible thanks to the improvement of the equipment life span, or the reduction of maintenance interventions.

The digital twin ensures predictive maintenance, with its ability to provide a representation of the state of the physical element in a constant and precise way through the sensors present on this physical element. The predictive maintenance is then based on historical, current or future data to predict tendencies using statistical or learning models. This makes production systems more proactive, and therefore more efficient. The anticipation of failures by the digital twin could reduce unexpected shutdowns, optimize equipment reliability and therefore extend its life. The added value of the digital twin consists in its capacity to pilot the machines from distance when interventions are necessary. The digital twin also has the ability to diagnose and propose solutions such as dynamic reconfigurations in the situation where a equipment is not able to perform its initial function. The digital twin can be used to locate defective equipment, which is useful in complex industrial installations or when interventions are carried out by a subcontractor. The digital twin applied to predictive maintenance can also guide the intervention stages of operators thanks to augmented reality. Finally, it is possible to

optimize decision-making in terms of intervention, by proposing options within a very short delay. These capabilities allow to improve the decision making related to maintenance activities.

The digital twin is characterized by a cyber-physical integration (Tao, Niu & Nee, 2019). This cyber-physical system in which the digital twin is embedded tends towards more autonomy due to the ability of the digital twin to act on the physical element. Therefore, questions emerge about the place of the human agent within this cyber-physical system. This desire to integrate the human move on to a cyber-physical-social system, in which the human operator is no longer considered as an external element but rather as an full-fledged entity, capable of acting on the system (Perez, Meza, Bravo, Trentesaux & Jimenez, 2021). The ability of the digital twin and the human to act on the physical counterpart makes necessary to consider a cooperative approach.

1.2 Human-system cooperation for decision making

Parasuraman, Sheridan and Wickens (2000) consider four categories of activity in information processing: information acquisition, information analysis, decision making, and action implementation. The allocation of one or more of these activities can be viewed as human-system cooperation between the technical agent (i.e., digital twin) and the human agent (Zambrano-Rey & Pacaux-LeMoine, 2011). We will focus on the "decision making" activity which is a key aspect in the human-system cooperation. According to the literature on human-system cooperation, the human agent and the technical agent are cooperative partners whose goals are to identify, share, or exchange informations in order to achieve common goals (Hoc and Lemoine 1998). According to Pacaux-LeMoine et Debernard (2002), the cooperative agents communicate through a "Common Workspace" characterized by common knowledge such as problems, strategies or solutions and allows a "Common Situation Awareness" (Zambrano-Rey & Pacaux-LeMoine, 2011). The definition of this space consists in providing an information support in order to help the agents in their cooperative activities (i.e. decision making). We note the

importance of a common workspace from which the digital twin and the human agent will be able to share common representations, goals and plans. As long as cooperation leads to interdependence between agents, we consider that the digital twin and the human agent will need a common workspace to collaborate. Figure 1 represents the common workspace of the two cooperating agents each performing activities such as decision making. Following Debernard, Cathelain Crevits et Poulain (2002), the model proposed by Parasuraman et al., (2000) has been used to define the common workspace. Thus, the digital twin and the human agent share information, problems or solutions to achieve their common goal.

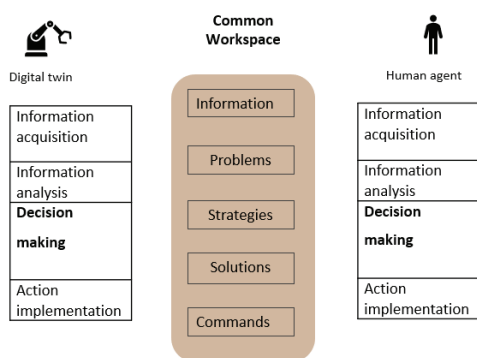


Figure 1: Digital twin and human agent cooperation based on the four activities.

