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A generic architecture to design Cyber-Physical and Human Systems

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Abstract: Although Cyber Physical Systems are widely implemented in many areas, model architecture for Human and CPS remains insufficiently studied. In this paper, a generic model is proposed to describe the architecture of a Cyber-Physical & Human System. This model deals respectively with the cognitive levels of the decisional process, the nature of the informative details and the sharing of the tasks execution between Humans and machines. Finally, the model is applied to a case study in the healthcare domain.

Keywords: Human-centered system, Human-machine system, cybernetic loop, task, cphs.

1. INTRODUCTION - MOTIVATIONS

Nowadays Cyber Physical Systems (CPS) are used in numerous areas such as smart industry, smart cities, smart energy systems and smart buildings. Through new communication means, artificial intelligence, and decision-making technologies, they become smarter and they interact more easily with their environment (Monostori et al., 2016). However, their autonomous behaviors and the numerous interactions render them more and more difficult to apprehend by humans. A deeper understanding of the interactions between cyber-physical systems and humans becomes crucial. As argued in (Garcia, 2019), in contrast to the third industrial revolution, CPS are not intended to substitute humans in industry, but to work with them in synergy. As highlighted in (Dworschak & Zaiser, 2014), two extreme alternatives can be considered: techno-centric and anthropocentric. In techno-centric approach, CPS will dominate, and human work will be determined and controlled by the technology; in the second one, workers will be master and make decisions, supported by CPS. The modeling of Cyber-Physical & Human System (CPHS) has been investigated recently and very few models and frameworks have been proposed. As claimed in (Fontani, 2020), in a manufacturing context, novel approaches are required to support the design and assessment of work allowing the co-presence of humans and CPS. Some recent works are listed hereinafter.

In (Nunes, 2015), a classification of Human-in-the-loop Cyber-Physical Systems (HiLCPS) is proposed. Three types of applications are considered: (i) applications where humans directly control the system, (ii) applications where the system passively monitors humans and takes appropriate actions, and (iii) a hybrid of (i) and (ii).

In (Sowe, 2016), the focus is held on human's general capabilities and the ability to perform specific tasks (e.g. sensing, decision-making). A human service capability description model (HSCD) is proposed to describe the tasks that a human can perform; the associated qualifications, the

types of human-interfaces and the identifier associated to the person.

In (Fantini, 2020), in an Industry 4.0 context, the authors proposed a methodology to support the design and assessment of different work configurations taking into account both human and CPS capabilities. The developed analysis and design framework is built according to six main points of view relative to the Human and the CPS, taking into account decision-making capabilities, innovativeness and social perspectives.

In (Cimini, 2020), the authors explore a Social Human-in-the-Loop Cyber-Physical Production Systems (Social HITLCPPS) architecture, based on three layers (physical, control and cyber). In the "Physical" layer, humans directly interact with resources that are equipped with local intelligence and communication means. In the intermediate "Control", control agents reproduce the behavior of the physical objects. In the highest "Cyber" layer, human operators can interact with the cyber representation of reality through software applications, which contributes to the interpretation of the behavior of the different factory entities. This architecture enables the design of different configurations from hierarchical to heterarchical structures.

In (Valckeners, 2020), the author proposes the ARTI model. This model is oriented control with a simulation-based optimization. An important point in ARTI is to consider in the world of interest any active entity (called "resource") as a potential executor of, so-called, "activities". ARTI is on the principle applicable to all system type and so potentially applicable to CPHS.

In (Pacaux et al., 2018), the authors propose a model of a cooperative "agent" (human being or artificial entity) with two main facets: the agent's ability to control the process, also called the Know-How (KH), and the agent's ability to cooperate with other agents involved in the process control, also called the Know-How-to-Cooperate (KHC). This model is then applied to the context of the Humanism ANR project (Pacaux et al., 2018; ANR-17-CE10-0009), to study and

experiment innovative human-machine to control intelligent manufacturing systems.

These works all adopted a Human-centered approach and emphasize on one or several aspects as for example Human/CPS capabilities in task performance, heterarchical/hierarchical architectures, cooperation, Human in the loop... Even, if these works are valuable contributions, they do not provide a generic architecture able to describe a CPHS. The next section aims to give some responses to this issue and proposes such a generic architecture. Section 3 illustrates the contributions on a case study. The last section concludes this paper.

