A new Paradigm and Meta-Model for Cyber-Physical-Social Systems

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Abstract: The notion of Cyber-Physical-Social System (CPSS) and similar concepts using different acronyms emerged as a major paradigm shift to facilitate the interaction between human and Cyber-Physical System (CPS). However, human interaction behaviour is the result of multiple social dimensions governed by complex environmental, cultural and contextual factors which are not yet fully understood. Additionally, works in this direction still lack a well established systemic foundation. Thus, handling properly the social factor in Human-CPS interaction remains an open challenge. In this paper, we present a new perspective and a formalisation for the CPSS paradigm, which is grounded on the theory of systems. The aim of this is to provide a general framework to handle social dimensions in Human-CPS interactions. We propose a meta-model, which provides a conceptual ground to design CPSS spaces where CPS are enhanced with social capabilities.

Keywords: Cyber-Physical-Social system, Cyber-Physical System, Human-Machine Interaction

1. INTRODUCTION

The introduction of Cyber-physical systems (CPS) and advances in Information and Communication Technologies (ICT) have played a great role in the building of Industry 4.0 (Moeuf et al. (2018), Yilma et al. (2019b)). Particularly in production and manufacturing domains, it transformed traditional working mechanisms by allocating tedious and repetitive tasks to intelligent machines and robots; Panetto et al. (2019). The resulting production and manufacturing systems heavily rely on CPS frameworks and are commonly referred to as Cyber-Physical Production Systems (CPPS). Nowadays machines are able to perform specialized tasks with the support of different enabling technologies. Nevertheless, in an industrial setting putting smart machines and robots with humans in the same physical space to co-create and collaborate is still encumbered by the lack of efficient interaction mechanism and safety concerns.

Particularly the situational awareness capability of CPS-based machines is still prone to errors, especially to ensure perfectly safe operation in the presence of a human. As a result, while many tasks are being allocated to machines, humans become nothing more than button pushers, Mourtzis et al. (2019). Nevertheless, human knowledge and skills remain indispensable. According to Bouffaron et al. (2014), putting humans and machines to work closely by promoting collaboration, learning and supervision can potentially deliver better outcomes than isolated operations. Different research efforts have been initiated over the past few years to enhance human-machine collaboration mechanisms aiming to reach a better synergy.

Particularly the works that evolve from CPS in order to accommodate human aspects can be categorised under the two main computing paradigms, namely *Cyber Physical Human System (CPHS)*, and *Cyber-Physical-Social System (CPSS)*. According to the state of the art both computing paradigms define an *interaction space* which is cohabited by humans and CPS objects; Yilma et al. (2019a). It can also be seen that CPHS and CPSS are used interchangeably by researchers focusing on the presence of humans and their interactions with machines in a socio-technical system they share. Despite the conventionally equivalent usage of the two acronyms, "Social" conveys a broader meaning. The term "Social" captures emotional and cognitive characteristics. It also conveys sociotechnical principles that govern the behavior of people in a context, which should be ultimately transposed to machines.

Building on this conceptual difference between human and social, we propose in this paper that CPHS and CPSS should be distinguished by the way the social factors, especially related to machines, are taken into account. Hence, when a better human-machine synergy is targeted, systems should be designed with the social aspect in mind, as CPSS. Especially in designing industrial systems that involve a close collaboration of human and CPS; taking into account social aspects offers better interaction experience and improves worker efficiency Yilma et al. (2019b). This way Human-Machine interaction can elevate to a more cognitive level, where machines can adapt their behaviour by identifying situations, understanding and reasoning on human needs in context; Naudet et al. (2018). However, in Industry 4.0 "Human focused" computing paradigms do not yet have a well established systemic

foundation. Hence, they often fail to fully link social aspects in CPS.

