# Cyber-Physical-Social Systems: Taxonomy, Challenges, and Opportunities

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**ABSTRACT** A Cyber-Physical-Social System (CPSS) is a novel paradigm of cyber-physical and cyber-social systems with a highly inhomogeneous and distributed nature integrating dynamic stochastic hybrid systems including computation, communication, sensing and actuation, and social systems.Their usage can be traced to homes such as smart homes, manufacturers in Industry 5.0, critical infrastructures, smart cities, medicines, healthcare systems, and many other examples. They can simplify and speed up tasks and provide a higher level of control and accessibility. In this study, we provide a systematic review of the definition of CPSS,and an uniform definition of CPSS. We propose a novel taxonomy to define CPSS to help future researches and system designing. The CPSS taxonomy aims to provide a comprehensive and understating of CPSS characteristics and aspects from system-to-system point of view. Furthermore, we discuss about social integration in CPSS and their relationships with CPS. We mention issues and opportunities in CPSS in the designing and implementing phases.

**INDEX TERMS** System of systems, taxonomy cyber-physical-social systems, human-in-the-loop, social systems.

## I. INTRODUCTION

The developments from isolated devices to homogenous control systems with specific networks, including smart devices, social networks, and Internet of Things (IoT) devices which are connected to the Internet more than ever. They have changed business models and ecosystems across many disciplines.The novel paradigm in Cyber-Physical System (CPS) is called the Cyber-Physical-Social system (CPSS) [75]. CPS technologies drive competitiveness and intelligence in a wide range of application domains including agriculture, hospitality and tourism, civil infrastructure, energy, healthcare, environment management, transportation, and manufacturing [19]. The US National Science Foundation (NSF) has identified the advances in CPS as one of its core research aims to expand the horizon of these domains through smart CPS technologies and innovations. The European Commission has also supported research and improvement in CPS since 2014, hence, it has reckoned that CPS is a key infrastructure for

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the futuristic world we live in. They believe that smart CPS bring superior quality of life for people and European industries [14] for which the German initiative ''Industry 4.0'' is one of the digitalizations of the manufacturing industry.

A CPS integrates computation, communication, sensing, and actuation with physical systems to fulfill time-sensitive functions with varying degrees of interaction with the environment, including human interaction [46]. The CPSS introduced changes in the relationship between humans, computers, and the physical environment. As a new research frontier, CPSS integrate ubiquitous computation, physical processes, social agents (Social IoT [21], social networks), communication, and effective control [92]. Widespread development of CPSS, and its essential role in industries, businesses, organizations, and individual's daily life, can be seen in personalized product productions [24], smart cities [13], [83], [85], intelligent transportation [84], and artificial societies, to mention a few. The key techniques for designing CPSS are combinations of CPS and Cyber Social Systems (CSS) including device management and discovery, human-computer interaction, seamless mitigation,

technologies of a heterogeneous network, social computing, context awareness, and management, user behaviour-based proactive services [92].

The CPSS by emphasizing human society and its interaction with other components of the system aims to gather and organize resources in a semantic manner that be used for machines and humans [99]. The CPSS obtain data from virtual and real entities including cyber, physical, and social systems through sensors, mobile crowds, social networks and aims to provide information for users to support their decisions and enhance their performance [84].

The CPSS is still in its early stage of development, and some issues have not yet been studied and solved when facing its design. Despite a variety of studies on CPSS, the social dimension is relatively unnoticed and studied, and there is still a lack of uniform modelling of cyber, physical, and social spaces [88], [92].

This paper reviews several streams of research on CPSS definitions, as well as proposed or used frameworks in different domains. Most past review papers on CPSS have largely focused on the conceptual framework and meta-model for CPSS, but this paper seeks to survey the state of the art of CPSS to define a uniform definition, formulate a taxonomy of CPSS and challenges, opportunities, and open issues in CPSS.

This review paper contributes to provide the following information for researchers and developers:

i. A review of published papers in CPSS represents the advancement in the most highly cited and important CPSS-based works.
ii. Discuss social entities in CPSS and human roles in similar concepts such as the Internet of People (IoP), Social IoT (SIoT) and Cyber Physical Human in The Loop.
iii. Propose a uniform definition for CPSS.
iv. Provide a taxonomy of this new CPSS paradigm.
v. Identify and classify open issues and challenges corresponding to CPSS as well as opportunities for rebooting products and services by adding social computing concept in their business model.

The remainder of the paper is organized as follows; In I-A we describe the CPSS paradigm and its relationship with CPS and IoT, in I-B we respectively define the social entity in CPSS and verify the human role in CPSS, and finally in sub-section I-C we provide a definition of CPSS. Next, in section II, a review of important works in CPSS from multi-disciplinary point of view is provided that can help to create a proper CPSS taxonomy. In Section III, we present the CPSS concept in a nutshell and describe open issues and challenges in CPSS as well as its study domains, following which we propose our CPSS taxonomy and describe each class. In Section IV we give our final remarks on CPSS challenges and future research opportunities. Finally, Section V summarizes the result of this work and draws conclusions.

## A. CYBER-PHYSICAL-SOCIAL SYSTEM AS A NEW PARADIGM FOR SUPPORTING SOCIAL RELATIONS IN CPS

Having initiated the Internet of Computers (IoC) to form cyberspace, cyber systems can work in parallel with physical systems, bringing more intelligence to physical space. The movement from desktop information to the Internet, linked information, and cloud computing has changed the relationships among entities. As a result, the integration of High Performance Computing (HPC) in daily activity and products paved the way for smart factories, smart cities and many smart productions. Also, it lead considerable changes in business models which might be viewed as shifting traditional business platforms to online and web-based platforms, such as YouTube, Instagram, and communications through video conference platforms such as Google Meet, Zoom, and Virtual communities [44]. Thanks to social computing [57], socials with basic knowledge of information technologies have integrated communication technologies and applied their applications to their daily lives, businesses, and communities.

All these technologies and developments are grounded in a paradigm such as the Cyber-Physical System (CPS) [37]. A CPS was coined with two-dimensional space; physical and cyber as "an orchestration of computers and physical systems. Embedded computers monitor and control physical processes, usually with feedback loops, where physical processes affect computations and vice versa." [46].

Although all the traditional CPS are designed for human interest, recent studies have found the importance of the human role in the context of CPS, and new terminology has been introduced called Human-in-The-Loop (HiTL) [42], [64], [74]. Such a concept includes works on Human-Machine Interfaces (HMI) within Industry 4.0 or natural Human-Machine Interfaces (NHMI) in human gesture recognition systems and Cyber-Physical Production Systems (CPPSs) [29].

Nevertheless, HiTL CPSs have some issues describing the human role in the traditional CPS framework and its human factors such as cognition, intents, emotions, behaviour predictability, and human motivation and performance. Therefore, considering HiTL in CPS, there is a need for another discipline which Jirgle [42] calls "Human Reliability Assessment (HRA)", and its critical area is human behaviour modelling and prediction. Therefore to overcome this issue and based on a new technology concept, Physical-Cyber-Social (PCS) computing [92], a novel paradigm in the cyber system domain, have been introduced called Cyber-Physical-Social Systems (CPSS) or Physical-Cyber-Social Systems (PCSS) [66].

