CITYSPIN

Cyber-Physical Social Systems for City-wide Infrastructures

Deliverable 2.1: Cyber-Physical Social Systems Blueprint (v.1)

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Dissemination Level	:	Public
Due date of deliverable	:	31.03.2018
Actual submission date	:	6.04.2018
Work Package	:	2. Designing Cyber-Physical Social Systems
Type	:	Report
Version	:	1.0

Abstract

The overall goal of WP2 is to derive a conceptual technological blueprint for CPSS consisting of a taxonomy of CPSS (T2.1), a social actor model (T2.2) and software engineering principles and methods for CPSS (T2.3). Deriving these components of the CPSS blueprint rely on findings derived from a thorough and systematic literature study of CPSS. This deliverable reports on how this literature study was performed as well as on its initial results with respect to the main components of the CPSS blueprint.

FFG

Project Funded by FFG – IKT der Zukunft Programme

Project Number: 861213 **Start date: 01.10.2017** **Duration: 30 months**

History

Version	Date	Reason	Revisited by
0.1	06.03.2018	Initial draft	MS
0.2	09.03.2018	Section 1	MS
0.3	14.03.2018	Section 2	AM
0.4	22.03.2018	Sections 5, 7, 8	MS
0.5	27.03.2018	Sections 3, 4, 6	AM
0.6	27.03.2018	Sections 9, 10	MS
0.7	04.04.2018	Section 12, executive summary	MS
0.8	05.04.2018	Review and improvements	MS, AM
1.0	06.04.2018	Final review	MS, AM

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Executive Summary

Cyber-physical social systems (CPSS) are an emerging category of systems that consist not only of software and raw sensing and actuating hardware, but are fundamentally grounded in the behaviour of human actors, who both generate data and make informed decisions based on data. Research on CPSS dates back to about a decade, and is spread across a multitude of scientific disciplines. Therefore it is important to obtain a comprehensive understanding of the CPSS concept and an overview of current state of research on this topic.

WP2 addresses this need by aiming to derive a CPSS blueprint consisting of a taxonomy of different CPSS models, a social actor model for formally representing the social component of these systems and a catalogue of software engineering principles of CPSS as well as architectural methods to support design, modelling and engineering of CPSS. A basis for achieving these planned contributions is a thorough study of the available research work.

This deliverable primarily reports about how this study was performed in order to collect a broad collection of research papers on the topic. We followed a methodologically principled approach by adopting the steps of a *Systematic Mapping Study*. Our study focused on the following research questions covering important aspects of CPSS: (1) What is an overarching definition of CPSS? (2) What are application domains, goals and stages specific to CPSS? (3) What are main characteristics of CPSS? (4) What is the role of human and social elements in CPSS? (5) What data sources are typically used in CPSS? (6) How is data processed and distributed in CPSS? (7) What architectural approaches are applied to design and describe CPSS? (8) What are key challenges and emerging future work trends in CPSS?

The collection of relevant papers was performed over 5 digital libraries of scientific work and led to 3729 papers which were filtered, merged and assessed in detail resulting in 229 papers relevant for CPSS. From these, 60 papers described concrete systems.

We performed an initial analysis of 22 papers and reached the following conclusions for some of the research questions that informed the study: (1) there is a broad spectrum of CPSS systems published, exposing a rather diverse interpretation of what the social aspect of a CPSS should be; (2) typical application domains for CPSS include smart transportation, smart city, smart buildings and smart factory; (3) key stages in a CPSS consist in data collection, data analysis and proactive recommendations, while data storage and data integration stages were less often reported; (4) humans can play a range of roles in CPSS ranging from mere users of the system, to social sensors, decision makers within the system or social actuators; (5) typical data sources in CPSS include data from physical sensors about the physical space, social data about the social actors and to some extent historical data; (6) key challenges in CPSS relate to dealing with multiple, heterogeneous, real-time and contextual data sources as well as addressing privacy and security issues. CitySPIN is well-positioned to address exactly these current weak points in CPSS.

