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Sustainability Aspects and Impacts in Cyber-Physical Social Systems

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Abstract — A Cyber-Physical-Social System (CPSS) is an emerging research trend that focuses on integrating the social dimension into Cyber-Physical System (CPS). The CPSS consists of social, physical, and cyberspaces. There is a lack of influential theories and design approaches to reach a unified structure of a CPSS. Furthermore, the impacts of a CPSS on the sustainability performance of systems and processes are still unexplored. The paper addresses this latter research issue by evaluating case studies on CPSSs discussed in the literature.

Keywords — *Cyber-Physical-Social system, Sustainable Development, Social System*

I. INTRODUCTION

A Cyber-physical system (CPS) aims at embedding computing, communication, and control capabilities (3C) into physical assets to empower and converge the physical space with the virtual space [1]. Cyber-Physical Systems (CPSs) give the possibility to sense the world through a network of connected devices. The combination of intelligent and sensing systems forms a large-scale distributed cyber-physical system with enormous potentialities to bring smartness into many application areas.

Human operators in the future production scenarios will need advanced competencies to cope with the new challenges regarding technological and organizational developments. A Cyber-Physical Social System (CPSS) may help human operators by integrating human knowledge, mental capabilities, and sociocultural elements [1], [2], [3]. A CPSS combines cyber, physical, and social space, creating a sustainable network for sharing data and information about products, production practices, materials, and human skills. The design of a CPSS is still a challenging task due to the heterogeneity of subcomponents, software complexity, and hardware entities. There is a lack of methodologies and design approaches to guide the practical design of a CPSS. Additionally, the effects of a CPSS on sustainable development and performance are still unexplored topic to be faced. The paper explores new potentialities and applications of a CPSS analyzing case studies presented in literature with the aims of defining how a CPSS can impact and improve sustainability performances.

II. STATE OF ART OF CPSSs

A CPSS focuses on social behaviors and relationships, thus considering aspects related to human facilities interdependency may significantly improve the cooperation and collaboration opportunities between production systems. Indeed, capturing skills and human habits may bring relevant information to improve the production system, including the working life quality of operators. A CPSS, exploiting new Key Enabling Technologies (KETs), such as big data, cloud computing, Internet of Things), allows capturing the social environment (behaviors, habits), improving the decision-making. For example, the implementation of CPSS in the transport system reduces road congestion and, therefore, traffic intensity and pollution [4]. In production systems, a CPSS decreases the number of delayed orders [5], improving productivity. It can also improve user satisfaction and social interaction. The development of a CPSS can facilitate the exchange of materials, best practices, skills, and human performances between different production systems.

Despite the numerous potentialities of CPSS's, few complete implementations are present, and still, the design of CPSS is a complex task. In particular, incorporating human aspects in a Cyber-physical system (CPS) has several open research challenges [2]. First, CPSS are complex systems due to the heterogeneity of network, software, and hardware entities, and a practical design approach is still lacking. Second, there are no practical and widely accepted approaches to model cyber, physical, and social space uniformly. Finally, it is necessary to investigate sustainability aspects and performances related to CPSSs.

The paper focuses on the relationships between the sustainability aspects and challenges with CPSS to foster convergence, methodologies, innovative tools, and applications.

III. OVERVIEW OF APPLICATION CASE STUDIES OF CPSSs

CPSSs finds application in different fields such as power grid, smart vehicles, energy, transport, agriculture [4], [5]. This

section reviews case studies found in the literature to speculate how a CPSS can improve sustainability performance.