The CPSS expands the CPS dimension by combining social systems. In this sense, the CPSS has changed the relationship between humans, computers, and the physical environment. A social system is an independent system with different characteristics, while considering its interaction with other components of CPS, the social system should be
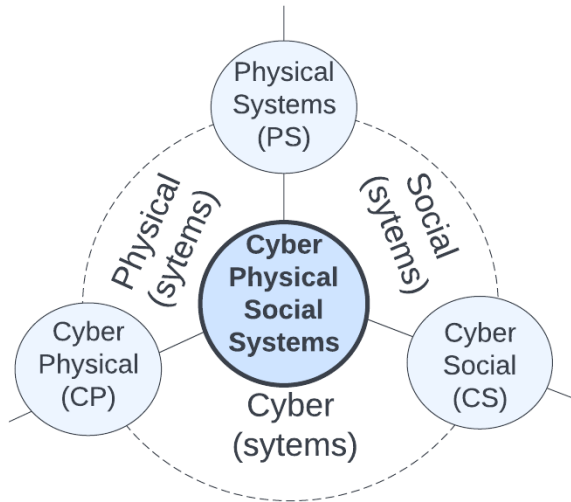
**FIGURE 1.** The dimensions of cyber physical social systems: CPSS.



**FIGURE 2.** The Cyber Physical Social System (CPSS) ecosystem.



**FIGURE 3.** Physical and social systems evolution.

equivalent to other systems (physical and cyber) terms of their interaction with other components. The interaction of each component of CPSS can be defined as the Physical-Social (PS), the Physical-Cyber (PC), and the Cyber-Social (CS), as shown in Figure. 1.

In other words, CPSS is an extension of CPS considering its integration with Cyber-Social Systems (CSS), as shown in Figure. 2, and has three-dimensions cyberspace, physical and human social spaces, so-called hyperspace [22]. Cyberspace or artificial world encompasses the social domain and human features such as cognition, physiology, experience, decision, behaviour, mental and environmental perception, human participation, and interaction to facilitate social users sharing and exchanging data by the close association with cyberspace and the physical world [71]. In this sense, the interaction within the CPSS include social characteristics and relationship between humans and other social communities/societies. This means that putting the human in the system introduces another dimension of mental space consisting of human knowledge, mental capabilities and sociocultural elements [75]. In this way, the CPSS is constituted by the physical system, its social system including human-to-human interaction, and the cyber system that connects both.

One of the main purposes of the CPSS is to use social behaviour data and relationship analysis such as sentimental analysis to provide high-quality, proactive, and personalized services for humans [81]. The CPSS receives human social commands and reacts physically as traditional control systems but with cyberspace interaction. In CPSS, social computing is a supporting technology that can discover patterns of human behaviour, prediction, and management.

The CPSS is a complex and multi-objective system and through its heterogeneity of networks and complication computation, the traditional mathematics algorithms and computing techniques are insufficient to control and manage this system. Withal, considering speed an accuracy of high
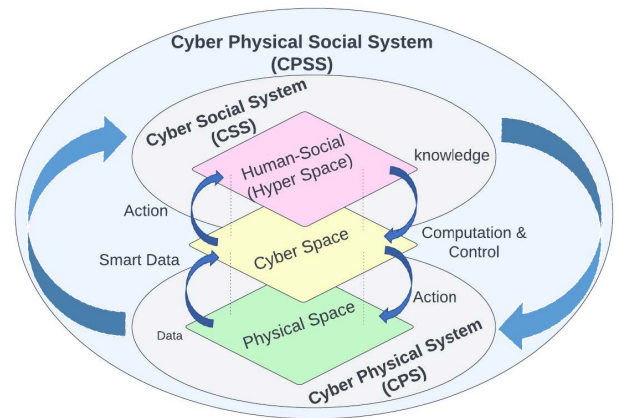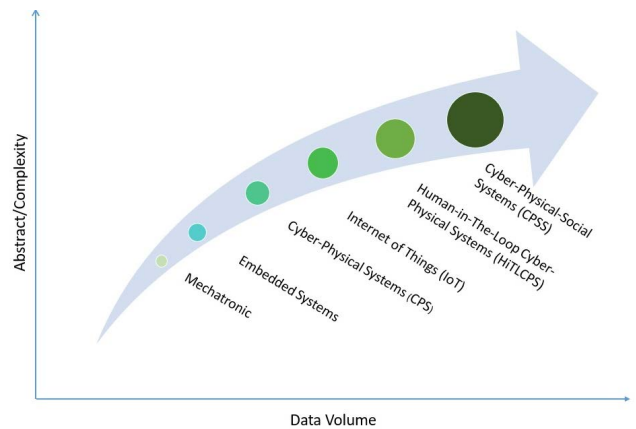
performance computing, they can address most of the issues in CPSS [78].

Figure 3 outlines the evolution of physical and social systems by integrating cyber systems. The evolution of cyber-physical systems shows that the abstraction and data volume increase since the dynamic and unpredictable components augment the system.

## B. THE SOCIAL ENTITY IN CPSS

Immense engagement of people in social networks and prodigious interaction between social systems and their active users means an increasing number of people share their ambient environment and personal information in near real time. The primal idea of social networks is providing social services for people as main contributions of the system based on the shared and computed information. Social computing applies Information and Communication Technology (ICT) in a social context to provide a platform for human communication and exchange experiences. Social computing goals transcend general personal computing, facilitate collaboration and social interactions, and spotlight social intelligence by capturing social dynamics, appointing virtual social agents, and managing social knowledge [54].

To trace back the history of social interaction with machines like computers, according to [77], the first discussion was initiated in the 1940s, in which the expression "As we may think" introduced a new term called "Memex" which means Memory and Communication device. Then, "the computer as a communication device" in the 1960s led the researchers to the concept of social computing in two main areas of technological and computation techniques or "groupware".

A social entity in Multi-Agent Systems (MAS) and the HiTLCPS approach -where an agent is able to interact with others- puts the human in the 'loop' as an embedded system interacts with their environment [64]. A cyber-physical network enables users to interact and connect to the physical world, which is mapped into cyberspace. In comparison, defining the social system as not being an external agent and pushing human-social- integration further in the CPS concept, conducts the idea of CPSS. In CPSS, social systems are independent agents integrated with physical and cyber systems; therefore, a cyber-physical social network with its own logical topology incorporates social entities such as individuals and special-interest communities, activities, and services [27].

The social aspect of CPSS has been investigated less than the physical and cyber aspects.The social dimension in CPSS focuses on social factors and conceptual evolution regarding the sociability of automated production systems [37] by integrating social entities in CPS. In the CPSS, human society as an interdependent entity monitors human activities and social occasions via social sensing. As a result, the services throughout providing supervision, coordination, restraint, and other effects enable people to manage different social domains, such as educational, behavioural conventions, legal regulations, social administration, public services, and other issues. CPS and CS integrated services consist of the user's behaviour pattern, proposing a proactive service that provides a pervasive environment for humans, to sense social phenomena [6], [92].

An early paper by Haouzi [37] categorized social interaction models in CPS and IoT into three types: Human-in-The-Loop, cyber-physical production system, and Social Interactions. They all are respectively based on peer-to-peer communication interfaces, social-network services(the approach is as a media for social interaction), human-inspired social relationships. The latter typically refers to the CPSS concept which was inspired by Popper's three worlds (physical, mental and artificial worlds) idea, and later on, Wang introduced the new paradigm as CPSS [75].

