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Integrating ergonomics into the early stages of Digital Twin design

From the design of a Digital Twin for short-distance dairy producers to the definition of a generic and tool-based method

FANNY GUENNOC

Lab-STICC – FHOOX – UMR CNRS 6285, fanny.guennoc@univ-ubs.fr

Naomi Kamoise

Lab-STICC – SHAKER – FHOOX – UMR CNRS 6285, naomi.kamoise@univ-ubs.fr

Clément Guerin

Lab-STICC – FHOOX – UMR CNRS 6285, clement.guerin@univ-ubs.fr

Nathalie Julien

Lab-STICC – SHAKER – UMR CNRS 6285, nathalie.julien@univ-ubs.fr

The Digital Twin (DT) is defined as a dynamic virtual representation of an object (product, process or service). The presence of this type of solution is increasing in companies, and inevitably brings about transformations in user activity. However, the design of innovative solutions is still too often technocentric. Ergonomists have a role to play in this type of project, ensuring that the activities and needs of users are taken into account throughout the design process. This calls for common methods and tools to facilitate dialogue between ergonomists and designers. The proposal of this paper is to enhance the approach first established by for the design of a DT with methodological contributions from design ergonomics and prospective ergonomics.

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1 Introduction

The digital twin is an emerging technology that requires multiple skills for its design and deployment (sensors, networks, system modeling, hardware and software architectures, etc.). However, there are currently no standards or methods to guide designers. Moreover, the approaches proposed in the literature are often techno-centric, which can lead to acceptability problems [1].

Previous work has highlighted the importance of defining the digital twin in relation to its uses, and of postponing technological choices until as late as possible, based on generic architectures that promote reuse [2]. Such an approach also aims to integrate human-system interactions throughout the process. However, to achieve this, it is essential to develop common methods between ergonomists and technologists, i.e. design tools that take ergonomics into account throughout the design of the digital twin (DT), while at the same time being understandable and usable by technologists. The various works concerning ergonomics and the digital twin focus on two aspects: Human in the DT or human with the DT. The human is modeled by the twin to evaluate or monitor his performance as an operator performing manual activities and thus predict musculoskeletal disorders, accidents, etc. [3] [4] [5] [6]. The operator can also be modeled to design and evaluate work situations involving human-robot collaboration [7] [8]. Other works are part of the HAT (Human Autonomy Teaming) trend and consider the human and the DT as two agents that can cooperate, e.g. for the planning of maintenance activities [9] [10]. This article addresses a third aspect, focusing on the work of designers and how ergonomists can support the various design stages of a digital twin.

The TERRA project is financed by the Brittany region, which brings together various partners with a common desire to put technology at the service of societal and environmental issues. The digital twin being developed will be aimed at dairy producers and processors working in short circuits. It will enable them to process quality and traceability data in real time. From an operational point of view, the aim is to produce a general-purpose, adaptive digital twin that can be deployed in various dairy processing units wishing to go digitalization. Various skills from engineering, IT, data processing, agri-food and ergonomics are mobilized.

Lab-STICC is leading a number of digital twin projects, each of which is contributing to the development of a generic design methodology [11]. Beyond the technological challenges, a frequent source of difficulty is the dialogue between partners from different disciplines. Sharing objectives and representations is indeed a crucial element in designing a DT that is operational, relevant and accepted by future users. The special feature of the TERRA project is the integration of an ergonomist right from the upstream phases of the project. The aim of this article is to use this specific case study to show how the ergonomist can encourage interdisciplinary dialogue. In addition, based on this experience, we propose to enrich the generic DT design methodology.

2 The digital twin: Principles and design methodology

2.1 Digital Twin Characteristics

The concept of the digital twin was initially defined by Grieves [12] as the set of data and models linked to an object all along its lifecycle. This vision subsequently evolved throughout the community, leading to a multiplicity of different definitions depending on the types of objects or applications considered.