[6] presents a CPSS for a transportation system to improve vehicular safety and energy efficiency to reduce pollution or road congestion using the ACP method. The ACP method is also proposed in [7] to set artificial societies, computational experiments, and execution modules for cyber-physical-social systems. The ACP approach has been proven in [6] to be the practical framework for the management and control problems of CPSS. The theoretical research results of CPSS and ACP methodology are applied and verified in traffic areas such as plan optimization, large-scale evacuation, and public traffic scheduling. In [8], the authors present the development of digital quadruplets for a CPSS-based parallel driving with the enlightenment of ACP-based parallel driving. Digital quadruplets can improve road safety, traffic efficiency, and driving cooperation for future connected automated vehicles. In [9], the authors propose road traffic signal control analyzing the social media data combined with physical sensors data to provide information about the road. Sensors provide physical data such as the vehicle count of a specific road, while social data inform the road user's perception of the road. In [10], the authors optimize the power load stability and the total cost of vehicle owners in the CPSS. Social aspects of traffic include driver's intention and driver's perception of road conditions.

[11] applies a CPSS in production networks. It allows the interaction between decision-makers making the networks more sustainable, responsible, and competitive. The authors introduce and review the social aspects, identifying three domains: individual, organizational, and contextual. A simulation study demonstrates how the management of social aspects can impact the production network competitiveness of CPSS. Traditional decision-making models do not consider human characteristics, such as age, gender, cultural background, and personality of operators. The authors [12] develop an algorithm to solve partner selection problems in cyber-physical production networks. A hierarchical Petri net-based model and social flow are presented in [13] to extend the control flow and formally describe the social interactions of multiple users, respectively.

In [14], the authors apply a CPSS to Agriculture Supply Chain System (ASCS) management to improve the welfare of people in rural areas and increase the sales of products. Also, in [15], the concept of CPSS for the agricultural sector has been developed by designing a prototype for hydroponic agriculture that can be monitored online via Telegram Messenger. The CPSS allows hydroponic farmers to know and monitor the condition of plants in real-time.

[16] propose a cyber-physical-social-connected (SioT) model for mass individualization to narrow down the contextual computing complexity in a cyber-physical-social connected space.

In [17], the authors propose a 7C framework for data-driven CPSS (D-CPSS) from a systematic perspective, including seven different levels: connection, conversion, communication, computation, cognition, configuration, and collective intelligence. Compared with the CPS configuration presented in [18], the D-CPSS configuration emphasizes the importance of social factors and being data-driven. Level 1, level 3, level 5, and 7 in the 7C model are distributed in both

the social space and physical space; level 2, level 4 and, level 6 in the 7C model belong to the cyber-space.

The analysis of case studies allows understanding how some factors and performance can improve with CPSS, such as customer/user satisfaction, social interaction, process automation. In [6] - [10], authors develop CPSSs for the transport sector, as already recalled, by endeavoring IoT and cloud computing technologies to connect drivers and vehicles, improving vehicular safety and energy efficiency, and reducing pollution or road congestion. The development of a CPSS can facilitate the exchange of materials, best practices, skills, and human habits between different production systems. Human characteristics and habits, such as age, gender, cultural background, and personal behaviors or needs, are evaluated and assessed in CPSSs solutions designed in [11] - [17].

IV. CPSS AND SUSTAINABILITY FRAMEWORK

This research intends to understand better the benefits that CPSSs can bring to sustainability performances to the system where the CPSS is applied. The paper investigates how the CPSSs functionalities and characteristics – available through various Key Enabling Technologies (KETs) – may be interconnected with the sustainability performances. For the scope of our study, we will focus in particular on the social sustainability dimension because it is still unclear how to include human rights, fair labor practices, living conditions, health, safety, wellness, diversity, equity, work-life balance, empowerment, community engagement into a virtual decisional tool.

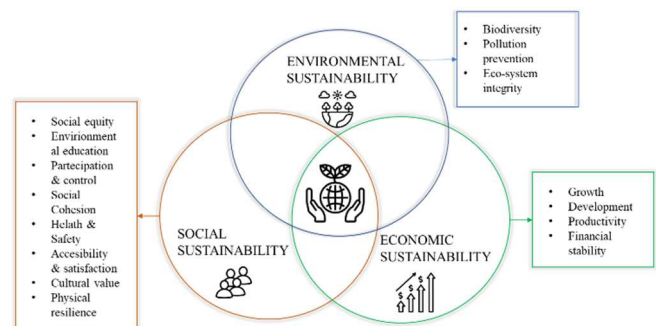


Fig. 1. Sustainability dimensions and related implications [19].