2. ARCHITECTURE MODEL FOR A CPHS

The aim of this paper is to offer to a modeler or a designer a generic model, simpler as possible, technological agnostic, to describe the architecture of a CPHS. The purpose is to guide, to help, and not constraint the search to a single rigid solution. The genericity concerns the adoption of a broad vision on the problem space (i.e. problem representation) related to a CPHS, so that, for example, he/she can make the right design decisions on what the Human (and/or the machine) supports in the system. The next section details the CPHS and the associated tasks.

2.1 World of interest and associated tasks

Generically speaking, a CPHS can be seen as compounded of Humans and machines for executing tasks in a huge variety of sectors (e.g. manufacturing, healthcare, logistics, transportation...). As illustrated Figure 1, the humans and machines are considered immersed in a context (e.g. physical, informational, legal...) in a world-of-interest. This last is the field in which the tasks execution occurs, (e.g. workshop, operating room, logistics network, etc.).

For genericity purpose, a task is considered as a process permitting to achieve an objective and conjointly or not supported (for execution) by Human(s) and/or machine(s). The task relies on the mature concept of (cybernetic) loop that is relevant to almost all type of systems (e.g., mechanical, physical, biological, cognitive, social...).

As highlighted Figure 1, two types of tasks are considered:

- The primary tasks: they are directly representative of the activities of the CPHS in the world-of-interest (e.g. an assembly task with a human and a collaborative robot in a workshop).
- The secondary tasks: they aim to improve the performance criteria associated to the primary tasks. For example, a self-diagnosis secondary task associated with a predictive maintenance system can improve the availability of a machine. Another secondary training task can be used to improve the skills of the humans by some training offers.

As highlighted Figure 1, a set of information and decision loops are associated to the secondary tasks. These loops connect the world-of-interest to different intervention

systems (e.g. maintenance systems, supply systems) that have to act on it. Each intervention system is composed of a collective of humans and machines operating in a specific context under the responsibility of a stakeholder. This last is defined as any entity (human or artificial) belonging to a company or organization and requiring information/knowledge to make decisions to improve the value chain associated with the world-of-interest, for example product provider, companies involved in the maintenance or supply of consumables, software robot, etc.

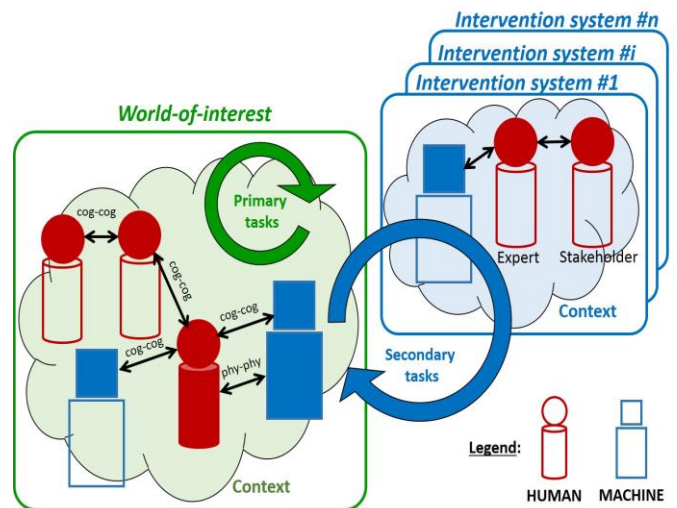


Fig. 1. Primary and secondary tasks in a CPHS

In the world-of-interest, Humans and machines are task executors. For that purpose, a generic model for both Human and machine and a generic model of the CPHS tasks have been developed. These two models are now described.

2.2 Generic Human/machine model

In our work, Human is central, so his two fundamental dimensions “mind” and “body” were retained (Marras and Hancock, 2014). Human being is not alone, a third dimension was added to consider the interactions with other Human(s) and/or machine(s). For the sake of genericity, the same type of model for Man and machine was adopted with the cognitive, physical and social dimensions, cf. Figure 2.