The digital twin is no longer a simple tool but an agent with a decision making capacity and autonomous actions, in the same way as the human agent. Within this scope, it becomes necessary to define the way in which these actions and decision making will be allocated between the two cooperating agents for an efficient cooperation. According to Traore (2021), decision making can be performed either by the digital twin (i.e., closed decision loop) or by the human agent (i.e., open decision loop). Julien et Martin (2021) introduce a mixed loop according to which the decision making by the cooperating agents would be dependent on the situation. In other words, the situational context in which the digital twin and the human agent are located would determine the agent responsible for this activity. The objective of this paper is to use CWA (Cognitive Work Analysis) to support the allocation of decision-making activity. This proposal will be illustrated with the JUPITER

project which aims to develop the digital twin of the SCAP platform for predictive maintenance. The SCAP Industry of the Future is a platform that represents an adaptive cyber-physical production system and serves as a support for the engineering school classes and as a demonstrator for the research projects of various members of the Lab-STICC research laboratory of the Université Bretagne Sud (UBS).

2. Method : Cognitive Work Analysis

CWA is a framework developed for the design of complex socio-technical systems (Rasmussen, 1986) Cognitive Work Analysis is a formative constraint-based approach with five successive stages : Work Domain Analysis (WDA), Control Task Analysis (ConTA), Strategy Analysis (StrA), Social Organization Cooperation Analysis (SOCA), and finally Worker Competencies Analysis (WCA). In this way, this formative constraint-based approach considers these five stages as five types of constraints in which different possibilities are offered to the human operator to perform his tasks (Naikar, 2005). The allocation of decision making activity requires knowing which functions should be allocated, the situations in which these functions are allocated and the resources available to this allocation between the digital twin and/or human operator. In this way, we will focus on WDA, ConTA and SOCA in order to highlight these functions, their situations and allocations.

The WDA focuses on the analysis of the functional structure of the physical, social and cultural environment of actors in a system (Naiker, 2013). The analysis does not focus on how activities are to be achieved, but on what needs to be fulfilled within the constraints of the domain (McIlron & Stanton, 2015). WDA is associated with an Abstraction Hierarchy (AH), a tool that describes the system across five levels of abstraction: functional purpose (the purpose of the work domain, its "raison d'être"), value and priority measures (the criterion ensuring that the system progresses toward the functional purpose), purpose-related functions (the general functions that are performed in order to achieve the functional purpose), object-related processes (processes and capabilities characterizing the objects used by the general functions), and

physical objects. This is a means-end relationship between the five levels of the abstraction.

ConTA describes the tasks to be performed in order for the system to function efficiently. This stage does not describe by whom (for instance humans or the digital twin) or how the task is performed but the constraints related to the realization of this latter. ConTA is associated with the Contextual Activity Template (CAT) tool to highlight the situations in which a function takes place.

SOCA describes the constraints related to the allocation of tasks between the agents of the system. A SOCA-CAT or a SOCA-WDA can be used with a color code for each agent performing functions.

The application domains of CWA are various and manufacturing systems are among them. Nevertheless, only a few papers have dealt with this field (Read, Salmon & Lenné, 2015). Rasmussen, Pettersen & Schmidh (1990) have established the WDA of a manufacturing firm. More recently, CWA has been used for Industry 4.0 purposes such as the design of a human agent assistance system (Pacaux-Lemoine, Berdal, Guerin, Rauffet, Chauvin & Trentesaux, 2021) or for the deployment of a decision support tool applied to the predictive maintenance of vessels (Simon, Guerin, Rauffet & Lasalle, 2021).

We propose a SOCA-AH and a SOCA-CAT to highlight the functions to be allocated to the digital twin and/or the human in terms of decision making applied to the maintenance of the SCAP platform in the context of JUPITER project.