The objective of this work is to define and model a new CPSS paradigm, grounded in systemics, and which accounts for the social dimension. The rest of this paper is organised as follows. In section 2 we discuss the state of the art and in particular the human and social dimension of CPHS and CPSS concepts, building on the interaction theories from social science. Subsequently we introduce a new perspective on the CPSS paradigm to allow the integration of social dimensions. Section 3 details the systemic foundation for the formalisation of CPSS, providing defintions of the main elements. Section 4 presents the meta-model of CPSS and its different components, relationships, and systems that can emerge. Finally section 5 presents future work and a concluding discussion.

2. FROM CPHS TO CPSS: A NEW PERSPECTIVE

The notion of CPHS was formally defined as *"a system of interconnected systems (computers, cyber-physical devices, and people) "talking" to each other across space and time, and allowing other systems, devices, and data streams to connect and disconnect"* Sowe et al. (2016). With rapid advances in technology and smart devices being part of daily life, the need for accommodating human aspects in machine programming is becoming more evident. Particularly in Industry 4.0, collaborative robotics applications mainly focus on the presence of humans and on supporting needs related to desired task executions, Zaatari et al. (2019). Depending on the application domain, other terminologies are also used, such as *Human-in-the-Loop (HitL)CPS* (Sowe et al. (2016)), *Human-centered CPS (HCPS)* (Wang et al. (2012)), and *User-centered CPS* (Merlo et al. (2019)). Despite the differences in acronym and application areas, all of the works refer to the presence of human at the vicinity of CPS devices with the goal of enhancing interaction experiences, Smirnov et al. (2013). At the same time the notion of CPSS also emerged, as a major paradigm shift from CPS to integrate important human aspects which were not fairly considered in CPS frameworks.

Currently, CPSS refers to an interaction space that could be called equally CPHS. However, the CPSS paradigm where the "S" refers to "Social" carries a broader semantics than that of CPHS. Thus, CPSS captures not only task related needs of a human but also behavioural, emotional and cognitive characteristics which are deemed as the three layers of human response in any kind of interaction. Norman (1988, 2014); Peruzzini et al. (2018).

In Social science, Turner (1988) defined a Social interaction as *a situation where the behaviors of one actor are consciously reorganized by, and influence the behaviors of, another actor, and vice versa* which can be extended to *the process whereby there is a mutual influence between behaviors of multiple individuals*. There are also other close interpretations all driven from most influential works of Goffman (1958) and Weber (1968). Most commonly recognised types of social interactions are: Exchange, Competition, Collaboration and Conflict. Overall, what qualifies an interaction as *social* is complex, but is inherently associated to specific characteristics of humans: consciousness

and understanding. According to Weber's social action theory, Weber (1968), a social interaction implies taking the actions of the other into account, which in turn means having a *sympathetic understanding*. Here, the adjective sympathetic resonates more of human behaviour in an interaction context because it relates to sentiments, compassion, and empathy.

Considering an interaction among humans, one can understand or at least interpret the other person's emotional, cognitive and behavioural responses because they are equipped with similar sets of sensors and information processing units. Today, CPS start only to have those capacities, especially driven by the work in social robotics, or emotion recognition. However they are far from being equivalents to human ones, and allow only weakly Human-CPS interaction at a social level. Hence, human-machine interaction in a truly collaborative manner demands efficient means to understand and reason such dynamic responses of a human. Cognition and understanding is a first prerequisite, which will allow the machine to adapt its behaviour to the presence of humans (situation identification), and to individuals (personalisation). Then, having sentiments, compassion or empathy (i.e. emotional responses) leads us to another level in the evolution of machines, which is related to anthropomorphism, a research topic in social robotics; Duffy (2003).

The process of ensuring seamless Human-Machine interaction requires incorporating all or at least most of the social dimensions in machines; Duffy (2003). Therefore, we propose to revise the CPSS paradigm.