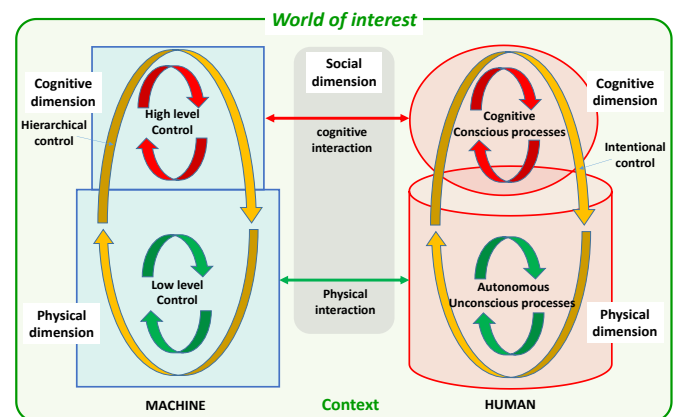


Fig. 2. Generic models: Human (right) and machine (left)

As illustrated Figure 2 (right), three dimensions are used to characterize the Human:

- **Physical:** this dimension concerns all the physical interactions acting/perceiving to/from the world-of-interest. Physical behavior is under the control of conscious or unconscious processes. For example, in an assembly operation, the coordination of movements to precisely insert a cable into a connector can be triggered by the “conscious brain” (i.e. controlled processes) but the execution is taken over by the “unconscious brain” (i.e. automatic processes) (Schneider and Chein, 2003).

- **Cognitive:** this dimension concerns all conscious decisions taken in relation to the solving of a problem (known or unknown). This dimension is also related to the intentional engagement, control, triggering, of the physical dimension to perceive and act. For example, the execution of a task requires to respect consciously a procedure/rules/protocol (e.g., to start-up/shutdown a machine, to interact with others).

- **Social:** this dimension is seen largely and is related with others (i.e. Humans and/or machines) in cognitive or physical interactions. For example, the human can collaboratively interact with a cobot seen as a physical assistant, or can interact with a decision support (or other Human), seen as a cognitive assistant.

The context can affect the human performance on the three introduced dimensions. For example, in the physical dimension, a tired human is slower. In the cognitive dimension, a human with limited expertise may make wrong decisions. In the social dimension, a human subject to psychological stress can divert from others, reducing interactions, and making errors.

This model can symmetrically be applied to a machine (Figure 2, left) with the same dimensions:

- **Physical:** concerning for example the mechanical parts of the machine, sensors, actuators and low level control to animate an entire structure.

- **Cognitive:** concerning the high level control of the machine managing the physical dimension. For example, the execution of a procedure to perform a machining operation, transport...

- **Social:** concerning the rules/protocols to interact with others (i.e. Humans, machines) and the participation to the execution of task.

As for Human, these three dimensions are affected by the context (e.g. temperature, vibration, energy...) impacting the machine. Even if machines and humans are modelled using the same approach as introduced, the choice between Human or machine to execute a task must be considered. This aspect is treated in the next section.

2.3 Generic CPHS task

A task must be shared (for execution) between Human(s) and/or machine(s) considering strengths and weaknesses of each of them.

The characterization of a task is based on different models. Two first models, SRK (Rasmussen, 1983) and DIK (Ackoff, 1989) models, allow characterizing respectively the cognitive levels of the decisional process and the nature of informative details. They help to consider the complexity of task (in term of capabilities, performance, error...) between Human and machine. Complementary to SRK and DIK, a third model AADA (Parasuraman et al., 2000) decomposes the generic loop perception-cognition-action in classes and describes the task sharing between Human and machine. These models are considered as references in the literature. They are generic, and used in several application cases. All these models are based on a view of the Human (and by extension for the machine) in term of perception, cognition and action. The articulation of these models in our architecture is suggested. Figure 3 provides an example and illustrates such an articulation. The placing of "H" and "M" has to be done according to the concerned application.

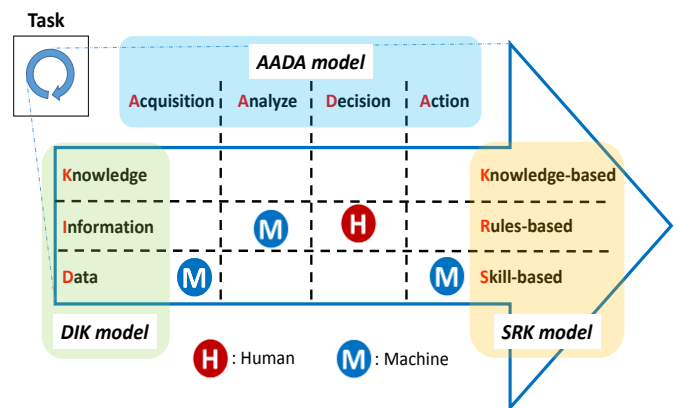


Fig. 3. Model of a CPHS task: articulation of models

The SRK model distinguishes three behavioral levels:

- At a lower level, which corresponds to the “Skill-based” behavior, the activity is instinctive and directly involves the sensorimotor system (in the case of a human). The associated treatment is of the innate reflex type or resulting from a training phase generally long.