This initial analysis already provided some basis for further investigating the components of the CPSS blueprint namely the taxonomy of CPSS models (T2.1), the social actor model (T2.2) and the software engineering principles and methods (T2.3). Next steps include (1) reading the remaining 40 papers in order to address the still open research questions and to extend our understanding of those questions that were already investigated and (2) creating the CPSS blueprint.

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1 Introduction

Cyber-physical systems (CPS) are systems that span the physical and cyber-world by linking objects and process from these spaces (see Fig. 1). In a typical CPS data is collected from the physical world via sensors and computation resources from the cyber-space are used to integrate and analyze this data in order to decide on optimal feedback processes which can be put in place by physical actuators.

CPS have started to diffuse into many areas, including mission-critical public transportation, energy services, and industrial production and manufacturing processes. While CPS affect the lives of people that rely on them on a daily basis, they so far only interact with humans as passive consumers. The results of a recent study about adaptation in CPS [21] revealed an emerging trend to add an additional *social* layer in a CPS architecture to address human and social factors (see Fig. 1). This trend shows the growing recognition of the importance of the social dimension of such CPS and of the need to evolve them into *cyber-physical social systems (CPSS)* [29]. CPSS consist not only of software and raw sensing and actuating hardware, but are fundamentally grounded in the behaviour of human actors, who both generate data and make informed decisions based on data [2, 9, 33]. This raises new research challenges due to additional complexity introduced by social systems in terms of (i) uncertainty due to social dynamics, (ii) privacy concerns associated with the processing of sensitive social data, and (iii) the number and heterogeneity of data sources that need to be integrated.

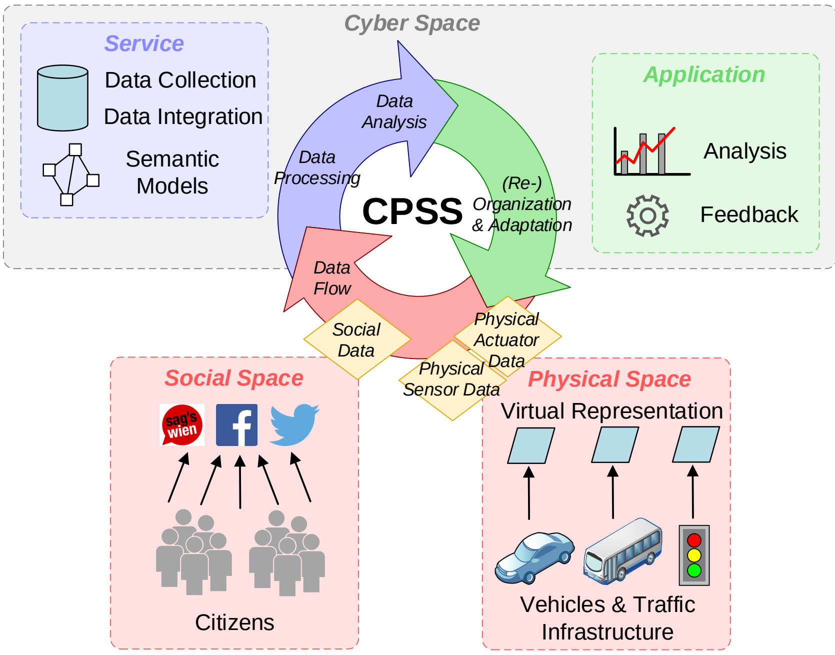

Figure 1: CPSS example: smart transportation system

Therefore, to address the needs and challenges of stakeholders it is important to obtain a comprehensive understanding of the CPSS concept and an overview of current state of research on this topic.

WP2 of the CitySPIN project, entitled *"Designing Cyber-physical Social Systems"*, addresses exactly this need. The overall goal of WP2 is to derive a conceptual technological blueprint for CPSS achieved by fulfilling the following sub-goals:

1. proposing a taxonomy of CPSS types, as part of task T2.1;

2. building a semantic model (ontology) that captures the key characteristics of the social actors involved in CPSS, as part of task T2.2;

3. providing a catalogue of software engineering principles and architectural methods for CPSS design, modelling and engineering, as part of task T2.3.