## C. CPSS DEFINITION

The development of computing systems has provided an opportunity to embed social systems into intelligent systems. Recently, social notion imported to different domains of studies created new terms as the Internet of People (IoP) [18]. Also, social aspects have been introduced in several works [8], [25] to integrate social networks with the IoT. In this regard, a new term "smart community" is formed which basically is close to CPSS but it emphasizes social aspects and social networks [82]. In a review by these authors [82], from 2019 to June 2021, the CPSS term was used in 114 pieces of research and technical papers in different publishers, including Elsevier and IEEE. The search strings were "Cyber-Physical-Social Systems" and "Socio-Cyber-Physical System". According to a systematic review by [88], the number of papers related to CPSS was approximately 431 from 2001 to May 2020.

In the CPSS, the human role should be well defined, and when it is related to shareable resources, the human is not an individual entity; hence, it should be considered in the social optima [13]. For instance, this can be seen in scheduling traffic in traffic information management, energy efficiency in energy management, and other frameworks such as e-business and social networks, smart tourism, and hospitality where people access the same information and share their data on defined platforms. Similarly, human role as a trainer of smart systems as well as social systems is an important point which need to be studied.

However, the social entity in CPSS has an arguably different role from those traditionally considered by CPS and smart systems, insofar as they are not concerned with CPSS as much as a certain social entity. Likewise, the social system is an integrated element in the CPSS that changes the system's design and analysis by providing human-human interaction in cyberspace. More recently, several studies have also addressed social space integrity with cyber and physical systems and introduced new concepts mainly as IoP, Cyber-Physical-Social Thinking (CPST) and Social Internet of Things (SIoT). The related definitions are provided as follows:

**Internet of People (IoP)**: "Personal mobile devices may act as their users would do when communicating, managing data, or computing. Indeed, IoP is device-centric, as users' devices play an active role in network algorithms, as today's core nodes are active elements of the Internet algorithms." [18].

**Cyber Physical Social Thinking (CPST)**: A broader vision of IoT by merging the thinking space into the CPS and highlighting the importance of cognitive intelligence and social organization [99]. Thinking space refers to the space created by human thoughts and thoughts of smart things.

**Social Internet of Things (SIoT)**: This idea is based on a "social network of intelligent objects" [7] and navigating a community of objects that are connected together [56]. The main objective comes about "publish information/services, find them, and discover novel resources to better implement the services also through an environmental awareness" [8].

System designs and models for social-integrated systems must describe human features that compromise experience, decision, and data including human participation and interactions in social systems. The difficulty, of course, is determining the human role in these systems. For instance, in **CPSS**, "humans are full members of it, sometimes they full fill role

**TABLE 1.** Human role in cyber social systems.

| System | Human Role | Features Individual in social interaction | Platform |
|---|---|---|---|
| HiTLCPS /HCS | Collaborative, command, and control | Consider human as an individual entity, improve virtual machine to be close to reality | CPS |
| IoP | "Main resources" sometimes replacement of physical sensors Provider of information (willing and unwillingness) via smart devices, end to end connection | Mostly seen as individuals who interact with other components, "center of the Internet system", Human and computers seen as "participant machinery" | Internet |
| CPSS | Full member of the systems, Producer, and Consumer of products-services | It is not isolated, however, has with interaction of other social and physical sensors, impacts on and from a social network, social economy, social culture, (social contexts), and environment | CPSS |
| CPST | Data provider (through contribution in online and social networks or offline physical presents and interacting with others) | Individual and in the social context | Hyper IoT |
| SIoT | Without human interaction | Human information is seen as an object of a social network of "things" | IoT |

of resources in providing information, knowledge, services, etc. Another time they are users of the CPSS in consuming information, knowledge, services, etc." [69]. Because of confusing definitions in human roles in each of the mentioned paradigms we identified common and different features in the human role in newly mentioned paradigms HiTLCPS, IoP, CPSS, CPST, and SIoT, which are summarised in Table 1.

In cyber-social systems, human actors and their interactions with a system play an important role in the state and functioning of the system, also, people's operating and system's operation depends on each other behaviour assumption [59]. Human roles in CPSS can be categorized from a system engineering point of view into human roles as a sensor, and human roles as a system component [88]. From an application point of view -based on human behaviour- its interaction with systems is mostly classified as active or inactive, where the former group is divided into contributors, disruptors and intruders, whereas the latter refers to legacy systems in which the user does not interact with the system intentionally or unintentionally [25].

Generally, from the authors' point of view, the main difference between CPS/IoT and HiTLCPS concepts with CPSS is cybering human and social factors such as movement, behaviour, and cognitive features to develop reliable, flexible, and scalable systems, which assist stakeholders in making their decisions faster and in a safe, secure, and reliable way.

The CPSS develops sensing, computation, and actuation. The control aspects and actuation are changed with regard to social sensing and computing integration. We argue that CPSS can be seen as System of Systems (SoS), which such as a CPS bridges multiple purposes, domains,and data [33]. We refer to SoS as: System of systems is "an integration of a finite number of constituent systems which are independent and operable, and which are networked together for a period of time to achieve a certain higher goal [20]". The CPSS domains, aspects, and facets are similar to the CPS domains,but the contrast is that in the CPSS modeling human behaviour-individually and in the social context- is more complex and stochastic than considering human-in-the-loop in the CPS. In addition, social networks and applications bring new sources and customers into system.

From the output of our investigation on the CPSS paradigm and according to the undertaken studies, mainly [66], [69], [71], [77], [81], the CPSS can be defined as follows:

*The CPSS tightly integrates data processing into physical systems, cyberspace, and the social world through heterogeneous resources, including sensors, actuators, and computational systems to form a unit in cyber environments. Furthermore, the configuration and computation in a CPSS aim to achieve superior Quality of Service (QoS), quality of experiment, and performance. Therefore, the multi-objective optimization of the CPSS operation strongly depends on trustworthy and efficient computation and communication among several layers of the three subsystems.*

## II. LITERATURE REVIEW - CPSS STATE OF THE ART
The relationship of each entity in the CPSS by emphasizing human factor incorporation which is tightly integrated with physical and cyber elements differs from traditional CPS. To the authors' best knowledge, a literature review that analyzes different approaches in designing and developing services in CPSS and associated taxonomy has not yet been conducted. Although, several studies and reviews have focused on the design of CPSS, there are still some interesting and relevant problems to be addressed.

The primary challenge in designing a CPSS is the manner in which physical, social, and hardware can be efficiently integrated and described in real systems [92], [99]. In the CPSS, both physical and social sensor networks are connected to their physical and social operating systems respectively. They communicate and be controlled through cyber system alike the CPS. Subsequently, physical and social systems based on their applications can be mapped equivalently to their cyber systems which forms the idea of platform-based approach for system-level designing in CPSS. Taking into account the heterogeneous networks and social components of the CPSS, system-level designing is one of the solutions to overcome the complexity of designing of the CPSS. Based on these ideas, Zeng *et al.* [92] proposed a

system-level design methodology called "Hyperspace Space Flow". The proposed methodology comes with three components. The function specification is considered in the Intermediate Representation Model (IRM), and the control flow is modelled by hierarchical Petri nets (upper Petri Net models that are refined by bottom Petri Net models), which model the states and events of the physical and social components. A drawback of this methodology is considering social system for one user which is not what social entity means in the CPSS. In another work by Zeng *et al.* [93], the same system-level design framework proposed but for fulfilling a functional specification requirement of a CPSS including energy consumption, user satisfaction, and security focusing on confidentially as well as corresponding constraints. They leveraged Dynamic Voltage and Frequency Scaling (DVFS) to reduce energy consumption and to solve several issues, including reliability and user satisfaction. They have used Multi-Objective Combination Optimization Problem (MOCOP) methodology and a genetic algorithm to find an optimal solution for the three objectives of their work. In another work by Pasandideh *et al.* [58], controlling traffic lights as CPSS is modelled using a web interface tool called IOPT-Tools [32]. In this work, human (social information) plays the role of information resources for the system. In this model, Petri nets are used to model the IRM to control the physical and social flow.