- At a mid-level, which corresponds to the “Rule-based” behavior, the activity is procedural, based on learned rules associated with familiar situations. On this level after recognition of a sign, a procedure is associated, triggered and then executed. An algorithm, like a recipe, generally can describe the behavior.

- At a higher level, which corresponds to the “Knowledge-based” behavior, the informative elements treated are typically "Symbols". They have meaning and correspond to knowledge elements. They offer a conceptual, cultural, detailed interpretation of the signals, signs and relationships between them helping to understand a situation. Once the situation has been understood, taking into account an objective to be achieved, an action plan could, for example, be created from scratch and then put into action.

The DIK model permits to complete the previous SRK model by describing the semantic of the processed “data”:

- D (for Data) are raw facts without important meaning issued from the world-of-interest (e.g., temperature, pressure...). D is equivalent to "Signal" which is associated to the "skill-based" behavior.

- I (for Information) are obtained by adding informative details to data (D) as "when", "where", "who", "how", "what" (e.g., operator (who), in a workshop (where) at a specific time (when)). I is equivalent to "Sign" which is associated to the "rules-based" behavior.

- K (for Knowledge) can be seen as groups of information (I) that are linked by semantic relations (e.g. robot UR5-1 used by an operator O3 in workshop WF2 in an operational context where the external temperature of the environment is 35°C). K is equivalent to "Symbol" which is associated to the "knowledge-based" behavior.

The AADA model aims to represent the sharing of the tasks execution between a Human and a machine. It considers four broad classes of functions: information Acquisition, information Analysis, Decision and Action. In this AADA model, the choice (according to a static or a dynamic policy) between Human and machine can be done, for example, on basis of capabilities, efficiency, risk, reliability, safety, cost... In a design perspective, the downside is that Human has to do everything that a machine is unable to do. Human is confronted with the "irony of automation" (Strauch, 2018) and in spite of himself becomes the "magic solver" (Trentesaux & Millot, 2016) for managing very difficult situations. This, in the long run, is obviously not tolerable for the Human in the system.

These models (i.e., SRK, DIK and AADA) do not give direct solution but must be considered as a guiding framework, which partitions the problem space and gives a broad vision. This last avoids a too limited view of the problem. It also limits what has been identified as "bounded rationality" (Gigerenzer and Selten, 2002). The next section illustrates our contribution through a case study.

3. CASE STUDY

The case study is relative to the development of an assistance system in the healthcare domain. Each year, after a stroke, more than 5 million people worldwide become hemiplegic. This neurological impairment affects the ability to get up and/or walk. The VHIPOD project (i.e. Self-balancing transport vehicle for handicapped person in standing position with support for verticalization (ANR-12-TECS-0001)) offers new support solution between the wheelchair and the walker (Allouche et al., 2018). The Figure 4 shows a Viphod at home used by a patient.

3.1 World of interest and associated tasks

The world of interest (cf. Fig. 4) is composed of a single Viphod product, of a single patient user interacting directly with the Viphod and of a context that is the patient's home. In this world-of-interest, two main primary tasks are directly associated to the global functioning of the Viphod assistance:

- The first primary task (denoted PT1) is relative to the control of the Viphod by the patient in two cases. Case #1, by the way of a tablet, the patient controls remotely the Viphod to move it very close to him. Case #2, when standing in up position, the patient can move in his/her environment by controlling the Viphod via an embedded joystick.



Fig. 4. A Viphod at home (left) and in use (right)

- The second primary task (denoted PT2) is relative to the assistance provided by the Viphod to the patient for the "sit to stand" move and for the inverse one.

A secondary task (denoted ST2) is considered for the remote monitoring of the Viphod health-status. An intervention system is composed of a human expert working in a remote maintenance center and of a stakeholder (i.e. the Viphod provider) in charge to manage and plan maintenance operations.