Core to achieving these goals is performing an in-depth survey of the research area in order to collect and interpret relevant research work with regard to these three aspects of CPSS. This deliverable reports on performing this envisioned survey using the principled methodology of a *Systematic Mapping Study* which we describe in Section 2. In Sections 3 to 8 we present first results based on the interpretation of a subset of the collected papers with regard to the research questions. In Sections 9 to 11 we describe the first versions of the contributions envisioned by tasks T2.1, T2.2 and T2.3 respectively, and then conclude with an outlook on the future work in this WP in Section 12.

2 Systematic Mapping Study of CPSS

CPSS share many characteristics with the well-researched CPS, but the additional social layer also brings with it new concerns of stakeholders to consider, new components and more complexity in the engineering and operation of the system, and thus new research challenges. Researchers and practitioners agree in their general picture of a CPSS as a CPS with involved humans and additional social data besides the traditional physical sensors and actuators and their collected data. But their concrete definitions and specific implementations of CPSS differ significantly, leading to an indistinct understanding of what constitutes a CPSS, CPS or related system types, what are their differences and the use cases they can be applied to. These existing varying definitions of CPSS are confusing for researchers and practitioners alike and highlight the urgent need for a common definition which describes any CPSS with its unique characteristics to emphasize its peculiarities and illustrate its boundaries. Such a definition is very relevant for the communication between researchers and practitioners to have a clear and shared understanding of CPSS. To achieve this goal, there is a need for a comprehensive overview of current state of research work on this topic, particularly of used definitions, approaches and system implementations. Based on this overview, a clear analysis and term definition provides a good basis to define research challenges to guide future research in the domain of CPSS.

In order to obtain an overview of the current state of CPSS research and get insights into the current understanding of the CPSS concept from a computer science perspective, we conducted a *Systematic Mapping Study (SMS)*. To apply this research method in an unbiased, objective, and systematic way, we followed the guidelines by Kitchenham and Charters [17]. The goal of a SMS is to review a specific software engineering topic area and to classify primary research papers in that domain [16]. In contrast to a systematic literature review, the research questions for a SMS are generally broader defined and more high level to provide an overview of a certain topic [16]. In the following, we summarize the study goals, its expected results and the performed study process and activities.

In detail, this study aimed to analyze primary studies on CPSS to (1) get a comprehensive understanding of the concept of CPSS (notion, characteristics, etc.) primarily from a computer science perspective, (2) get an overview of current state of research on CPSS and current research directions, (3) get insights into current approaches of CPSS architectures and their design (characteristic systems elements, relations, processes, architectural design methods), and (4) get an overview of existing use cases and application scenarios of CPSS. Based on the consolidated and analyzed study results, the expected output of the SMS included a collection of literature (primary studies) discussing CPSS and an interpretation of the analysis results with regard to the research questions of the study. The collected different definitions on CPSS are synthesized to an initial draft of an overarching definition of this new type of cyber-physical systems. A clear definition supports the understanding of the key characteristics and architectural design of CPSS which allows the development of a common architectural model and an initial taxonomy of system types along dimensions relevant for the CitySPIN project.

2.1 Research Questions

To achieve the study goals, we identified the following main research questions:

RQ-1: *What is an overarching definition of CPSS?*
Since CPSS is a new concept and many different definitions exist in the literature, it is very important to extract an overall definition as a common basis for communication between researchers and practitioners to have a shared idea of the CPSS concept. In addition, it is essential to define the difference between traditional CPS, CPSS and related systems.
Sub questions include: What are synonymous terms that denote these systems? What notions are used for describing and explaining CPSS? What is the difference to a typical CPS? What is not considered as a CPSS?