In previous works [11], we not only defined the digital twin as a dynamic virtual representation of an object (product, process or service) but also identified its major characteristics as:

A continuous digital thread between real and virtual spaces,

- An architecture allowing to permanently increment and enhance models on-line and off-line,
- A formalized decision-making loop with partial or total control of the object or its environment,
- Learning and prediction abilities in a delay compatible with decision support.

2.2 Methodology for Digital Twin Development

The lack of a generic standard for the digital twin concept is also reflected in the absence of a design methodology. Barth, Ehrat et Rockel [13] point to the lack of a shared conceptual framework that would enable discussion between the different disciplines involved in the development of digital twins. Julien and Hamzaoui [2] highlight the importance of designing the digital twin according to its uses and interactions with its whole environment, physical, digital, and human. They have developed a complete design and deployment methodology based on generic architectures, to enable reuse by postponing technological choices as long as possible. Such an approach also encourages multi-disciplinary approaches, enabling the integration of regulatory constraints, architecture sizing for eco-design and the integration of human-system interactions. This methodology was first derived from the 5C CPS (Cyber Physical System) architecture proposed by Lee, Bagheri and Kao [14] and specifically adapted for digital twins as represented in Figure 1.

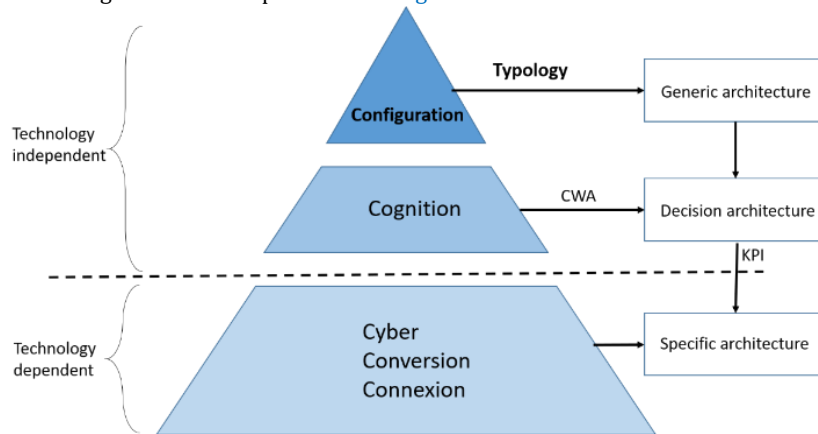


Figure 1 : Deployment Methodology based on the 5C CPS Architecture [11]

At the top of the pyramid, we find the Configuration level, followed by the Cognitive one. These two layers are technology independent, therefore, a generic development approach can be considered at an early stage.

At the **Configuration Level**, we define the major characteristics of the DT architecture for the targeted application; this typology aims to guide efficiently DT designers through this step to provide a first generic architecture.

This generic architecture is then refined at the **Cognition Level**. The focus here is to determine the allocation of decisions between human and systems (including the considered digital twin). A powerful methodology like CWA (Cognitive Work Analysis) can be applied, in order to obtain the formalization to the decision architecture. At this level, we also can define the required KPI (Key Performance Indicators) to support decision, which will be derived from data and models detailed in the lower levels.

The **Cyber Level** aims to determine the data architecture by listing all the required data and models, and to evaluate their criticality; hence first technological choices can be made such as whether or not to use the cloud computing, how to share or protect data, together with cost estimations. The two other levels, **Conversion** and **Connection** consist in refining the technological choices as sensors, networks, and protocols in order to obtain the specific architecture.

Using the Terra project as an example, we propose to enrich the first stages of this generic methodology to meet the challenges of technology relevance and acceptance by future users.

3 Ergonomics in the development of innovative devices

3.1 The Dialogue between Ergonomists and Technologists

For some forty years, ergonomists have been developing ideas, tools and approaches to help design projects take present and future activity into account. Design projects are still very often techno-centric and often encounter the pitfalls of "the lack of political management and of actual cooperation in project management" and "the work that takes place in the organization is approached only as a set of theoretical tasks in project management" [15]. The current context of corporate digitalization brought about by the Industry 4.0 program is accelerating the need for ergonomists to make progress on design with technologists to encourage the consideration of real or future work in the design of new technologies. The quality of cooperation with designers is a crucial aspect. Co-design is not self-evident, and requires the creation of a "common world" despite differing knowledge and points of view [16].