As a matter of fact, the integration of social systems and relationships with other systems brings more challenges to CPSS in terms of modelling and designing. Wang [76] perfectly mentioned this issue and was in an option that a new science is needed for social studies. The social systems need to be studied from a new multidisciplinary approach involving the physical, social, and cognitive sciences integration with the cyber world. He reckoned that Artificial Intelligence (AI)- based systems will be key to any successful construction and deployment of the CPSS. He proposed adapting a traditional three-stage model including modelling, analysis, and control. He called his new model ACP, which is one of the pillars of CPSS applications and models. The ACP approach stands for artificial societies for modelling, computational experiments for analysis, and parallel execution for control. Artificial societies include agents, environments, and rules for interactions for describing and modelling the system, Computational experiments, which are an extension of computer simulation techniques to evaluate a system, and Parallel Systems, by comparison, evaluation, and interaction of artificial systems to control and manage complex system. The introduced approach can solve the complexity of CPSS, and the core of the approach is based on data and knowledge discovery. Current advanced and smart technologies, such as cloud computing, big data analysis, and high-throughput communication, are in line with the ACP approach.

The efficient interaction of the resources of both physical devices and humans in a CPSS as a self-organization system was formulated by Smirnov *et al.* [68], [69] in a context ontology inspired by Zimmerman *et al.* [100]. The context consists of information; individuality, activity, location, time, and relations. Information is captured from the agent's environment and the results of its activity, the individual defines the entity by properties and attributes; activity is related to the allocated tasks to the entities in the community that define events and vice-versa; location and time provide the spatiotemporal information about the respective entity, and finally, the relations category depicts possible relations between one entity and others [67]. The well-defined definition and interaction of entities (especially social entities) and the multi-agent approach in this ontology can be considered an important reference for understanding the CPSS, designing convenient models and development services in the CPSS ecosystem.

The data-fusion framework is another challenging issue when considering the heterogeneous nature of CPSS. Wang [79] proposed a tensor-based Cyber-Physical-Social big data framework with seven layers for CPSS design to overcome the lack of a uniform data fusion model in CPSS. The tensor-based framework layers 1 to 7 consist of:

- Data source ("Tri-Spaces": Cyber, Physical and Social);
- Perception layer (which is divided into "Hard sensors": physical devices and "Soft sensors": networked sources like a social network);
- Data representation;
- Fusion layer (which uses Tensor-based Uniform Fusion (TUF) model);
- Data processing/mining by applying Tensor Decomposition algorithm (TD);
- Rule layer by introducing Eigentensor;
- and the last layer is the Application layer.

The architecture consists of four modules, namely Inter-Sensing Module (ISM), Data Fusion Module (DFM), Rules Module (RM), and Application Module (AM).

From the CPSS framework point of view, Guo [35] presented a D-CPSS (which stands for data-driven CPSS) framework for design and deploying CPSS applications and services considering a four-layer architecture, namely resource management, cooperative sensing, data processing, and data analysis. Each of these layers have different functionality. In this cross-data fusion framework resource management and cooperative sensing, the layers correspond to data collection but the data processing task is covered by data processing and data analysis. This framework provides an initial step for researchers to understand data mostly in the context of urban management and can be helpful in designing and applying a proper data management system for CPSS domains.

Another fundamental issue in the CPSS is big data management. Taking into consideration the heterogeneous networks and inhomogeneous big data in CPSS, in a review study by De *et al.* [22], a new framework was introduced based on fusion models in urban big data for urban monitoring and management. The framework is a four-layered horizontal management model consisting data sources, data

**TABLE 2.** Proposed CPSS models and frameworks.

| Approach | Data driven | Tensor Based | Event Driven | Model Based | Platform Based |
|---|---|---|---|---|---|
| Multi-level | [22, 79] | [79] | | | |
| System-level | | | | [88, 68, 58] | [92, 93] |
| Multi-Agent | [83] | [79] | | | [67] |
| Upper-level Ontology | | | [69] | [88, 68] | [67] |

processing, data fusion and application in urban management. Data sources that refer to big data captured from inhomogeneous and distributed sensors include near real-time physical sensors: sensing fixed sensors and mobile sensors; social sources: social networks. Data processing includes technologies related to event detection, classification, clustering, decision support, and rule formulation and management. Data fusion technologies consist of semantic approaches, tensor decomposition, social data as context descriptors, and physical-social correlation.

A CPSS is a concept that is defined from different point of views, such as multi-agent systems, or multilevel systems. The manner in which we describe and define CPSS components and the relationships among them can change the system model. Different categories of these approaches are provided in Table 2.

In all of these conceptual models the computation mechanism is not well remarked. Sheth, Anantharam & Henso in 2013 [66] introduced Physical-Cyber-Social (PSC) computing as a relatively novel and strong emerging paradigm to support and formulate CPSS. It supports Computing for Human Experience (CHE) vision by involving observation, experiences, background, knowledge, and perceptions. It encompasses a holistic treatment of data, information, and knowledge from PSC worlds to integrate, correlate, interpret, and provide contextually relevant abstractions to humans.

One of the issues in real-time and big data computation in CPSS is redundancy. This might occur with historical and periodic incoming data, for which Wang [38] proposed a Distributed column-wise High-Order Singular Value Decomposition (DHOSVD) and Incremental HOSVD (IHOSVD) algorithm to perceive dimensionality reduction, extraction, and noise reduction for tensor-represented supporting online computation on temporally incremental data streaming big data. Processing massive CPSS data is a considerable issue. The k-nearest neighborhood (kNN) as one of the widely-used clustering machine learning techniques for processing massive amount of data has gotten attention [15]. Nevertheless they have limited storage capacity and computational power. In this regard, Zhang [95] proposed a Distributed storage and computation k-Nearest Neighbor algorithm (D-kNN). Their experimental results showed that this algorithm can be easily and flexibly deployed in a cloud-edge computing environment to process big datasets in CPSS.

## III. CPSS IN A NUTSHELL
While CPS is widely discussed and many researchers, industries, and official institutes (such as NIST) have provided
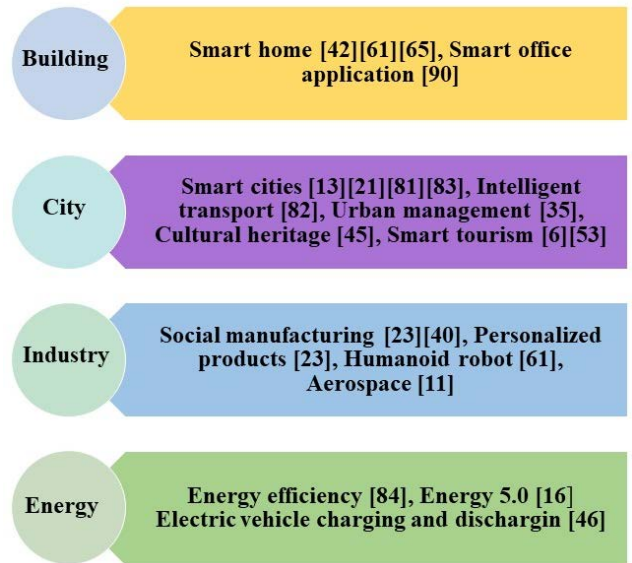


**FIGURE 4.** The applied-domains and sub-disciplines of cyber physical social systems.

frameworks for CPSs in June 2017, the CPSS concept is relatively new and mainly used in Chinese research. There is no solid framework or defined taxonomy for it. Considering standard definitions for the CPS, it is inferred both the CPS and the CPSS have to do with in several common domains and have alike facets. The CPSS domains consist of manufacturing, transportation, and health. Facets are views on CPS encoding the identified responsibilities in the system engineering process.