RQ-2: *What are application domains, goals and stages specific to CPSS?*
Today, we live in a knowledge and data-driven era where people are supported by many different CPS in their everyday activities, e.g., in the car, in public transport or building controlling, that are used to handle a specific task. Those systems are slowly reaching their limits in sensing, communication and controlling capabilities. The social component should provide new insights and evolve traditional CPS into networked embedded social systems connected to each other through the Internet. Distinct domains integrate the social component for various purposes, such as improved traffic flow, reduced accidents, energy provision or optimized production process. The human involvement and data differs depending on the domain and the purpose. An in-depth investigation of typical application domains where CPSS are used, their goals and purposes, as well as of the different processes, stages and activities implemented in a CPSS allows us to better understand the different types of CPSS and the distinction to CPS and related systems. The results are also important for identifying a common architectural model of CPSS and can support researchers to identify existing research gaps in approaches for various system activities as well as under-researched application areas.
Sub questions include: What are typical application domains and scenarios of CPSS? What goals are typically achieved in such a system? What are different stages/activities that can be identified in a CPSS?

RQ-3: *What are main characteristics of CPSS that could be used for their classification?*
The answer to this research question provides us with a list of key characteristics which constitute a CPSS, but also reveals what not. It supports the formulation of an overall CPSS definition and the development of a taxonomy of CPSS types along defined dimensions.

RQ-4: *What is the role of human and social elements in CPSS?*
Since the social dynamics and human factors are important aspects of a CPSS, the understanding of the roles of human participants and their concerns as well as the social elements is essential for future research and CPSS engineering.

Sub questions include: What is the role human participants play in the system? What elements describes the "social" part of a CPSS?

RQ-5: *What data sources are typically used in CPSS?*
CPSS extend the traditional data sources, which comprise sensors in physical devices, with "human sensors". The kind of data collected from these sensors and used for analysis and making decisions, should be wisely chosen to achieve the system's goals and needs to be considered already during the design phase of the CPSS. The answer to this research question gives us an overview of commonly used types of data sources in CPSS and the kind of data which is collected. In addition, it should provide an overview of approaches that have been applied or proposed for the collection and integration of the heterogeneous data which represents a merge of physical sensor and human sensor data. In addition, this question addresses the role of historical data and how relevant past events are for the system to work efficiently.
Sub questions include: What different data sources are involved in a CPSS? What technologies and methods are used to collect human input? What types of social data are collected? What is the role of legacy data and historical data? How is integration of various data sources achieved? How are data streams processed? Which technologies and paradigms are involved (e.g. cloud computing, fog computing)?

RQ-6: *How is data processed and distributed in CPSS?*
In the cyber component of a CPSS the collected data from physical and human sensors is cleansed, integrated and processed in order to obtain various types of information and make decisions which are needed to fulfill the system's goals. The results foster system flexibility and adaptation and are distributed by applying suitable actuation strategies both in the physical and social components of the CPSS. The additional complexity introduced by the number and heterogeneity of the collected data raises the need for appropriate approaches to process and analyze the data streams in order to fulfill the system's goals and purposes. The answer of this research question should provide an overview of commonly used approaches that have been applied or proposed. In addition, a better understanding of the distribution process of system results and the feedback loop in CPSS is needed.
Sub questions include: What technologies and methods are used to analyze the heterogeneous data? How is result distribution achieved? What are typical actuators involved in a CPSS?

RQ-7: *What architectural approaches are applied to design and describe CPSS?*
As a basis for the engineering of CPSS, we need a better understanding of the underlying design and architecture of a CPSS so that we can formally describe a common architectural model and pattern. In addition, the results of this research question should support the development of architectural methods that can be applied by practitioners in their engineering activities.
Sub questions include: What are key elements, relations between these elements and characteristic processes that have been identified in CPSS architectures? Which types of architectural models of CPSS exist? How does the system perform (self-)adaptation? What is the goal of self-adaptation?