We note that, beyond the desire to conduct projects in a participative and collaborative way, there is still a lack of operational proposals for taking into account the social, organizational and technical challenges of work [15]. Our aim is therefore to think about how to implement our tools and methods from the ergonomics of design (and sometimes prospecting) in a generalist approach mobilizing standardized tools for the development of a digital twin.

3.2 The Ergonomic Design Approach

Barcellini, Van Belleghem and Daniellou [17] indicate that the effectiveness of ergonomists' intervention in design projects lies both in their ability to enrich decision-making with data on activity, and in their capacity to create the conditions for the development of designers' activities. These authors have produced a model illustrating the different stages in the ergonomist's intervention (cf. Figure 2).

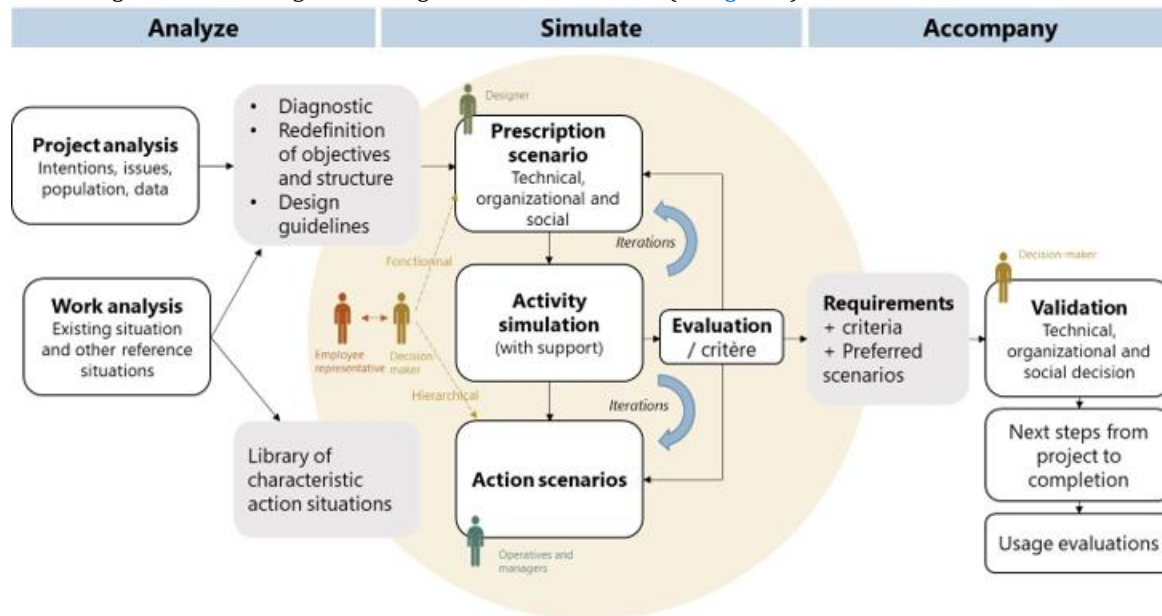


Figure 2 : Project management approach proposed by the ergonomics of activity [17]

The first phase corresponds to the **analysis of the project** and the work that will be modified. During this phase, the ergonomist identifies the intentions of the different project stakeholders and analyzes the structure of the project. At the same time, it produces knowledge about the activity. This first phase of analysis helps to redefine the objectives and, if necessary, the structure of the project. The knowledge produced during the analysis of work situations (existing or reference) will be formalized in the form of design guidelines. The **simulation** will then aim to have the future work performed by the people concerned either in full size (using a prototype) or using reduced simulation supports (for example a model). The results of the simulations must feed the dialogue between future users and designers to define compromises. The design criteria retained during the simulation sessions are drawn up and submitted to decision-makers for validation. The ergonomist then **supports** the iterative development of the solution by the designers [17].