A CPSS relies on communication, computation, and control infrastructure, commonly consisting of several levels for the three worlds with various resources, services, and humans. Their applications are observed in many application areas.

Indeed, the technologies related to the CPSS are multidisciplinary, including robotics, related mathematical optimization algorithms for scheduling the CPSS workflow providing patterns and predictions, psychology, and biology [63]. In the CPSS, data are acquired from a variety type of sources, such as biological information from sensors including wearable [34], [72] or biosensing [13] therefore complex computation and techniques such as AI techniques can be applied to analyze and predict the human body functionality. Human body analysis helps to diagnose, track and improve body state (physical) and mental (hyperspace), which for high accuracy of the analysis, all types of correlated information are needed to be considered in modelling and computing, the data/information such as human experience, social, and culture characteristics, and economic background [66]. In Section III-A, we in details describe supported technologies for communication, computation and management of the acquired big data/information in the CPSS.

In Figure 4, some studied application areas in the context of CPSS are shown. The smart city domain has taken

a leading role in CPSS discussions. While smart cities are widely discussed in the CPS, solving issues such as shareable resource management and recommendation algorithms for public services needs to take social systems and CPSS into account. To open a discussion about the CPSS application, in the first step, we categorized CPSS domains into four main application domains based on their functionality in CPSS. These domain groups are building, urban, city [11], [83], [98], industries, energy efficiency, and optimization. In Section III-A we extend the grouping based on the subjectively of the system and describe each category.

## A. CPSS TAXONOMY

Our proposed CPSS taxonomy is described with six categories and related areas and disciplines (Figure 5). Based on the paper's objective, we have studied several resources that CPSS is examined and presented. We found the footprint of CPSS in many types of research and applications that have taken them into account to make our taxonomy.

The goal here is to conceptualize the CPSS through surveying, sanitizing, and explaining works in the domain. A taxonomy of the CPSS in six categories is created using a combination of literature review and systematic research methods. Existing studies and research within each category were studied, and the results are provided. This taxonomy will help formulate and conduct future research and prototype products related to CPSSs in a more structured way and method. In further studies, this taxonomy can be expanded for the user's best interests.

Considerable lacunae in the direction of CPSS work have been determined. Little work has been conducted on modelling the interaction of social objects with cyber and physical systems, which are the most challenging components in a CPSS to assess and model. Considering the studies done in the CPSS, there is still no taxonomy for this new paradigm. In the following, we propose a CPSS taxonomy based on the CPSS definition, state-of-the-art, and supported technologies. We consider the proposed taxonomy as an initial step, with the potential to be developed in the future. The proposed CPSS taxonomy paves the way for a better understanding of the CPSS ecosystems and their characteristics.

### 1) DEFINING A TAXONOMY OF CPSS

This work is the first attempt to create a CPSS taxonomy. For generating the CPSS taxonomy, we studied and analyzed recent articles, literature on CPSS databases. We were inspired by the taxonomy of system of systems from NIST to provide a framework for CPSS [33]. We categorized CPSSs based on facets, domains, applied technologies, theories, and design approaches. Each category aims to present a different dimension of the system, thus, the proposed taxonomy makes it easier to understand CPSS aspects and characteristics towards developing design mechanisms, and reliable and accessible services considering user satisfaction. The taxonomy is also leveraged to identify open problems that can lead to new research areas within CPSS domains.

#### a: COMPONENTS

The components of CPSS includes physical, cyber, and social systems.

*Physical Systems*: Physical systems refer to all geographical objectives in the world including infrastructure, physical devices, sensors, cooperative actuators for collecting real time-data, and communication networks. In CPSS, physical space represents real-world physical systems through smart objects and communication systems.

*Cyber Systems*: Cyber systems refer to computing, storage information processing, and sharing services especially situations awareness and decision support services that directly command and control and are represented by cyberspace. Cyberspace is a time-dependent set of generalized information from resources including virtual and digital abstractions aims to have interconnect cyber entities [87], [99].

*Social Systems*: Social systems that are represented by social space in CPSS reflect social attributes and interactions in the human society world either from cyber entities or physical systems in a semantic way. Indeed, social systems are logical components of CPSSs [99].

#### b: ASSETS

Any tangible and intangible valuable resources for individuals, communities, organizations, and governments can be categorized as assets [45] of the CPSS. These assets include any hardware: physical devices for digitization and Communication (or IT) objectives such as switches, routers, computers; software, and applications which consist of all platforms, databases publicly and privately available and used.

Another asset is information that refers to critical and sensitive information-related to individuals, communities, organizations, and critical infrastructure- collected by information systems/services, stored, analyzed, and transmitted through cyberspace. Finally, people in a CPSS refer to those who interact with cyberspace, either customer or provider data and services.

#### c: APPLICATION AND PLATFORMS

The CPSS offers various applications such as managing traffic, autonomous vehicles [84], customization in industrial products and services [89], recommendation systems for tourists to choose the best routes [6], and behavioural profiling to predict future behaviours [59] which have both security and marketing purposes, and many other examples.