The current CPSS view, shared with the CPHS approach, refers to an interaction space cohabited by humans and CPS entities. However, as explained, CPSS can be understood as something more than CPHS. To elaborate on this, we introduce two distinct kinds of CPSS, namely, the *CPSS Space*, which corresponds to the current understanding, and the *CPSS Object*. Making this distinction allows in particular to consider a next generation of CPS that is enhanced with social attributes allowing a better handling of human dynamics (*i.e.*, complex behavioural, emotional and cognitive aspects) and able to somehow socialize. With the *CPSS Object* concept, Cyber-Physical systems gain human-like social interaction capabilities. This perspective of the CPSS paradigm is proposed with the primary goal of promoting human-centered systems of the future that are socially capable, *i.e.*, cyber entities that are able to interpret and learn from human's social responses and actuate socially, for a seamless human-machine collaboration. To distinguish between the current CPSS approach, we could talk about a CPSS 2.0 perspective, where *CPSS Spaces* are no more populated by humans and CPS, but instead by humans and CPSS objects. Examples of CPSS objects are social or collaborative robots, or machines and smart devices extended with social capabilities. CPSS Spaces could also be called smart environments; they are smart enterprises, smart buildings, smart homes, smart cities, etc.

3. A SYSTEMIC FORMALISATION OF CPSS

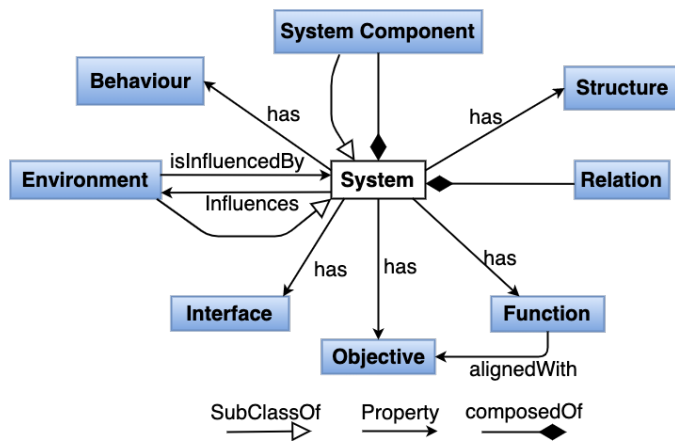A CPSS is before all a system. Originally, a system is defined as *a complex set of interacting elements, with*

Fig. 1. The systemic model, a basis for CPSS modelling.

properties richer than the sum of its parts; Von Bertalanffy et al. (1968). It is characterised by its components and the interactions between them, where each component can itself be a system, thus forming a System of Systems (SoS).

In this work, we adopt the following definition, from Naudet et al. (2010):

Definition 1. A **System** is a bounded set of interconnected elements forming a whole that functions for a specific finality (objective) in an environment, from which it is dissociable and with which it exchanges through interfaces.

Having recalled what a system is, we can define a CPSS the following way, together with the CPSS Object and CPSS Space as introduced in section 2:

Definition 2. **Cyber-Physical-Social system (CPSS)**: is a system comprising cyber, physical and social components, which exists or emerges through the interactions between those components. A CPSS comprises at least one physical component responsible for sensing and actuation, one cyber component for computations and one social component for actuating social functions. We distinguish between two categories of CPSS, namely CPSS Object and CPSS Space.

Definition 3. **CPSS Object**: a Cyber-Physical System enhanced with social capabilities. Globally, this is a system with functions for sensing, actuation and computation, and social functions related to *e.g.,* cognition, emotion or social behaviour, which has the capacity to understand and adapt to the needs and behaviour of a human.

Definition 4. **CPSS Space**: a system, or more precisely a system of systems, where humans and CPS or CPSS objects cohabit a physical and virtual space of interaction. While today's CPSS Space refer to humans and CPS objects, which are socially constrained, our new perspective considers spaces with humans and CPSS objects, *i.e.* machines capable of social interactions.