Our communication focuses on the first stages of the process, in particular on how to integrate the project analysis and transmit design guidelines from the activity analysis to complete the 5C methodology presented above.

3.3 Methods and Tools of the “Analysis” phase

When **analyzing a project**, the ergonomist's contribution can be differentiated according to two situations. For innovative projects in the inception phase, the ergonomist can draw on methods from prospective ergonomics to enrich the project's objectives. He may call on scientific and technical experts (who have professional expertise in the target field) or on precursor users (individuals experiencing activities or artifacts identified as precursor or prospective in a field) [18]. When the project moves into the implementation phase, the ergonomist carries out a strategic analysis by meeting the various players involved in the project (decision-makers, designers, future users, staff representatives) to identify their strategies, needs and representations about the project. He can help structure the project and promote decision-making by creating collaborative discussion forums [19].

Work analysis methods will also need to be adapted to each specific case. If the work situation concerned exists and is accessible, the ergonomist carries out observations and interviews with the people concerned. Otherwise, activity analysis can be carried out on reference situations. During the development of an innovative tool, prospective ergonomics proposes methods designed to help potential future users make their own plans. Examples include the use of prospective personas [20], interviews to anticipate future needs [18], or Guided Imagery Projection - GIP [21].

Ergonomists must translate the results of activity analysis into **design guidelines**. The format of these guidelines varies widely depending on the type of project (architectural, product design, organization, equipment, etc.). Nevertheless, Duarte and Lima [22] and Daniellou [23] identify three types of specifications. Firstly, technical specifications provide data on standards (anthropometric, visual, etc.). They do not, however, provide information on actual activity. Secondly, Characteristic Action Situations (CAS) are specific guidelines linked to the activities analyzed in reference situations. They provide designers with information on the use of technical systems, and are particularly useful for simulation sessions. Thirdly, usage configurations are halfway between technical specifications and CAS. Their purpose is to crystallize the experience of users of different units. We understand them as a generalization of the CAS to guide general design decisions. They then serve as a basis for specifying the more particular reference situations and characteristic action situations to be analyzed for project deployment in a defined unit. Finally, as part of the development of an innovative tool, the guidelines can take the form of prospective usage scenarios to describe future usage contexts in a general way [18].

4 The Terra Project

4.1 The Origins of the project

The Terra project brings together four partners working on a common project to give small dairy producers working in short supply chains access to digitalization. Small producers do not have the same resources as large agri-food companies to manage their data on the quality of finished or semi-finished products, the presence or

absence of allergens, energy consumption and so on. Yet managing data throughout the production cycle helps to ensure transparency on the origin, processing and quality of products, thereby attracting, reassuring and retaining consumers.

Common general objectives have been identified, such as the desire to produce a system that serves short-distance producers, and to integrate values linked to reducing the industry's impact on the environment, food transparency and digital sobriety. While the common direction is clear, the internal stakes of each are sometimes not very explicit.

4.2 The Partners

A presentation of the four partners, based on an analysis of the project carried out by the ergonomist, is summarized in [Table 1](#).

Table 1 : Description of TERRA project partners

Partners	Activities	Areas of expertise	Expectations
Alma Food (1 member in the project)	Alma Food is a Young Innovative Company. Its aim is to make tools and services available to small producers, like those available to large companies. The head of this company has developed expertise in the ontology of short-circuit products and processes.	Extensive knowledge of the agri-food industry Experience in information systems innovation	Creation of an open-source, resilient PLM (Product Life Management), which would feed the DT.
Center for Food Experimentation and Processing (2 in the project)	CETA is an association governed by the French law of 1901. It is a "mini-factory" that can produce and market dairy and meat products. Its main missions are training and R&D.	Extensive knowledge of the agri-food industry Training experience	Digitizing CETA Stay competitive by expanding the training catalog to include digital technology and energy management
DnRSys (2 members in the project)	DnRSys is a design office for electronic and mechatronic systems. The customers are companies operating in harsh environments, i.e. those subject to sealing and user-survival issues (agricultural, maritime, industrial).	Both members have strong expertise in manufacturing processes and materials (milk).	Marketing a tool that is profitable in the short term
Lab-STICC (4 members in the project)	The project is led by the Shaker team, which works on the optimization of software and hardware systems according to the constraints and hazards of their environment.	The four members involved bring together expertise in: Digital twin design methods IT development Data intelligence Ergonomical design	Develop a demonstrator Capitalize on knowledge and create a generic approach applicable to other digital twin projects.