These applications provide services for users to monitor, control, and manage the assets and the environment of the system. CPSS application data can be obtained in either an active or passive manner using homogeneous and heterogeneous sensors. We have categorized these applications based on the business purposes including smart cities [13], smart homes [63], smart tourism [6], [55], intelligent transportation [84], social manufacturing explanation of Industry 4.0 [24], [41], Critical Infrastructure (CI), smart healthcare, smart energy, humanoid robots [63] and safety and security.
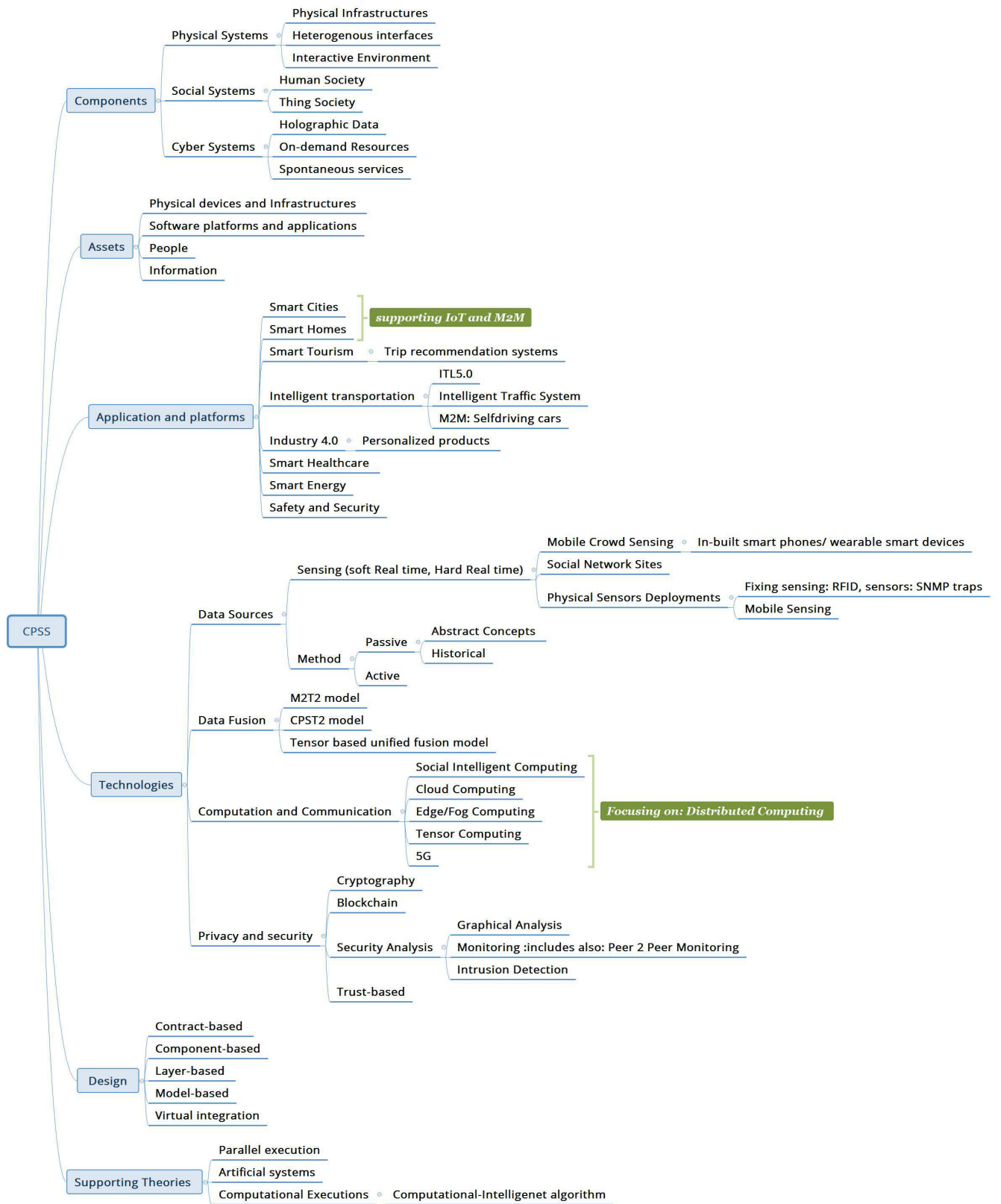
## CPSS taxonomy

**CPSS**

- **Components**
  - Physical Systems
    - Physical Infrastructures
    - Heterogenous interfaces
    - Interactive Environment
  - Social Systems
    - Human Society
    - Thing Society
  - Cyber Systems
    - Holographic Data
    - On-demand Resources
    - Spontaneous services

- **Assets**
  - Physical devices and Infrastructures
  - Software platforms and applications
  - People
  - Information

- **Application and platforms**
  - Smart Cities — *supporting IoT and M2M*
  - Smart Homes
  - Smart Tourism — Trip recommendation systems
  - Intelligent transportation
    - ITL5.0
    - Intelligent Traffic System
    - M2M: Selfdriving cars
  - Industry 4.0 — Personalized products
  - Smart Healthcare
  - Smart Energy
  - Safety and Security

- **Technologies**
  - Data Sources
    - Sensing (soft Real time, Hard Real time)
      - Mobile Crowd Sensing — In-built smart phones/ wearable smart devices
      - Social Network Sites
      - Physical Sensors Deployments
        - Fixing sensing: RFID, sensors: SNMP traps
        - Mobile Sensing
    - Method
      - Passive
        - Abstract Concepts
        - Historical
      - Active
  - Data Fusion
    - M2T2 model
    - CPST2 model
    - Tensor based unified fusion model
  - Computation and Communication
    - Social Intelligent Computing
    - Cloud Computing
    - Edge/Fog Computing
    - Tensor Computing
    - 5G
    - *Focusing on: Distributed Computing*
  - Privacy and security
    - Cryptography
    - Blockchain
    - Security Analysis
      - Graphical Analysis
      - Monitoring :includes also: Peer 2 Peer Monitoring
      - Intrusion Detection
    - Trust-based

- **Design**
  - Contract-based
  - Component-based
  - Layer-based
  - Model-based
  - Virtual integration

- **Supporting Theories**
  - Parallel execution
  - Artificial systems
  - Computational Executions — Computational-Intelligenet algorithm

**FIGURE 5.** CPSS taxonomy.

*Smart Cities*: The population residing in urban areas is increasing every year, as of 2018 forms 55% of world's population and it is expected to reach at about 68% by 2025 [1]. In this regard, the key issues are management and sustainable urbanization which can provide social welfare to citizens. A new prototype called a smart city by emerging new information communication technology with urban management infrastructure seeks to bring a convenient quality of life, improved services, and a clean and safe global environment [4], [5], [91]. Smart city characteristics can be defined as sensible, connectable, accessible, ubiquitous, sociable, sharable, and visible [13]. In this sense, the IoT, CPS frameworks, and architectures are mostly applied for designing platforms of a smart city [61], but the social factor is not the well-defined or human role is seen as an individual, which will be a problem for managing shareable resource systems unless defining smart cities as a CPSS [13]. The social space for humans in smart cities in the context of CPSSs refers to the participants of different activities in the city [85]. Distributed Sensor Networks (SNs) [51] and sensing physical systems alongside inhabitants' sensor-enabled smartphones and online social networks provide near real-time large-scale sensing for big data mining and knowledge discovery which it allows the systems to offer more proactive and responsive services for their users and citizens [22]. The deployed platforms and implemented services increase people's awareness about the dynamics of their environment, and prediction of citizens' activities and movement, including smart parking systems, environment monitoring [22], and event sensing [35].

Smart city platforms in the CPSS framework can lay the foundation for correlated applications such as smart homes, smart tourism, and intelligent transportation. They carried out studies and work on designing and conceptualizing CPSS for smart cities categories into the data-driven approach, and networks and communications approach. The objective of the smart city platform is to generate smart data and obtain urban intelligence, which owing to the unstructured or semi-structured data in the CPSS requires a different conceptual framework for the data management framework [70]. A data-oriented conceptual CPSS framework was proposed in [22] which consisted of four layers: data sourcing, data processing, data fusion, and application by leveraging big data and mobile sensing in their approach.

*Smart Homes*: Smart homes integrate smart devices and Smart Home Technologies (SHTs) consisting of sensors, actuators, monitors, interfaces, appliances, and devices that are networked to provide information and services considering multiple preferences. SHTs enable automation, localized and remote control of the domestic environment [43]. Successful scenarios and implementations of smart homes would be more adaptable to human daily life. They need to consider human preferences and design psychologically-inspired systems [67] which require the integration of social systems with traditional information computing. In this regard, Smirnov proposed [67] self-organization approach for CPSS and devices, using a cleaner robot as an example, they

presented an ontology-based information model for smart home device interaction in cyber-physical space. In this platform, the devices, domains, and vendors are independent of the smart space. The three-level organization is applied at the top-level called the strategic level to adjust customer preferences that are transmitted to the physical level and in the middle layer, and planning-level services are designed to control domains.

*Smart Tourism*: "Smart Tourism", which is web-based, inherits from "Smart City" as a platform. Smart tourism should provide attractive and real-time information such as location, route, images, rating, and captions of tourist attractions anytime and anywhere [10], [55]. CPSS in smart tourism is a new approach that integrates social systems and Service-Oriented Architecture (SOA) methodology increases the quality of trips and tourist information and computes the influence and accuracy of exchanged and shared information via the social networks and web platforms as well as the influence of shared information and experience with other users, and for further actions [6].