3. Results

We conducted semi-structured interviews with teacher-researchers with expertise with the SCAP platform (Table 1). The topics discussed during these interviews concerned the maintenance functions currently carried out on the SCAP platform and the activities that would be carried out the future digital twin applied to predictive maintenance. For this last topic requiring a projection into the future, we associated to the CWA a prospective ergonomics method named Need Anticipation Interview (Martin, Agnoletti, & Brangier, 2021). The objective of this method was to facilitate the projections of the

interviewees. Thus, before starting the interview, we asked the interviewees how they imagined the future of maintenance with the introduction of the digital twin of the SCAP platform, such as their frequency of use or its location. This phase, called "Future projection", has the particularity of enriching the prospective statements (Martin & al., 2021). The next phase corresponded to "Future ideation" in connection with the objectives of our interviews.

Table 1 : Topics and questions discussed during the interviews.

	Topics	Questions
Future Projection	Frequency use Location	How they imagined the future of maintenance with the introduction of the digital twin of the SCAP platform.
Future Ideation	Current maintenance activities on the SCAP platform	-What are the maintenance interventions that can be carried out on the SCAP platform ? -What are the tools (i.e., documentation, tools) used during the maintenance interventions ? -Thanks to this tool, what is the process that will allow the repair of the failed element ?
	Future activities of the digital twin	-What would be the functions of this future social-cyberphysical system applied to implement maintenance interventions ? -What are the current and/or future tools used to perform these functions ? -How will this tool enable this function ?

3.1 WDA

In addition to the current activities, the work domain analysis was used to collect data on future activities performed by the digital twin and the human agent within the SCAP platform (Figure 2). The identified functional purpose was to ensure predictive maintenance of the SCAP platform through the digital twin. The values and measures priority are associated with maintenance indicators such as MTBF (Mean Time Between Failure) or MTTR (Mean Time To Repair). Maintenance levels (e.g., simple work, major work, etc.) and maintenance cost reduction, temperature and energy consumption are indicators considered for the measurement of the functional objective. Seven purpose-related functions have been identified : "Extract

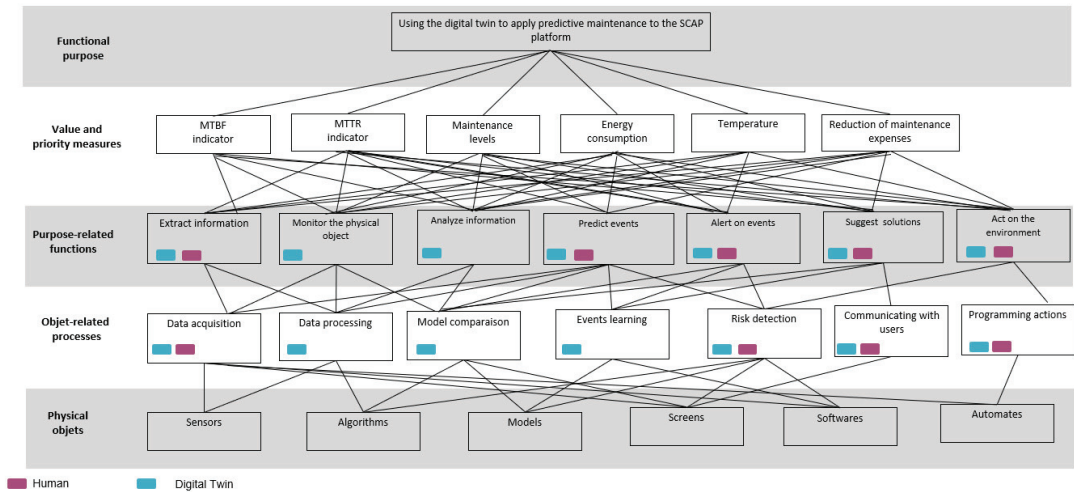


Figure 2: Work Domain Analysis for predictive maintenance of the SCAP platform.

information", "Monitor the physical object", "Analyze information", "Predict events", "Alert on events", "Suggest solutions" and "Act on the environment". These functions are related to the functional purpose (i.e., to guarantee the predictive maintenance of the SCAP platform) because they allow to reach it. The object-related processes differ between data acquisition and processing, model comparison and event learning, risk detection and communication with the users of the digital twin or action programming. The digital twin uses several types of tools to ensure the maintenance of the SCAP platform, such as sensors placed on physical objects to obtain data, algorithms, models and softwares for the comparison and learning processes. It also includes human-machine interfaces for communication and automates that allow programming actions on the environment. The WDA-SOCA also represents the allocation of functions between the human agent (purple dot) and the digital twin (blue dot). Concerning purpose-related functions, the digital twin is able to perform the seven functions mentioned. The human agent has the ability to extract information (e.g., sensory information imperceptible by the digital twin), to alert on events, to propose solutions and to act on the environment. The object-related processes identified at the lower level are also all possible by the digital twin. The human agent can acquire data, detect risks, communicate with users and program actions.