For modelling a CPSS with a systemic perspective, both the ontological and teleological aspects have to be considered (see Dietz (2005)). A CPSS is indeed a complex system where more than the structure, the interactions between components need to be taken into account. The main components and their relationship have first to be identified. Then, functions and behaviours of system components should be formalised, as they can constrain
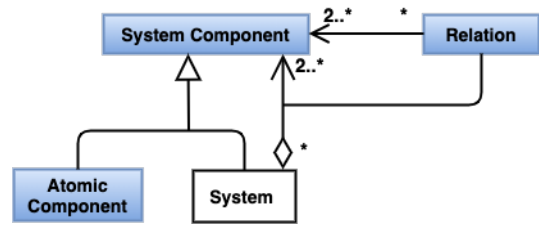

Fig. 2. [System, System Component, Relation] structure under the not-everything-is-system assumption.

the objectives of the CPSS; Zeng et al. (2016). Figure 1 presents the systemic model we use as a reference to build our CPSS meta-model, representing a system and its main components and properties based on Definition 1. It is extracted and modified from the Ontology of Enterprise Interoperability (OoEI); Naudet et al. (2010).

We have re-labeled the concept of *System Element* into *System Component*, to account better for the composition aspect. A *System* instance is composed of *System Component* instances that are linked by some *Relation*. According to the systemic model, following definition 1, a *System* is composed of *System Component*s and *Relation*s (between the components). It is influenced by its *Environment* and can influences it in return. Then, it has a *Structure*, *Behaviour*s, *Interface*s to its external world, *Objective*s and *Function*s. The environment represents potentially anything outside of a systems' boundaries, in contact with the system. It comprises the context, to which system's behaviour and functions are dependent. The interfaces are components of a system through which a connection between a system and its environment can be established, materialising the system's boundaries. The finality or objective defines a system's goal at a given time. It is fulfilled thanks to the system's functions, or set set of actions the system can execute.

In this model, a system component is a system itself, following the simplifying hypothesis that everything is a system. In reality however, especially to model a CPSS, the boundary between a system and a non-system is often fixed. To account for this, we propose a new model for the system - component - relation part, using the composite design pattern, see Fig. 2. With this model, a *System* is a composition of *System Component*s and *Relation*s, and there exist *Atomic Component*s that are not systems.

The complexity of any system depends on the nature of relations between its components, their individual nature, functions, objectives and behaviour. In CPSS Space, CPS and CPSS objects have their own functions and objectives. The space also has its own objectives which may imply some specific response from those CPS / CPSS objects, but also some specific behaviour from humans. However, humans evolve in such kind of space in compliance with their own personality, capabilities and objectives. As a consequence, their behaviour cannot be predicted easily, and can generate instabilities in the CPSS Space.

Additionally, humans might not be tolerant when it comes to following or respecting rules that are not aligned with their personality, way of thinking or convictions, thus adding to the complexity. The fulfillment of a CPSS Space objectives while considering the constraints and complex-

ity due to dynamic interactions between entities (humans and CPS or CPSS objects) having their own objectives and behaviour, remains a challenge. This requires solutions that go beyond what CPS frameworks can offer currently. The formalisation we propose for CPSS is a step towards providing a suitable solution, which allows to first clearly identify the entities and their interactions, to help further identification of their functions, constraints and objectives, to identify in turn possible conflicts and better manage instabilities. To support this, we detail in the next sections a meta-model for CPSS that defines its different components, their relations and the different kinds of systems that emerge as a result of the interactions between these components.

4. A META-MODEL OF CPSS

Previously a meta-model of CPSS was proposed in Yilma et al. (2019b). It was a partial extension of the the CPS meta-model from Lezoche and Panetto (2018). To the best of our knowledge it was the first meta-model of CPSS ever proposed, proposing to integrate a social dimension in CPS. In this section we adapt the concepts of this first meta-model to the new CPSS paradigm and propose a new meta-model. In particular, the latter models systemic properties and relationships between components that are responsible for the emergence of systems.