The ergonomist involved in the TERRA project is a teacher-researcher and one of the four members of the Lab-STICC laboratory. She is directly involved in the development of the digital twin design method. Her background as an industrial engineer also enables her to contribute to the choice of common generic tools.

4.3 Specific Objectives to converge

Table 1 shows the wealth of expertise involved. However, interdisciplinarity is not self-evident, and the partners' objectives can be difficult to reconcile. For example, the IT development practices of some partners were focused on tools customized to customer requirements, while others wanted highly generic, configurable tools. In addition, the scope of the digital twin had to be redefined. After various meetings, it was decided that the digital twin would cover the extended dairy process (from the arrival of raw materials to the dispatch of finished products, rather than the entire supply chain).

If we focus on the expectations for the Lab-STICC partner, on the one hand, the challenge is to complete the development of a digital twin demonstrator for dairies. At the same time, the challenge is to capitalize on knowledge of methods to encourage the development of other digital twins, whatever the type of object and sector of activity. Lab-STICC members already have a number of experiences in digital twin design, and have identified the benefits of integrating acceptance issues right from the start of the design process. However, we are still lacking a structuring framework to achieve this, and this is what we are being asked to do as ergonomists.

5 Generic design stages for the DT, integrating ergonomics right from the start

The generic DT development approach we are proposing is based on the 5C approach presented above. We make it evolve with two objectives in mind: To have a clear project structure that encourages dialogue between the decision-maker, designer and ergonomist, and to propose an approach that encourages the design of a tool that enables the development of future users' activity. To achieve this, we propose to add a project analysis phase, and to enrich the configuration and cognition phases with activity and needs analysis (Figure 3). The contributions to this model are shown in green. They are then detailed below and illustrated using data from the TERRA project.

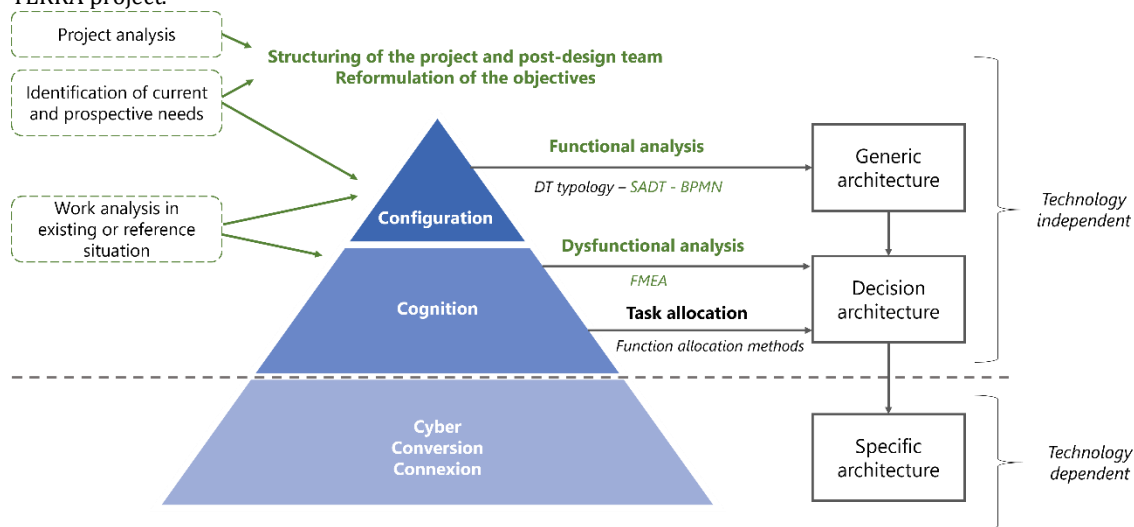


Figure 3 : Deployment Methodology based on the 5C CPS Architecture and including an ergonomic approach (adapted from [11])