The main CPSSs functionalities on social sustainability aspects are identified in [19] and listed as follows: Safety management; Ergonomics and human factors; Learning and training; and Work-Life Balance. The authors in [19] propose a framework (CyFL Matrix) composed of six functionalities that a CPSS must enable at three different levels of analysis, as shown in Figure 2. The framework allows understanding the impacts of a CPSS-oriented solution on social sustainability aspects but does not evaluate the Key Performance Indicators (KPIs) in each area.

	Smart Resource	Smart Resource System	Smart Resource System Orchestra
Silent Teacher	Operator's Training Level Operator's Learning (Speed and Retention)	Labour Flexibility (Process Cell) Human Error Incidence	Employee Satisfaction Labour Flexibility (Area) Human Capital
Knowledge Manager	Traceability (Product) Information Capital (Resource)	Information Capital (Process Cell) Communication Quality (M2M, HCM and M2H, H2H)	Plant Accessibility Information Capital (Area) Innovation & Knowledge
Resource Integrator	Product Flexibility	Production Flexibility Volume Flexibility Mix Flexibility Process Flexibility	Market Flexibility Operation Flexibility Expansion Flexibility
Caregiver	Wellbeing • Physical Strain • Psychological Strain	Human Error Incidence (Failed Defence)	Adaptability to a diverse workforce Attractiveness of the workplace Internal Quality
Risk Manager	Availability (Resource) Maintenance cost Failure modes occurrence Failure modes impact	Availability (Process Cell) Health and safety risk (Process Cell) Operational Risk (Process Cell)	Resilience of Production System Operational Risk Health & Safety Risk
Flow Master	Resource Efficiency (Time) External Quality (Task Execution, Process Output)	Scheduling Robustness Routing Flexibility Throughput time, Throughput Efficiency (time, energy, resource) WIP level Process Flexibility	Inventory costs Frozen Period Cost Efficiency External Quality Production Lead time

Fig. 2. CyFL matrix [19]

The rationale behind the performed analysis is by the technology transfer. On the one hand, we consider the Key Enabling Technologies (KETs) - such as IoT, Big Data, advanced simulation, and others) - used for designing CPSSs in the case studies discussed above. On the other hand, we consider the research on sustainability indicators and performances. The final objective is to link the Key Enabling Technologies (KETs) with social sustainability indicators to facilitate and clarify the impact of CPSS technologies on social sustainability performances. Following this, we develop a complete framework, as shown in Figure 3, to evaluate the relationships between technologies used for developing CPSSs and the social sustainability indicators. The development of a CPSS is made possible by the Key Enabling Technologies (KETs) below summarized [20]:

- Sensors and actuators are the most basic technologies for collecting and controlling data in real time [21].
- Big data analytics refers to a new generation of technologies and architectures that enable organizations to economically extract value through discovering, capturing, and analyzing vast volumes of a wide variety of data [22].
- Blockchain enables transparent, secure, trustworthy, and swift public or private solutions [23].
- Augmented reality (AR) is an up-and-coming technology that visualizes computer graphics placed in the physical environment [24].
- Virtual Reality (VR) provides an immersive, interactive, computer-mediated experience in which a person perceives an artificial environment through human-computer interaction equipment [25].

- Cloud Computing allows access to software and data storage in the cloud representation of the internet [26].
- Collaborative Robots perform specific tasks autonomously or using remote-control commands [27].
- Additive manufacturing or 3D printing denotes the manufacturing technique in which parts are built by melting thin layers of powder and adding one layer of material, either plastic or metal, on top of another, based on the geometry suggested by Computer-Aided Design (CAD) [24].

- Digital Twin is a high-fidelity virtual model of the physical entities having the scope of replicating and simulating the states and behaviors of these latter's [20].
- In our framework, we relate the CPSS-KETs with social sustainability indicators [28] - [30].