Fig. 3 presents our meta-model of CPSS using UML 2.0 notation. The meta-model formalises the main components of a CPSS as combinations of fundamental (C)yber, (P)hysical and (S)ocial elements, as well as the relation between them. It allows representing the different kinds of systems that emerge when relations are instantiated: Cyber-Physical-Social System (CPSS), Cyber-Physical System (CPS), Physical-Social System (PSS), and Cyber-Social System (CSS).

The CPSS meta-model is built on top of the systemic meta-model presented in Section 3. Formally, all component classes (*Cyber Component*, *Physical Component*, *Social Component*) are subclasses of *System Component*, and all system classes (*CPS*, *PSS*, *CPSS*, *CSS*) are subclasses of the general System class. As systems, the latter inherit from all the properties detailed in Section 3.

The notion of *CPS* has long existed as introduced earlier, representing the composition of computational and physical elements. A typical example is a *Robot*. *PSS* is a composition of physical and social elements, where the social part is materialised through the physical part. The main representative is the *Human* system: the physical part is the physical body, while the social part is composed of the attributes that generate social responses such as cognition, behaviour and emotion, manifested through the body but distinct from it. The reader could argue that for Human, the social system is indeed a part of the physical system, but we will keep things simplified for now and leave this for further discussion. *CSS* corresponds to a system where the social component is manifested through the cyber component. A typical kind of CSS is a *Social Network*, Doostmohammadian et al. (2019), where the social activities actually result from interactions in the virtual world.
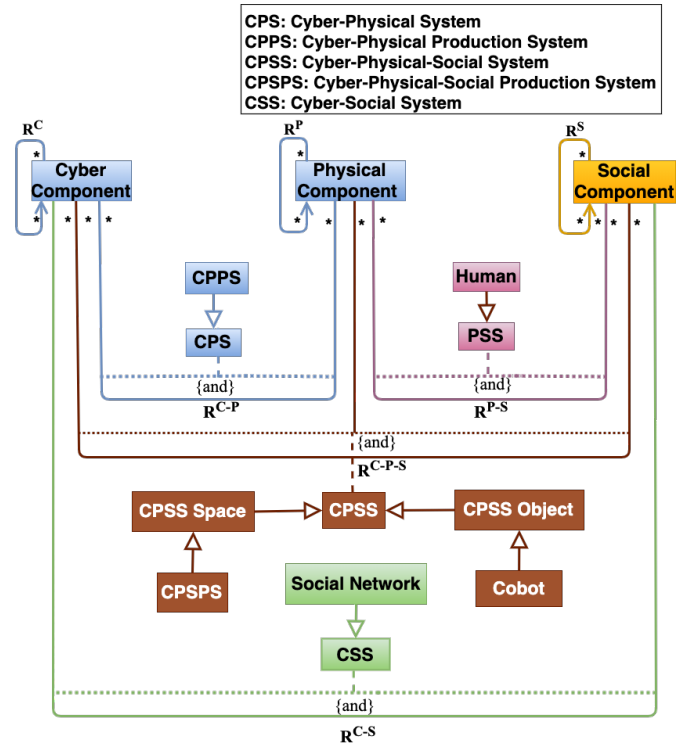

Fig. 3. CPSS Meta-model

Let C, P, S be respectively the set of cyber, physical, and social components, and R be the set of existing relations, in a system of interest. We define three kinds of relations:

- R^X: $X \times X \to R$, where X is "C", "P" or "S"
- R^{XY}: $X \times Y \to R$, where X and Y are "C", "P" or "S" and X $\neq$ Y
- R^{CPS}: $C \times P \times S \to R$

There are in total seven types of relations we detail in the following: R^C, R^P, R^S, R^{CP}, R^{PS}, R^{CS}, and R^{CPS}. For a better readability in Fig. 3, relations are represented by a link, but all should be understood as subclasses of the systemic *Relation* class.