RQ-8: *What are currently main research areas and topics and what are key challenges and emerging future work trends in CPSS?*
The additional complexity introduced by the number and heterogeneity of the collected data in a CPSS raises new challenges with respect to integration, analysis and distribution capabilities. Besides this complexity, the social data are partially very sensitive data which needs to be

considered. Therefore, it is important to create awareness about these new challenges and future topics in terms of CPSS, so that future studies can address them and propose solutions. The answer to this research question should give an overview of current research directions and provide a list of identified research challenges which can be focused on in future work. Sub questions include: Is privacy and security playing a main role in CPSS? How is it enforced?

2.2 Study Process

The SMS research method complies with a well defined sequence of steps according to a previously developed protocol. Since the protocol is a critical element of a systematic study, it was piloted by reviewing a sample of two papers. In the following, the study protocol was revised with respect to the pilot results. Once all researchers agreed on the protocol, the phase of conducting the study started by applying the search strategy and selection criteria, data extraction strategy, data analysis methods, and reporting strategy defined in the protocol. Fig. 2 shows the overall systematic mapping study process that we applied.

The SMS was conducted by a group of three researchers with expertise in the areas of software engineering, human computation, data integration as well as with previous experience in performing SMS. They were supported by a group of six undergraduate students enrolled in an academic course for scientific research work. The researchers designed and guided the study and closely supervised and collaborated with the students. For each step, the students received detailed instructions on how to perform their tasks and data collection sheets where they should put their results for later analysis. Two researchers defined the initial study protocol which was reviewed by the third researcher. The piloting of the protocol was done by the students under the supervision of the researcher team in a workshop. The retrieving and selecting publications process as well as the data extraction from the selected studies were performed by the students. After each step the results were crosschecked by the researchers and discussed with the students. Finally, two researchers synthesized and analyzed the data as well as prepared the final study report. The final step was crosschecked by the third researcher. Detailed information about each step is provided in the following.

2.3 Search and Selection Strategy

The identification and collection of paper candidates was done by the students. Each student applied the search strategy on two defined databases as sources to identify potential study candidate papers. Each database was searched by two students. The students decided whether a paper is potentially relevant based on its title and keywords, although the abstract could also be consulted in unclear cases.

Papers to include in the study must be published in established and scientifically accepted online databases. Therefore, to cover as many as possible relevant studies about CPSS, we performed searches in five of the largest scientific online databases as sources of primary studies:

- Scopus
- ISI Web of Science
- IEEE Xplore Digital Library
- ACM Digital Library
- ScienceDirect