3.2 SOCA-CAT

The aforementioned purpose-related functions are contextualized within the SOCA-CAT. Stanton & Bessell (2014) provide a graphical code to distinguish expected, optional and impossible situations related to functions (Figure 3).

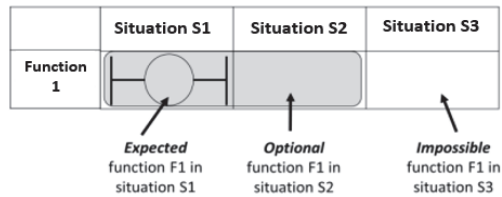


Figure 3: CAT layout (Adapted from Bessell and Stanton, 2014).

We have identified two types of situations (Figure 4). Nominal situations refer to a context in which the system works efficiently without the occurrence of events (e.g., prediction of a failure). Degraded situations refer to the occurrence of events such as a slowdown. Two functions remain constant among these situations : "Extract information" and "Monitor the physical object". Indeed, the capabilities of the digital twin are based on the monitoring of the physical object in order to extract information otherwise the other functions would not have been possible (e.g., predicting events, proposing solutions). The SOCA-CAT highlighted allocation of functions between the digital twin and the human agent

where the latter is also able to extract information and monitor the physical object. Nevertheless, the monitoring of the physical object remains optional in nominal situations. The degraded situations specifically mobilize the functions "Predict events", "Alert on events" and "Act on the environment". Only the digital twin is able to predict events based on information analysis and past events. The human agent is able to alert on events and to propose solutions as well as to act on its environment. The human agent is also able to predict events. These predictions are based on the operator's experience or on heuristics (i.e., deductions made from environmental characteristics). These capabilities present in both cooperating agents contribute to a cooperation based on complementarity. The digital twin bases its predictions on more indicators, which allows it to detect trends that are less obvious to the human agent. The information provided by the human agent to the digital twin is one of the indicators on which the predictions are based. Among the degraded situations, we find failure situations characterized by their consequences. These consequences are standardized by the AFNOR NF X60-500 standard. Thus we find :

- A minor failure: affects a minor function of the physical object. The object remains able to perform its required function.
- A major failure: affects a major function of the physical object. The object is likely to no longer perform its required function.
- critical failure: likely to cause human, environmental or material damage.

4. Discussion

The WDA highlighted features unique to the digital twin such as its ability to extract information, monitor the physical object, and analyze information and predict events. Although the human agent is able to extract information (e.g., sensory information), the other functions previously mentioned are difficult to perform. For example, it seems constraining for the human agent to perform a permanent monitoring of the physical object. Likewise, the human agent is not able to analyze a large amount of data to provide prediction models. Nevertheless, the human agent is able to alert, propose solutions and act on the environment. The functions identified by the WDA can be considered in terms of the four categories of activity described by Parasuraman & al., (2000), as illustrated in Table 2.