- R^C:- refers to a connection between cyber components, existing in the virtual space, for example an information flow, a command, query, etc. It can also refer to the sharing of a computational resources. *e.g,* two software packages sharing the same processing unit.
- R^P:- refers to a connection between physical components, existing in the physical space. An example could be the connection between mechanical parts of a machine.
- R^S:- refers to a social relationship between social components. It can materialise as an information flow or a transfer of knowledge between social components. It also reflects cognitive ties that govern human behaviour, *e.g.*, an intellectual conversation between people.
- R^{CP}:- refers to a relationship that exists between cyber components and physical components that can potentially result in the integration of computation with physical processes (sensing or actuation), *e.g.*, the relation between components of a smartphone to

function. The R^{CP} relation leads to the emergence of a CPS.

- R^{PS}:- refers to a relationship that exists between physical components and social components that can potentially result in cognitive processes and observable social behaviours. This is the property that enables a human to take actions that reflects his emotion, cognition and behaviour in a given context. The R^{PS} relation leads to the emergence of a PSS.

- R^{CS}:- refers to the relationship between Cyber and Social components that can potentially result in the integration of computation and social capabilities, *e.g.*, virtual representation of people in a social network. The R^{CS} relation leads to the emergence of a CSS.

- R^{CPS}:- refers to a relationship that exists between at least one cyber, one physical and one social component, that can potentially result in the integration of sensing, actuation, computation and social processes. For R^{CPS} to exist it needs at least one R^{CP} and one R^{PS}. The R^{CPS} relation leads to the emergence of a CPSS.

Formally, we define the emergence of a CPSS by the following rules:

$$\exists C, \exists P, \exists S, \exists R^{CP}, \exists R^{PS} \Leftarrow \exists R^{CPS} \qquad (1a)$$

$$\exists R^{CPS} \Rightarrow \exists CPSS \qquad (1b)$$

A CPSS emerges *iff* there is at least one Cyber, one Physical, and one Social component, with at least two relations between them, R^{CP} and R^{PS}, which lead to an R^{CPS} that is responsible for the emergence of a CPSS. In Fig. 3, the constraint {*and*} is used to represent the mandatory requirement of at least one component from each part in relation in order for a new system to emerge.

The CPSS meta-model offers a framework to model a CPSS with its structure and components, helping to identify the different interacting entities and their respective objectives, functions and constraining factors. It is completed by the systemic model (Fig. 1 and Fig. 2), which can be applied to all System subclasses, *i.e.*, CPS, PSS, CSS and CPSS. In particular, once all such systems interacting in a CPSS have been identified, their objectives should be listed, as they are sources of instabilities in the CPSS. In particular because CPSS involve humans, the best sources of unpredictability, conflicts between them and the global CPSS objective or of any of its components should be avoided. By listing objectives and constraints linked to each entity in the CPSS and identifying potential conflicts that can occur through the interactions, algorithms can be defined to adapt the CPSS or the behaviour of some components in such a way it keeps a global equilibrium.

5. DISCUSSION AND FUTURE WORK

In this paper, we have presented a new formalisation of the CPSS paradigm and its systemic foundation. A distinct definition of CPSS Object and CPSS Space was proposed to establish a ground for a next generation CPS that is enhanced with social attributes allowing a better handling of human dynamics. Following this a meta-model of CPSS was proposed. This models relationships and interactions between components leading to the emergence

of CPSS and other systems. The meta-model provides a conceptual ground to design a CPSS, where social aspects are realised in machines. In general the systemic perspective offers a design methodology to clearly identify the main systemic entities, their objectives, constraining factors and interdependencies. Ultimately, aiming for CPS objects of today to gradually evolve and become CPSS objects so that they can interact with humans seamlessly.