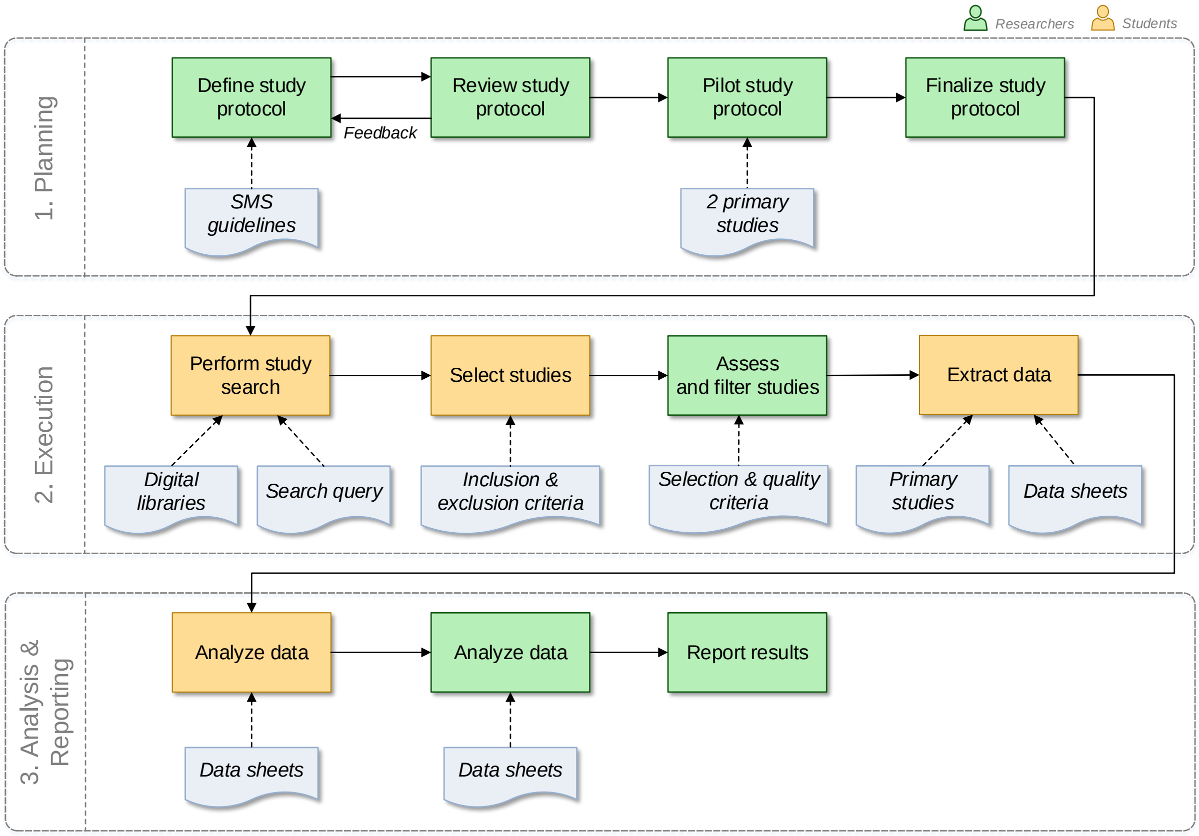

Figure 2: Applied systematic mapping study process

To identify potential study candidates, we applied a manual search method using the following search keywords to search in paper title, keywords and abstracts in each individual database search engine:

```
(cyber AND physical AND soci*) OR
(cyber AND physical AND human) OR
(cyber AND physical AND soci* AND distributed) OR
(cyber AND physical AND participatory)
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The students applied the search strategy to identify potential study candidates. The scope of the search included studies from 2007 to 2017. The search results were documented in a spreadsheet where the identified candidate papers were collected and stored. This spreadsheet was provided by the researchers. In addition, duplicates were removed in this process step. Each paper was indexed by a unique reference ID and its title. Each student kept a search log to document search as well as any changes to the search strategy.

The identified set of candidate studies was carefully assessed and filtered for their actual relevance to answer the research questions. Therefore, the study goals and well-defined study selection criteria were used to determine which studies to include or exclude. Each identified study was assessed by two students by inspecting the title, abstract, introduction and if needed the full paper to decide in terms of the study inclusion and exclusion criteria. The selection of studies resulting from this step were cross-checked by the researchers who also assessed the quality of the papers. A study was included if it is compliant to the following inclusion criteria and does not fulfill any of the following exclusion criteria:

IC-1: Studies focusing, proposing, leveraging, or analyzing a CPSS in detail. We are looking for papers that provide at least a minimal description of a concrete system in an application scenario or use case. At least one section of the paper should describe a system.

IC-2: Studies subject to peer review [31] (e.g., journal papers, papers published as part of conference proceedings).

IC-3: Studies published since 2007.

EC-1: Studies that are written in a language other than English, or that are not available in full-text.

EC-2: Secondary studies (e.g., systematic literature reviews, systematic mapping studies, and surveys), which do not provide novel research results by their own and instead just summarize work done by other researchers.

EC-3: Studies where a CPSS is only mentioned as a side-topic, e.g., this term appears only in the title or a reference or as an example.

EC-4: Studies focusing only on CPS in general, not on CPSS specifically.

Results of selections and rejections were crosschecked by a second reviewer and any disagreements on whether to include/exclude a study were discussed and resolved among both students. If an agreement could not be reached, the researcher team looked at these papers and made the final decision. The selection results were documented in a spreadsheet and, in case of exclusion, a rationale was documented why a specific paper was excluded (e.g., by specifying the relevant IC/EC that determine the decision). Finally, the researchers finalized the set of studies to be included in the data collection process and distributed the papers to the students.

2.4 Data Extraction