*Intelligent Transportation*: Merging result integration social systems and human dynamics level up the transportation system and bring wide perspectives and advantages. CPSS-based transportation systems called Transportation 5.0 or ITS 5.0 aim to optimize traffic control and management by adapting strategies on control technologies, data perceptions, and analysis, as well as the management of which social aspects become paramount. To solve the social system complexity in these systems, the ACP approach is applied to model and design ITS 5.0 [84] in CPSS. Another promising application of CPSSs in intelligent transport is an integrated hybrid system for enhancing driver behaviour prediction which can be useful for autonomous driving [25].

*Social Manufacturing*: Following the Industry 4.0(I4.0) -and recently Industry 5.0 (I5.0)- paradigm, the new manufacturing concept is integrated with social systems and is called social manufacturing [41] with three core aspects of Dynamic Resource Communities (DRC)-based self-organizing and configuration. Therefore, a CPSS service-oriented platform was introduced [24] to provide personalized products and services in the context of I4.0. This platform integrates different manufacturing resources in the social manufacture environment to provide mediators for customer-producer interaction.

*Smart Healthcare*: Smart healthcare is one of the domains in smart cities but with a different approach and business model, and includes assisting diagnosis and treatment, assisting drug research, health management, disease prevention, risk monitoring, virtual assistants, and smart hospitals [73]. Despite the strengthening of smart healthcare systems to assist physicians and patients, it is challenging to secure and maintain the privacy of their sensitive data [60]. Smart devices and Wireless Body Area Networks (WBANs) with multiple sensors as wearable devices are gaining popularity and providing information about body temperature, heart rate, falling detection, oxygen saturation, etc.

To the best of our knowledge, there is no CPSS framework for smart healthcare systems but here we believe the ideas and works in CPS [38], [96] should be expanded and promoted based on social integration in the systems as one of the important constituents of smart health.

*Smart Energy*: Smart energy systems seek the most efficient and least costly solution by using all infrastructure, low-temperature district sources, and renewable energy heat sources. Smart Grids (SGs) are a traditional concept that is widely used in smart energy systems. SGs are electronic networks that use ICT, self-healing technologies, and control theories and models to provide better connection and operation for distributors and generators as well as more reliability, security, and flexible choices for users [86]. In the CPSS framework, for the energy efficiency area, a novel concept of a robot for energy control based on parallel cyber-physical-social systems for the next generation of energy and electric power systems is proposed [12]. Considering environmental factors, economic, social, and human behaviour for smart energy modelling, a CPSS conceptual model was introduced [86] taking SGs as a core, but also other factors such as gaming behaviours of participants, carbon markets and their regulation, strong volatility, and intermittent renewable energy sources.

*Safety and Security*: Security and privacy can be considered as a service category and application. Their mechanism provides support services, and products as an important and broad domain in CPSS. The privacy of a CPSS is important for eventual acceptance by the public. Therefore, any communication must preserve data privacy anywhere and at any time. CPSS security -like CPS- presents several characteristics that distinguish it from more conventional IT systems security. The security objectives have not changed compared to traditional IT systems, and they are not the only service expected from CPSS security and safety. Designing this new generation of CPSSs requires other requirements in terms of system security. In this case, the conceptual model might be different, and the systems' behaviour changes owing to the interaction of human decisions [31], [65], [97].

*d: TECHNOLOGIES*

In CPSSs, technologies are adapted and integrated from IoT, CPS, social networking, and computing with new approaches and conceptual models. Technologies in CPSS can contribute to solving human-computer interaction, seamless mitigation technologies of a heterogeneous network, security, privacy, social computing, context awareness, management, and user behaviour-based proactive service. With the homogeneous and complex nature of CPSSs, there are a variety of challenges regarding data fusion, processing, and analysis, computing and communication, privacy, and security. In this section, we provide an overview of proposed solutions from different works and points of view.

*Data Sources*: The initial step in deciding on data management and usage is up to determine how and where the data is acquired [9]. In this study, the data sources were categorized based on the data collection method to answer "how" and in terms of methodology and to answer "where" in terms of technology for data acquisition. The methodology is grouped into passive and active, and technologies are categorized based on mobile crowdsensing, social network sites, and physical sensing. The term Mobile Crowd Sensing is defined as "where individuals with sensing and computing devices collectively share data and extract information to measure and map phenomena of common interest" [28]. Generally, crowd systems are systems that congregate people who are interjecting and communicating with each other and exchange experiences and information physically or virtually towards the fulfillment of the system's objectives [64]. As is the case in CPSSs, the complexity of crowd systems arises from the existence of a human factor that can never be fully controlled. Consequently, certain inconsistencies and systemic instabilities remain in crowd systems. Examples of such systems include crowdsourcing platforms, Wikis, and museums equipped with smart guidance systems [89]. People interaction in social online services called Social Network Sites (SNS) provides social big data in any topic on large volumes with different formats and contents, and to some extent, SNS reflects the social circumstances [31]. Along with social sensing, physical sensing reflects what happens in the physical world through physical sensors. Physical sensor node deployment can be classified into static and mobile, both of which can be deterministic or random [2].

*Data Fusion*: Data fusion in CPSSs is a very challenging task that is mainly related to how to represent and address higher-order and higher-dimensional heterogeneous data from multiple and heterogeneous sources [94]. Despite the traditional data fusion method that is simply processed from physical devices, in CPSS, social data can be collected on a large scale, multiple resources such as transportation applications and devices such as cars, wearable sensors, medical services, social media/networks application, web browsers, cross languages, heterogeneous networks with different formats and representations, etc. [79]. A widely used method for categorizing data fusion-related functions is the data fusion model which is maintained by Joint Directors of Laboratories (JDL). They define data fusion as: "A multi-level process dealing with the association, correlation, combination of data and information from single and multiple sources to achieve refined position, identify estimates and complete and timely assessments of situations, threats and their significance" [36]. Data fusion methodologies are classified mainly by their space in the work by Wang [79] into CPS, CSS, and CPSS groups. They introduced their model in CPSS called tensor-based models by extending the Markov Chain (MC) model to the transition matrix of MC. They proposed a multivariate multi-step transition tensor M2T2 model to fuse data arising from CPSSs, including mobile sensor data, and Point of Interest (POI) in the city. To overcome the multi-space service problem, they proposed a social network information Cyber-Physical-Social Transition Tensor (CPST$^2$) to fuse the CPSS data in a unified form.

Generally, tensors in a CPSS represent objects and they are heterogeneous. In another work by [16], a sensor-network-conversion-based data fusion approach was applied, which can simultaneously analyze multiple matrices and tensors. CPSS data processing challenges should be addressed by an overarching approach that attacks the problem from different perspectives, i.e. Edge/Fog Computing – on the one hand, and Big Data – on the other, converging into a lightweight solution for data processing through computation offloading to collocated edge devices.

*Computation and Communication*: The dynamic, customized, mobilized, complex nature of CPSS, in addition to the challenges in data fusion, brings unsettled data processing frameworks and models in CPSS from a computational and communication point of view. One solution [21] is augmenting CPSS data processing modules with current technologies such as cloud computing, edge computing, and big data. In the context of SIoT(Social IoT), Dautove uses multi-tier computational with Data Information Knowledge Wisdom (DIKW). Studies have shown that combining multiple techniques tackles limitations and problems of a single method and enhances the data processing and computing objectives [99]. A brief explanation of each of these technologies is provided below. Cloud/Edge computing is useful in the presence of big data, as it can provide on-demand computation and storage resources for CPSS applications and it has been deemed the key technology for practical use in various fields of CPSS [29], [52]. Socially Intelligent Computing (SIC) aims to merge intelligence, knowledge, and human experiences through the social, crowd, and end-user computing to provide knowledge and wisdom called collective intelligence and social perceptions [3].