3.2 Characterization of the primary tasks

The characterization of these tasks is performed using the CPHS architecture introduced in section 2.

Figure 5 shows the modelling of the PT1 task, as an instance of Figure 3. For this task the Human has a tracking activity (Skill-based). The patient controls remotely the Viphod (considered as a vehicle unable to move autonomously in the home environment) from a departure location to a destination location. The human intervenes continuously during the successive phases of the task loop until the destination is reached. The Viphod participates only to the action phase. On basis of the model, a critical analysis of the PT1 task exhibits that the Viphod is very passive in the cognitive domain.

Figure 6 illustrates the modelling of the PT2 task. In this task, the Human has to follow a learned procedure to use the Viphod. For example, after placing the feet on the base of the Viphod with the help of his/her unaffected limbs, the patient is ready for a sit-stand movement. Then he/she presses a button sequence and perceives the moving of the Viphod structure. The cognitive complexity is here at the "Rules-based" level. The informative elements considered are of "Information" type (e.g. Moves of the structure of the Viphod #7, used at home in the beginning of the day to move from "sit to stand"). The Human is assisted by the mechanical power of the Viphod in the action phase.

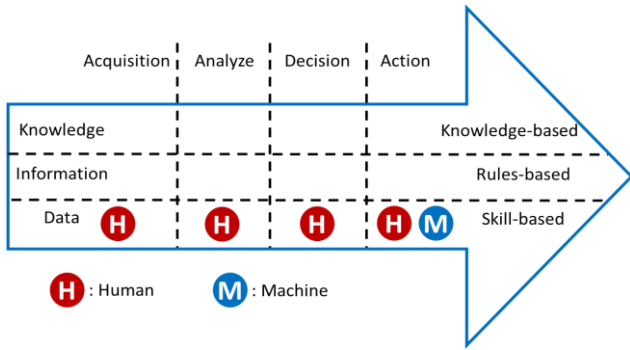


Fig. 5. Characterization of PT1 task

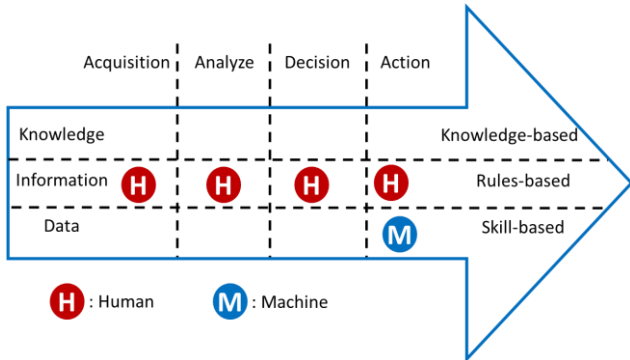


Fig. 6. Characterization of PT2 task

3.3 Characterization of the secondary task

In the remote support system, the Viphod expert operates a fault diagnosis cognitive activity, considered as a “knowledge-based” process. The knowledge and the temporal evolution of the Information are exploited by the expert to perform the diagnosis.

Figures 7 and 8 illustrate respectively the characterization of the ST2 task, considering SRK, DIK and AACA models, and a candidate architecture to support ST2. The numbers from 1 to 7 establish the correspondence between these Figures. This correspondence can be interpreted as the mapping of the specified secondary ST2 task on candidate architecture to support it (without the techno-push stress).

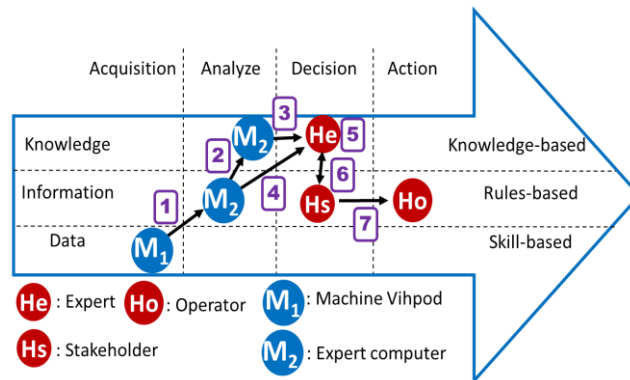


Fig. 7. Characterization of ST2 task

From a DIK point of view, measurements are performed on the concerned Viphod to obtain Data (e.g., battery voltage,

current, charging time...). By the way of so-called aggregation, the Data are tagged with tags as What, Where, When... to turn into Information (e.g., What: charging time value = 6h For-what: the battery #345 In-what: Viphod #77 When: after primary task “stand to sit” execution...) (1 in Figures 7 and 8). The expert, if needed, during his/her diagnosis can consult time series information (4).