[28] - [30] define eight social sustainability indicator categories explained as follow:

- The social equity category has two indicator sets: equity of process and fair distribution measuring the access to information, participation in decision making, formation of governance structure, planning of space, use of natural resources.
- The environmental education category includes environmental awareness and sensibility and ecological literacy as indicators sets.
- The participation and control category measures the involvement through the following indicators: user participation, willingness to act and improve the environment, creative place-making opportunities.
- The social cohesion category involves social programs and social interaction
- The health and safety category includes five indicators: health impacts of materials, energy sources, the health impact of water consumption, health impacts of Indoor Environmental Quality (IEQ), feeling of safety.
- The accessibility and satisfaction category involves two indicator sets: the ease of accessibility set and the satisfaction level set.
- Cultural value local identity category assesses the design of spaces indicator set through indigenous environmental management practices and intercultural dialogue indicators.
- The physical resilience category has disaster resilience and mitigation set indicators.

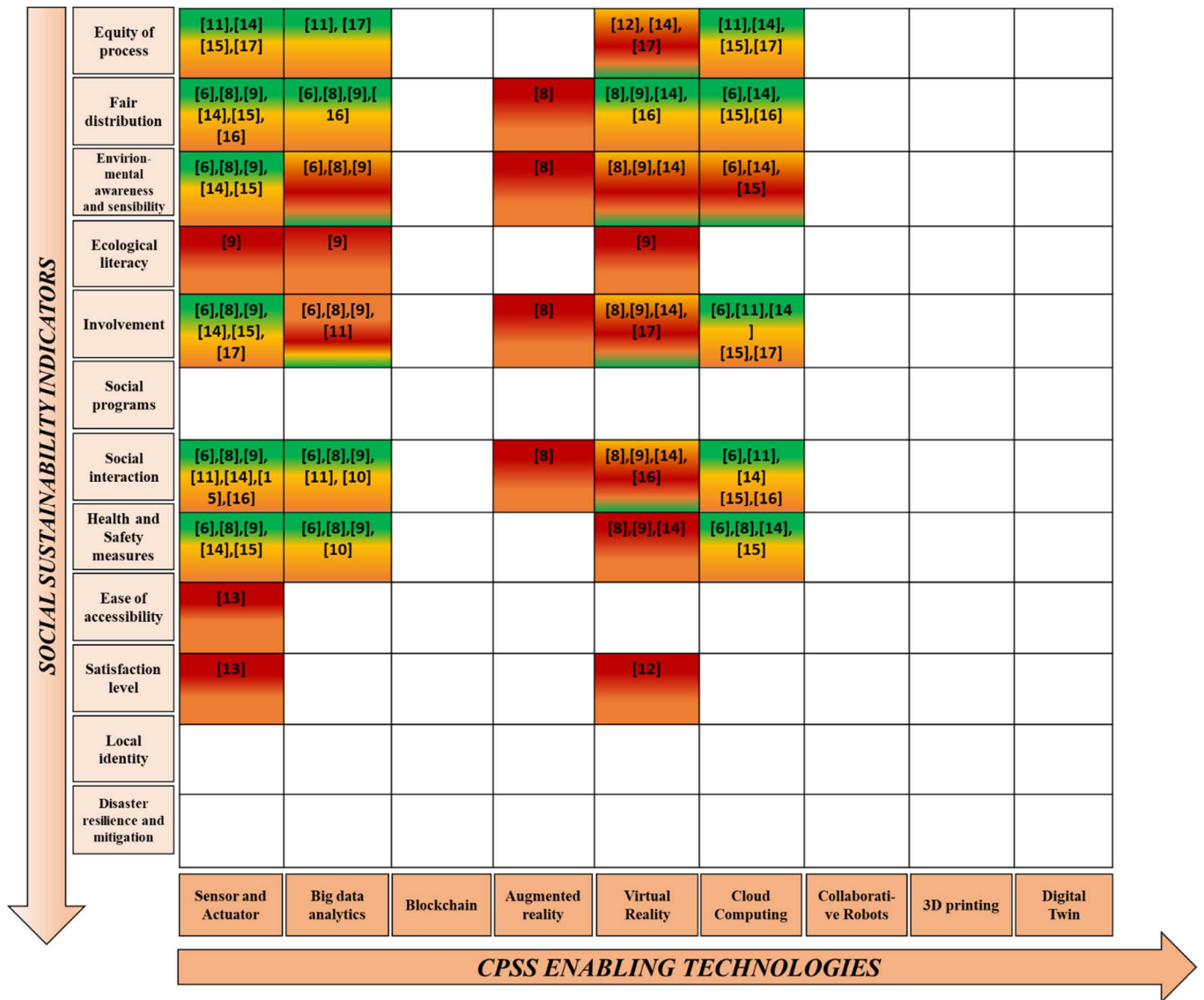


Fig. 3. CPSSs-Sustainability Framework proposed and the Mapping case studies accordingly (The number on the map refers to the literature references belonging to different case studies)

The case studies presented in section III are classified in the framework in Figure 3 to understand the above-referred link between technologies adopted and CPSS's impact on social sustainability.

We also adopted the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda to classify the case studies for evaluating the CPSSs' impacts on sustainability. The 2030 Agenda comprises 17 Sustainable Development Goals deepened into 169 targets, as shown in Figure 4. The case studies are classified in the framework in Figure 3. This information is reported on the framework using the same color scale of the goals defined in [29]. For example, the application of a CPSS in the transport sector in [6] improves vehicular safety in line with goals 3, 7, and 11 targets 3.6, 7.3, 11.2, and 11.6. [8], [9], [10] are aligned with the targets 3.6 and 11.2, goals 3 and 11.

The resulting picture proves that sensors and actuators, cloud computing, big data analytics, and virtual reality technologies support the impacts of a CPSS on the sustainability performance of systems and processes.