5.1 Adding Project Analysis

Digital twins development projects are subject to the same pitfalls as any other project, and are also confronted with specific risks such as access to data and the sustainability of the tools over time, which requires a solid project structure from the outset. Data access is dependent to technical constraints (existence of sensors), economic constraints (possibility of investing in new equipment/sensors if necessary), and legal constraints (who owns the data before and after processing, and who owns the connectors). Another major issue in the design of the DT is its exploitations i.e. the life of the digital tool after its development. The DT manages several models and databases using connectors that may belong to different entities. It is essential to define post-development project management from the outset, to ensure the DT's continuity and resilience over time and through technical and organizational changes. Moreover, the digital twin is still in its infancy, and there are few clear ideas about what can be done with it. Even general objectives can be difficult to define. The ergonomist has a role to play in identifying the prospective needs associated with the tool. He or she can mobilize the prospective needs identification methods defined in prospective ergonomics.

The analysis of the TERRA project was carried out by the ergonomist, who focused on the history of the project, the context of the various partner structures and, at individual level, on skills, project activities and constraints. Project members greatly appreciated the opportunity to express their wishes and fears within the project. Following the presentation of the results of the analysis, we noted a greater fluidity in the dialogue between the various partners. The structure of the project does not need to be reshaped. It already provides space for exchanges, sharing of practices and decision-making.

5.2 Enriching the functional and the dysfunctional analysis

The configuration phase aims to define an initial generic architecture, with the identification of the first generic bricks corresponding to the main functions of the object to be modeled with DT.

As indicated in the ergonomics design intervention approach, the ergonomist provides knowledge of work situations through the analysis of existing situations, reference situations or through the analysis of prospective needs. Such a work analysis (nominal and degraded situations, elements of variability) enriches the building blocks to be integrated.

In the TERRA project, ergonomist took a tour of a dairy considered as mature in terms of digitalization (reference situations) to understand the process and what can be digitalize. Collected data were formalized in such a way as to feed into a functional analysis and a dysfunctional analysis. The standardized tools proposed are 1. SADT (Structured Analysis and Design Technique) for a generic representation of unit operations, 2. BPMN (Business Process Model and Notation) for the representation of a specific process, and 3. FMECA (Failure Mode, Effects and Criticality Analysis) for dysfunctional analysis. To describe only BPMN, it is a tool governed by graphical standards. It is used to model activity successions (orchestration diagram) and to show interactions between two processes (collaboration diagram) [24]. The diagram below (Figure 4) illustrates an extract from an orchestration diagram applied to the production process for plain yoghurts at CETA.