*Privacy and Security*: Cyber security is of paramount importance when designing and modelling CPSSs. Interoperation among heterogeneous devices and applications and unpredictable humans behaviour is a complicated task. However, the interaction of physical components with cyber processes in CPSs and social elements in CPSSs brings new challenges for identifying, classifying, and analyzing cyber-attacks and determining a proper defence strategy to design cyber-secure systems. The attackers implement five steps of intrusion: access, discovery, control, damage, and clean up, to gain complete control of the system directly or indirectly, and to hide any traces of any caused intrusion [53]. Current technologies such as blockchain cryptography [90] can be applied to CPSSs security and privacy policies.

### e: DESIGN

Combining human and artificial intelligence is a promising direction for enhancing efficiency and meeting customer requirements. CPSS is a suitable solution that adds a Human Intelligent Teaming (HAT) layer to the design of elegant systems [11]. Based on a survey by [92], CPS system-level design can be extended to CPSS, and categorized into five categories: component-based, layer-based, model-based, virtual integration, and contract-based design. In addition, they

proposed a flow-based methodology showing data, physical and human flow. It is based on a directed acyclic graph, and to determine how specific state transitions and events occur in CPSSs, they successfully applied the Petri nets model.

The tools which can be applied in modeling and designing the CPSS should adaptable with three CPSS subsystems. From exiting tools, the model driven languages/techniques can be consider to be useful are those compatible for the heterogeneous nature of CPS and not be specified for one domain. In a conducted survey by Liu and *et al.* [48], they compared ten different tools and showed among them, the Ptolemy and the Ptolemy/CyPhySim can cope with CPS challenges. The selected assessment criteria were some of the CPS modelling requirements including heterogeneous modelling,time, concurrency, system evaluation and meeting diverse Quality of Services (QoS).

To ensure the system are effectively designed, it is crucial to establish tests for the developed processing design. For this purpose, in [49] learning factories is considered an effective way in the CPS environment namely manufacturing and I4.0 which we reckon that can be applied in the CPSS context as well. The leaning factory integrates real world application in a small-scale model to explore the developed design and improve the knowledge related to the systems.

### f: SUPPORTING THEORIES

The CPSS supporting theories proposed by Wang [77] called ACP is described in Section II. The fundamental idea of ACP has been applied in intelligent transportation [84], and artificial healthcare systems [80] as a method for controlling and managing these systems. In the ACP theory, as mentioned above, artificial systems (A) image/mirror and transmit the data and events flow in the physical-social systems in cyberspace, computational experiments (C) are used for the validation of the control plans, and finally, parallel execution (P) determine the stepwise control and management of the CPSS.

## IV. CPSS CHALLENGES AND FUTURE WORK OPPORTUNITIES

Generally, the intrinsic heterogeneous, concurrent, and sensitivity to the timing of CPS and CPSS poses many modelling and analysis challenges. Moreover, this means that time plays a critical role in the performance of a CPSS, not only the function of a task [33].

The integration of social aspects in systems brings challenges, such as safety from a medical perspective, human rights, security, scheduling from energy, traffic management, and even sharing resources such as car sharing, urban management, and many other examples. Therefore, before designing systems that are included social components, it is necessary to think from the CPSS point of view and consider social entities that interacted with other components not isolated.

Another issue is related to social acceptance. Social acceptance of new technologies such as IoT and CPSS is something

**TABLE 3.** CPSS open issues.

| | Domain | Studies |
|---|---|---|
| **CPSS Open Issues** | Data Fusion | [35, 31, 94, 22, 79] |
| | Performance Optimization | [78, 47] |
| | Privacy and Security | [31, 26, 62, 59] |
| | Network and System Design | [25] |

that if the human is not considered as the user and provider of the system's information, we cannot make user-friendly applications and even appealing human interfaces [50]. Energy consumption plays an important role in the CPSS design. The development of next-generation smart-energy systems requires innovative computational methodologies and models. The design of the energy-aware and data-driven CPSS has become critical for sustainable development [17], [60], [86]. Another challenge besides energy management in data collection and actuation methodology is integrating heterogeneously distributed devices into a common platform [13]. The main issues addressed by researchers are provided in table 3. We categorized these into four classes: data fusion, energy efficiency, privacy and security, and network and system design.

In the future, CPSS applications can be expanded to different businesses such as robotics, and smart education systems, smart societies s-Society 5.0- moving from e-learning 3.0 [39] to Learning 4 [40] using Virtual Reality (VR), Augmented Reality (AR) and adaptive Massive Open Online Courses (MOOCs) [30]. Moving from traditional social systems to cyber social systems under the CPSS ecosystem requires a closer and more precise methodology for implementation. As seen in the pandemic crisis in 2019-2021, some e-learning Information Communication Technology (ICT) infrastructures are not ready [23]. One of the ultimate goals in intelligent systems such as CPSS is to provide information "anytime anywhere" for their users. For instance for a natural tourist accessing to an accurate location is necessary, which is still an issue in current smart solutions [6].

## V. CONCLUSION

Designing and deploying CPS without paying attention to human behaviour in the shadow of social behaviour – crowd behaviour– will fail to satisfy goals such as the best recommendation and optimizing decision making. Therefore, social systems are pivotal components of CPSSs, and they are already transforming how humans interact with the physical environment by integrating it with the cyber-physical world. The integration of social systems in CPSSs provides new frameworks for smart cities, intelligent transportation, energy management, and sustainability to enhance people's daily life tasks, system availability, and reliability. This is a relatively new research field that requires new approaches and techniques. In this paper, almost all applications of CPSSs are studied and introduced for further research and future developments. The operation and configuration of CPSSs require methods for managing the variability at design time and the

dynamics at runtime caused by heterogeneous resources and complex ecosystems. The literature review in this paper provides a deeper look at CPSSs and what advantages they bring for users as individual and public interests. Furthermore, we describe state-of-the-art CPSS approaches and methodologies. The key techniques, theories, and design approaches are clustered based on the categorization and description of previous studies. In addition, the present and potential applications of CPSS are argued.

A uniform definition of CPSS provided in this paper helps to find a common understanding from this new paradigm. The given comparison of SIoT, IoP, HiTLCPS, CPSS, clarifies the human role in designing a CPSS. To describe CPSS, this paper delivered a taxonomy of this new paradigm based on the system-of-systems approach inspired by the CPS-NIST framework. The CPSS taxonomy includes assets, components, applications, platforms, technologies, design methodologies, and newly supported theories. This taxonomy is an initial attempt to formalize the CPSS, and subclasses can be expanded by introducing new methodologies and theories in the future.

The CPSS as a new paradigm tackles some issues that can be seen as opportunities for research. The issues that researchers consider in CPSS are in the following domains, data fusion, analysis, performance, network, system design, and security/privacy. Another important issue is that there is insufficient work related to the human role in CPSS. Even though the challenge, it is an advantage of CPSS in terms of social learning techniques. To that extent, a technique such as deep learning is applied to integration, and interaction with physical and cyber systems, and still the human role, and interactions in CPSS are not well-defined. Even in some CPSS studies, the human role is considered as individual and not in the social context.

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