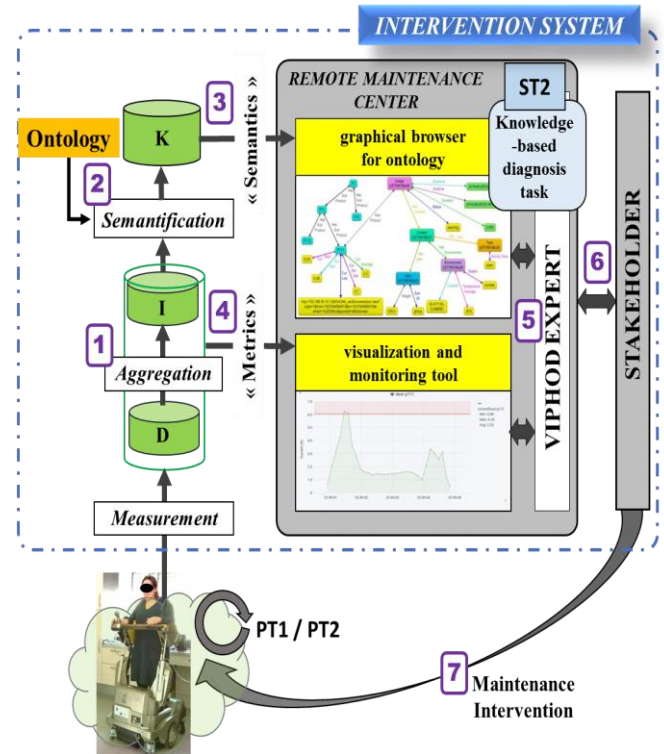


Fig. 8. The architecture supporting ST2

From the start to the end of a primary task, Information are stored with semantic relations, as for example: charging-time=6h “Of The” battery=#345 “Used By” user=#9 “In Environment In Which” high-shock=True “Concerned Product” Viphod=#77 “In” home=Paris. These semantic relations add meaning and generate a Knowledge. This process corresponds to a semantification (2) done by the way of an ontology (Basselot et al., 2019) including the product (here a specific Viphod and its subsystems as for example the battery subsystem) and (in order to interpret the usage situation) its context (i.e. patient user, primary task, and environment).

Let consider the following illustration: after having received a notification about an abnormally long charging time of one of its battery, the Viphod expert determines the reason and advises the maintainer stakeholder on the interest to consider an intervention. For that, the Knowledge and the temporal evolution of the Information are exploited by the expert to perform the diagnosis. The expert (consulting time series Information) detects that the charging time becomes long after a specific usage situation (4). Consulting the Knowledge relative to the usage situation (3) (with the assistance of an interrogation tool (i.e. machine)), the expert determines that the Viphod has suffered from a shock (example of environment information). The expert concludes that the

battery is not faulty but the electronics card managing the recharging (5) is. Therefore, the expert proposes to the stakeholder a maintenance operation (6). The stakeholder decides to accept the proposal and schedules an intervention (7) which corrects the default.

4. CONCLUSIONS

A huge diversity of works on CPS and CPHS exists, but few federative works has been done to adopt a generic view of their architecture. The proposal of this paper is a generic model for Human or machine, and a task model cybernetic-based were proposed. Such an architecture is intended to help, without constraint, the designer of CPS and CPHS to correctly specify their need, the activity led and the entity in charge of its operation (human, machine). The applicability of the architecture model was illustrated in the context of home healthcare. However the proposal is certainly a first version to improve. Future works and challenges concern: (1) the development of a guideline to help applying the architecture model, (2) the confrontation of the architecture model with other case studies to detect limitations and drawbacks, (3) the development of a strategy to allocate dynamically tasks between Humans and/or machines all over the time taking into account the objectives to achieve, ethics... and capabilities of Human and machine in the system, (4) a study to evaluate the theoretical and managerial implications of the proposed architecture.

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