The CPSS paradigm has a broad range of application areas in modern life. Together with the advances in technology and automation, a typical CPSS can emerge almost everywhere. With the strong tendency to globalization and interconnectedness, the world can also be seen as one giant CPSS Space. Environments such as Smart Cities, Smart Homes, and medium to large scale industries are among the main sectors, where applications of the CPS notion has gained momentum. Particularly in Industry 4.0 a peculiar trend that fits in this setting is the emergence of Cobotic production system. *Cobotics* refers to a collaborative manufacturing space where human workers collaborate with Cobots (Collaborative robots) in a production line. Generally production systems in Industry 4.0 are often referred as Cyber-Physical Production Systems (CPPS) because they heavily rely on CPS frameworks. Hence, neglecting important social dimensions that govern the behaviour and characteristics of humans during interaction. In this kind of settings ensuring seamless collaboration between humans and cobots essentially requires efficient means of understanding human dynamics. Thus, a design framework that goes beyond CPS is needed. This makes Cobotics an ideal candidate to benefit from the proposed CPSS paradigm. This leads to define a new framework of intelligent manufacturing for Industry of the future. This is Cyber-Physical-Social Production System (CPSPS), which proposes to embed human-like social characteristics on cobots and machines. It can be defined as a *CPSS Space* since it corresponds to an interaction space which is cohabited by humans and CPSS Objects(Cobots) *Definition* 4.

Nevertheless, harmoniously integrating Social dimensions is not something that can be achieved only by Engineering or Computer science. It requires thorough investigation and interdisciplinary research effort. Particularly the fields Cognitive science, Affect/Emotion recognition, Behavioral studies and related sub-fields of Artificial Intelligence are achieving promising results in specialised areas of human dynamics. While the full integration of social aspects remains open for research; our formalisation aims to opens CPSS as a multidisciplinary research field and create opportunities of leveraging successful results from these fields in order to ensure human-machine synergy.

The primary aim of this work is to make a first step in formalising the CPSS paradigm for having a holistic understanding of the notion that considers social dimensions. In future works we plan to apply the formalisation presented in this paper in Collaborative robotics case studies. This way different techniques and algorithms will be explored to design CPSS spaces with enhanced Human-Machine synergy.

REFERENCES

Bouffaron, F., Dupont, J.M., Frédérique, M., and Morel, G. (2014). Integrative construct for model-based human-system integration: a case study. *IFAC Proceedings Volumes*, 47(3), 12317 – 12324. doi: https://doi.org/10.3182/20140824-6-ZA-1003.02459. 19th IFAC World Congress.

Dietz, J.L.G. (2005). Enterprise Ontology keynote lecture.

Doostmohammadian, M., Rabiee, H.R., and Khan, U.A. (2019). Cyber-Social Systems: Modeling, Inference, and Optimal Design. URL http://arxiv.org/abs/1903.12371.

Duffy, B.R. (2003). Anthropomorphism and the social robot. *Robotics and Autonomous Systems*, 42(3), 177 – 190. doi:https://doi.org/10.1016/S0921-8890(02)00374-3. Socially Interactive Robots.

Goffman, E. (1958). *The Presentation of Self in Everyday Life Editorial Reviews*. 9780385094023. University of Edinburgh, Social Sciences Research Centre, Edinburgh.

Lezoche, M. and Panetto, H. (2018). Cyber-physical systems, a new formal paradigm to model redundancy and resiliency. *CoRR*, abs/1810.06911. URL http://arxiv.org/abs/1810.06911.

Merlo, C., Akle, A.A., Llaria, A., Terrasson, G., Villeneuve, E., and Pilnière, V. (2019). Proposal of a user-centred approach for cps design: pillbox case study. *IFAC-PapersOnLine*, 51(34), 196 – 201. doi: https://doi.org/10.1016/j.ifacol.2019.01.065. 2nd IFAC Conference on Cyber-Physical and Human Systems CPHS 2018.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S., and Barbaray, R. (2018). The industrial management of smes in the era of industry 4.0. *International Journal of Production Research*, 56(3), 1118–1136. doi:10.1080/00207543.2017.1372647. URL https://doi.org/10.1080/00207543.2017.1372647.