The primary evidence from the picture is that CPSSs can be a solution with high potential on the following social sustainability categories: social equity, environmental education, participation and control, social cohesion, health, and safety. Considering the equity of process indicator set, CPSSs support and improve access to information and participation in decision-making processes. The presence of case studies in the environmental awareness and sensibility indicator sets demonstrates that CPSSs can improve the use of natural resources, material choices, energy sources, water, waste management, and pollution. Furthermore, the case studies in involvement, social interaction, and health and safety indicators reveal that CPSSs impact user participation and social interaction sustainability indicators.

The overall framework allows evaluating the relationships between the social sustainability indicators, the key enabling technologies, and the Sustainable Development Goals (SDGs), assessing the global impacts of a CPSS on sustainability performances.

SUSTAINABLE DEVELOPMENT GOALS



Fig. 4. Sustainability Goals [29]

V. CONCLUSIONS AND FUTURE WORKS

The present study aims at defining if CPSS may play an essential role in social sustainability and how and if the related technologies can impact this. The framework discussed in section IV presents the classification of the case studies analyzed in section III based on the social sustainability indicators, the key enabling technologies, and the Sustainable Development Goals (SDGs).

According to the outcome of this analysis, it is possible to envision two research challenges to address in future works. In particular, we highlight two main questions:

Research Challenge #a.

(a) Which categories and indicators should be used to evaluate the impacts of CPSSs-KETs on sustainability in building assessment tools?

Our study focus is limited to social sustainability aspects. In the future, sustainability aspects related to external stakeholders, such as customers, suppliers, and the community, could also be addressed. Further, environmental and economic sustainability dimensions should be integrated to support a holistic view of the overall sustainability of a CPSS.

Research Challenge #b.

(b) How would they work in an assessment tool?

According to the research question, the first aspect of addressing is the state-of-art on design methodology for CPSSs defining the critical concept, perspective, applications, and techniques of CPSS. Further, the design methodologies of CPSS discussed in literature should be analyzed in detail, evaluating layer-based design, component-based design, model-based design, virtual integration, and human-based design in order to design, formalize and develop a new widely accepted systematic design methodology to guide the practical design of a CPSS. The design methodology is the basis for developing an assessment tool for evaluating social characteristics and social business opportunities.

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