For each study remaining after the selection process, the students independently investigated the papers assigned to them. For each paper they extracted pre-defined data based on the provided data collection sheet. The definition of pre-defined extraction forms with data items allows to survey each study in the same way (objectively) and reduces the room for bias. Before data extraction, during the protocol piloting, we discussed each data item to be extracted to clarify the expected output and meanings of the data items to all reviewers and to make sure that all reviewers have the same understanding. Table 1 gives an overview of the data items to be collected from the primary studies to answer the research questions. First of all, the data extraction form should provide bibliographic information about the publication to be investigated: publication title, publication year, publication type, venue, author affiliations, publication keywords, study type, and abstract. Besides bibliographic information, we collected data items relevant to answer our research questions, e.g., CPSS definition, application domain, CPSS purposes and goals, CPSS process steps/activities, involvement of human actors, data sources, collected data, and architecture design approaches. After discussion of the individual results for each study with the other reviewers, the collected and agreed data will be documented in a spreadsheet in a consistent manner.

Table 1: Data Extraction Form

Data Item - Bibliographic Information	
D1	Publication title
D2	Publication year
D3	Publication type (e.g., journal, conference, workshop, or book chapter)
D4	Venue (name of the publication venue of the study, e.g., conference name, book title, journal title)
D5	Affiliations of all authors
D6	Keywords provided by the authors of the publication
D7	Paper type (e.g., survey, system paper, vision paper, aspect paper, architecture paper)
D8	Paper abstract
Data Item - Study Information	
D9	CPSS definition used in the paper
D10	CPSS-related notions
D11	Application domain supported by CPSS
D12	CPSS purposes/goals
D13	Major CPSS stages/activities/processes
D14	Involved human actors and their roles
D15	Data sources and collected kind of data
D16	Mechanisms used to collect human input or data
D17	Data integration mechanisms
D18	Data analysis mechanisms
D19	Result distribution mechanisms
D20	Role of privacy and security
D21	Adaptation in CPSS
D22	Architectural design approaches
D23	Challenges of CPSS engineering
D24	Future work topics
D25	References to other CPSS

2.5 Data Analysis and Reporting

For analyzing and interpreting the collected data with respect to the research questions, descriptive statistics have been applied. The results of the analysis describe the most interesting aspects of the data set and show frequency distributions, central tendencies as well as dispersions. The distribution density of variables are visualized in form of histograms or pie charts. Finally, after the review is completed, the questions answered and the results consolidated, the review will be reported and disseminated. We plan to write a review report in form of a scientific paper to be submitted in an academic software engineering journal. In addition, the review protocol, filled data extraction forms and data analysis results will be made publicly available on our website.

3 Overview of the Systematic Mapping Study Results