Mourtzis, D., Fotia, S., Boli, N., and Vlachou, E. (2019). Modelling and quantification of industry 4.0 manufacturing complexity based on information theory: a robotics case study. *International Journal of Production Research*, 0(0), 1–14. doi:10.1080/00207543.2019.1571686. URL https://doi.org/10.1080/00207543.2019.1571686.

Naudet, Y., Yilma, B.A., and Panetto, H. (2018). Personalisation in cyber physical and social systems: the case of recommendations in cultural heritage spaces. In *2018 13th International Workshop on Semantic and Social Media Adaptation and Personalization (SMAP)*, 75–79. doi:10.1109/SMAP.2018.8501890.

Naudet, Y., Latour, T., Guedria, W., and Chen, D. (2010). Towards a systemic formalisation of interoperability. *Computers in Industry*, 61(2), 176–185. doi: 10.1016/j.compind.2009.10.014.

Norman, D.A. (1988). *The Design of Everyday Things*. Basic Books, New York, first edition.

Norman, D.A. (2014). The design of everyday things. *Choice Reviews Online*, 51(10), 51–5559–51–5559. doi: 10.5860/choice.51-5559.

Panetto, H., Iung, B., Ivanov, D., Weichhart, G., and Wang, X. (2019). Challenges for the cyber-physical manufacturing enterprises of the future. *Annual Reviews in Control*, 47, 200 – 213. doi: https://doi.org/10.1016/j.arcontrol.2019.02.002.

Peruzzini, M., Grandi, F., and Pellicciari, M. (2018). Exploring the potential of operator 4.0 interface and monitoring. *Computers Industrial Engineering*, 105600. doi:https://doi.org/10.1016/j.cie.2018.12.047.

Smirnov, A., Kashevnik, A., Shilov, N., Makklya, A., and Gusikhin, O. (2013). Context-aware service composition in cyber physical human system for transportation safety. In *2013 13th International Conference on ITS Telecommunications (ITST)*, 139–144. doi: 10.1109/ITST.2013.6685535.

Sowe, S.K., Simmon, E., Zettsu, K., de Vaulx, F., and Bojanova, I. (2016). Cyber-physical-human systems: Putting people in the loop. *IT Professional*, 18(1), 10–13. doi:10.1109/MITP.2016.14.

Turner, J.H. (1988). *A theory of social interaction*. Stanford University Press.

Von Bertalanffy, L., Braziller, G., and York, N. (1968). General System Theory Foundations, Development, Applications. Technical report.

Wang, H., Deng, X., and Tian, F. (2012). Wip abstract: A human-centered cyber-physical systematic approach for post-stroke monitoring. In *2012 IEEE/ACM Third International Conference on Cyber-Physical Systems*, 209–209. doi:10.1109/ICCPS.2012.32.

Weber, M. (1968). *Economy and society an outline of interpretive sociology*. Bedminster Press, New York.

Yilma, B.A., Naudet, Y., and Panetto, H. (2019a). Introduction to personalisation in cyber-physical-social systems. In *On the Move to Meaningful Internet Systems: OTM 2018 Workshops*, 25–35. Springer International Publishing, Cham.

Yilma, B.A., Panetto, H., and Naudet, Y. (2019b). A meta-model of cyber-physical-social system: The cpss paradigm to support human-machine collaboration in industry 4.0. In L.M. Camarinha-Matos, H. Afsarmanesh, and D. Antonelli (eds.), *Collaborative Networks and Digital Transformation*, 11–20. Springer International Publishing, Cham.

Zaatari, S.E., Marei, M., Li, W., and Usman, Z. (2019). Cobot programming for collaborative industrial tasks: An overview. *Robotics and Autonomous Systems*, 116, 162 – 180. doi: https://doi.org/10.1016/j.robot.2019.03.003.

Zeng, J., Yang, L.T., Lin, M., Ning, H., and Ma, J. (2016). A survey: Cyber-physical-social systems and their system-level design methodology.