Table 2 : WDA functions related to categories of

Categories of activity (Parasuraman & al., 2000)	WDA functions
Information acquisition	Extract information
	Monitor the physical objet
Information analysis	Analyze information
	Predict events
	Alerte on events
Decision making	Suggest solutions
Action implementation	Act on environment

The WDA also allowed us to identify where the allocation of decision making is located among the functions carried out by the digital twin and the human agent. Indeed, this decision making concerns particularly the function "Suggest solutions". According to Debernard, Guios, Poulain, Crévits, Annebicque et Millot (2007), cooperating agents exchange solutions through the common workspace. The issue is to know who is responsible for the final decision among the solutions proposed by the digital twin and the human agent. This choice depends on different

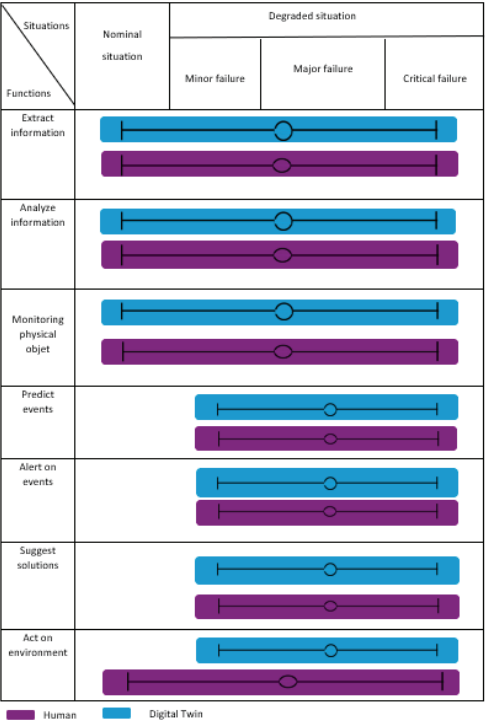


Figure 4: SOCA-CAT

consequential criteria highlighted by the SOCA-CAT. Indeed, the decision making will be different according to the minor, major or critical consequences of the failure. The function "Suggest solutions" can be considered by the levels of automation proposed by Parasuraman et al. (2000). According to these authors, an activity can be automated at different levels on a continuum ranging from 1 (low automation) to 10 (high automation). Level 1 would correspond to a scenario in which the human agent would make decisions without assistance from a system. On the contrary, the 10 would refer to a scenario where the system would act in a totally automated way, without taking into account the human agent. Considering the prediction of the unhooking of the top conveyor of the SCAP platform in one month. This failure will have major consequences given the risk of human injuries, production shutdown and repair costs. The digital twin and the human agent propose solutions to avoid the occurrence of this failure. For example, the digital twin may propose an intervention in the next few days at the most appropriate time (e.g., during a low production rate), while the human agent may judge that the appropriate time would be in two weeks. The question is which of these two cooperating agents will make the final decision in this given situation. Automation level 1 would assume that the technical agent makes the decision, without intervention from the digital twin. At automation level 10, the digital twin would make the decision without consultation with the human agent. An intermediate level such as level 6 would place the digital twin and the human agent in a cooperative setting where the human would have a veto right on the decision taken by its partner. A debate cooperation would take place between them. In other words, the cooperative agents would confront their solutions to obtain an optimal one. Parasuraman et al., (2000) suggest that a high level of automation of "Decision Making" activity would be preferable in low risk situations such as the occurrence of a minor failure. A critical failure would however be linked to a low level of automation.

5. Conclusion

The objective of this paper was to identify how decision making activity could be allocated

between digital twin and human agent in the framework of predictive maintenance. The WDA highlighted the functions carried out in order to ensure the predictive maintenance of the SCAP platform and the allocation of these functions between the digital twin and the human agent. The SOCA-CAT emphasized the situations in which the functions should be allocated to the digital twin and the human agent. The decision-making activity represented by the "Suggest solutions" function in the WDA and SOCA-CAT can be considered in term of automation. In this way, a low automation level of this function refers to a decision-making activity by the human agent. Otherwise, a high automation level indicates that the decision-making activity is conducted by the digital twin. In a cooperative approach, the objective is an intermediate level where both cooperative agents contribute to a solution. The outputs collected by the CWA will provide recommendations for the deployment of the digital twin to JUPITER project. The allocation of decision-making have been considered in a static perspective. Nevertheless, a failure can modify the requirements so that the system meets its functional purposes. Dynamic allocation of decision-making activity can be a way to control the ability of the system to react to the occurrence of a perturbation by retaining performances.

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