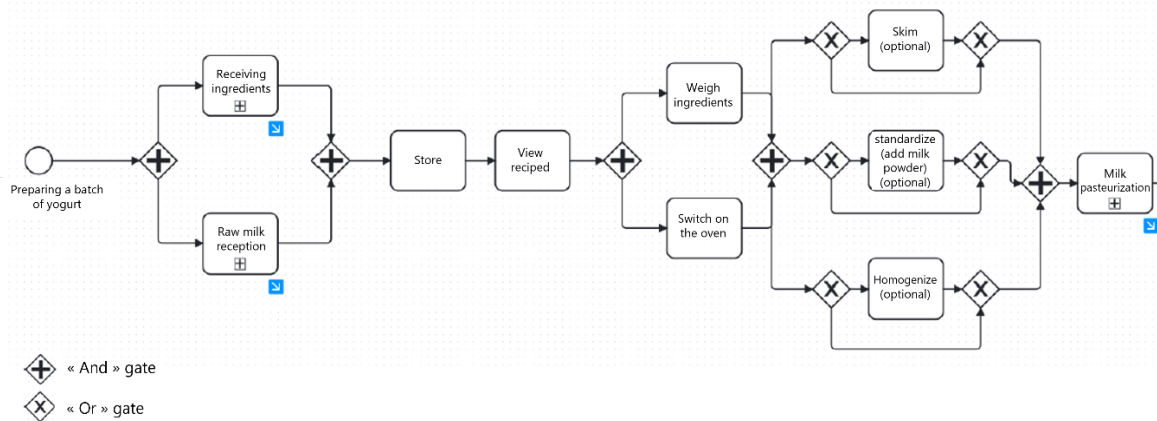


Figure 4 : BPMN extract applied to a generic yogurt manufacturing process

Figure 5 shows a representation of the possible distribution of unit operations between the physical world (equipment, sensors, etc.), the human agents, and the DT. We chose to use the BPMN tool because it's a graphical representation that facilitates the interdisciplinary dialog. It enables IT specialists process-related requirements to be understood by the designers who will execute the computer code. Moreover, after rapid training in BPMN, professional experts can easily correct the model (identify gaps, add subtleties linked to real-life situations). Finally, the ergonomist can also use this representation to get future users to discuss the tasks and decision-making allocations between technical equipment, users and the DT.

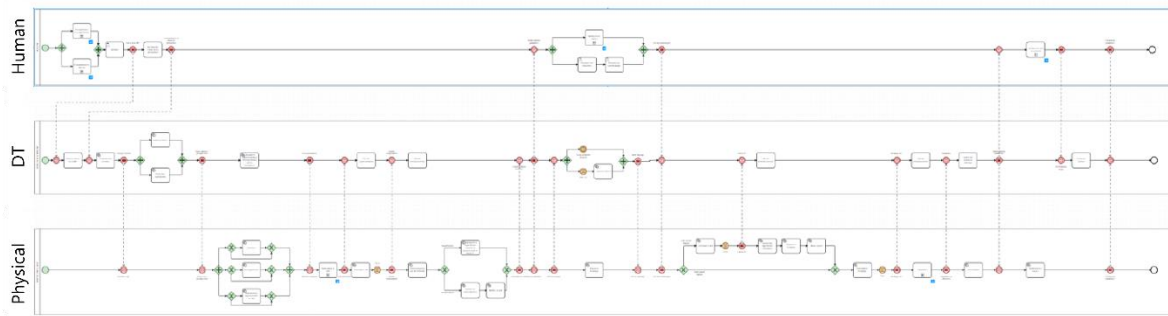


Figure 5 : Collaboration BPMN diagram between physical world, Data twin and human agents

The work analysis phase is still being carried out. We currently rely mainly on the knowledge of expert partners (Alma Food and CETA) for the description of generic processes. and we are looking for more reference situations to analyze.

6 Conclusion and perspectives

Terra is a particularly interesting project in which to deploy an ergonomic approach as the project members are conscious of the importance of integrating elements of the activity right from the start of the project. What's more, several members of the project group have multidisciplinary profiles. This greatly facilitates the connection between the "worlds".

However, despite this strong desire for interdisciplinarity and the integration of ergonomics, we note a lack of methodological framework to achieve this. We need to think collectively about the most appropriate tools for laying the foundations for interdisciplinary dialogue (agri-food engineers, developers, electronics engineers, ergonomists). What's more, we need to generalize our approach to avoid these difficulties in other digital twin projects, both current and future.

This paper makes a proposal for the integration of ergonomics in the early stages of design. The project is still under development. We have yet to carry out a more extensive field phase, which would require research into several reference situations. Our ideas will have to be put to the test in a field analysis to validate the first phases of this methodology.

The next step is to integrate approaches from cognitive ergonomics to define the allocation of tasks between humans, processes and digital twins. Methods from cognitive ergonomics will be considered, such as traditional methods (MABA-MABA; LOA) and or other additional methods (CTA-CWA, HTM) [[25] [26]. The simulation phase will be carried out with experimenters (dairies producers) using a demonstrator that will help with design choices of the digital twin.

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