Figure 3 gives an overview of the different steps of the study execution phase with the number of remaining papers after each performed activity. The 3729 papers returned by the *(1) keyword-based search* were assessed for relevance based on their titles, keywords and abstract and collected into a spreadsheet which allowed *(2) duplicate detection and removal* and led to a total of 229 papers. From these papers, 60 papers were identified as paper candidates for the study by *(3) applying a set of selection criteria* on the information provided in their titles, abstracts and introductions. Researchers involved in the study *(4) assessed the quality* of the candidate papers and selected 22 of them to include into the study for data extraction. *(5) Data extraction* was guided by pre-defined extraction forms which allowed to survey each paper in the same way (objectively) and reduced the room for bias.

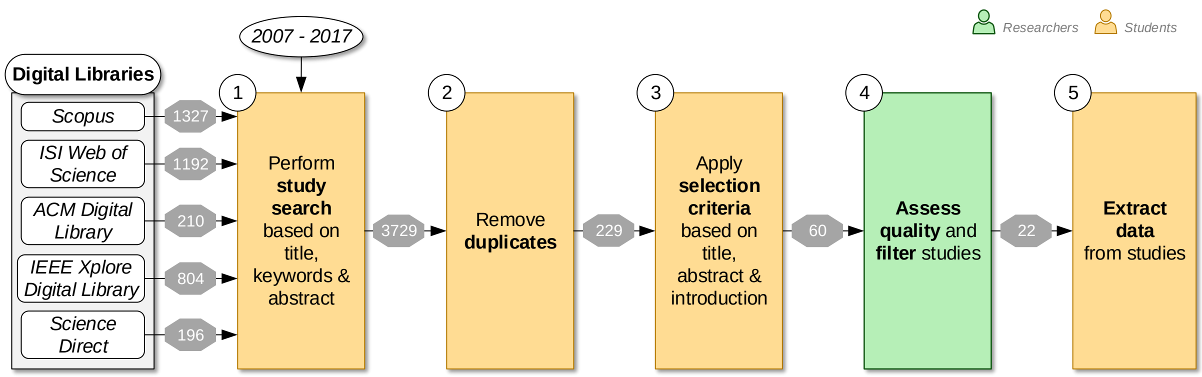

Figure 3: Execution of the systematic mapping study with collected number of papers

3.1 Included Papers in the Study

Table 2 provides an overview of the 22 papers selected for our study. In this section we briefly summarize each of these papers.

Paper 1: Parallel driving in CPSS: a unified approach for transport automation and vehicle intelligence (2017) [30]. This paper describes two systems. The goal of the first system is to create an intelligent, automated vehicles parallel parking. Therefore, an AI-system is implemented and trained to learn parking skills from humans. The second system is the so called iHorizen, used for driving assistance. IT calculates the driving style of vehicle drivers and from that gives future short and long term speed predictions. These are used to improve safety and energy consumption. In general this paper focuses on calculation models, but lacks of the human element, which is why this paper is considered as a borderline paper.

Paper 23: Cyber-physical-social system in intelligent transportation (2015) [34]. In this paper a CPSS-based intelligent transportation system (ITS) is introduced. The system includes intelligent vehicles, traffic management and control, artificial transportation and cloud computing technologies. It also takes into account all types of traffic participants, such as passengers, drivers, pedestrians and others. Examples are intelligent autonomous vehicles navigating through crowded intersections, based on previous sampling. Or special travel guidance for drivers, based on agents reserving future space-time in the road sections, with special travel guidance.

Paper 31: An ontological ubiquitous city information platform provided with Cyber-Physical-Social-Systems (2016) [5]. This paper describes an approach of how CPSS and decision systems

Table 2: Overview of papers selected for the study. Some of these papers were judged as weakly relevant for the study and marked as borderline.

Paper ID/Ref	Paper Title	Pub. Year	Core vs. Borderline
1 [30]	Parallel driving in CPSS: a unified approach for transport automation and vehicle intelligence	2017	Borderline
23 [34]	Cyber-physical-social system in intelligent transportation	2015	
31 [5]	An ontological ubiquitous city information platform provided with Cyber-Physical-Social-Systems	2016	
41 [14]	Dynamic Social Structure of Things: A Contextual Approach in CPSS	2015	
45 [13]	A CPSS Approach for Emergency Evacuation in Building Fires	2014	
65 [7]	A Real-time Complex Event Discovery Platform for Cyber-Physical-Social Systems	2014	
66 [36]	A System-Level Modeling and Design for Cyber-Physical-Social Systems	2016	
79 [8]	Incorporating Social Sensors and CPS Nodes for Personalized Production under Social Manufacturing Environment	2016	
86 [23]	A framework to design a human-centred adaptive manufacturing system for aging workers	2017	
126 [4]	Consumer-Centered Energy System for Electric Vehicles and the Smart Grid	2016	Borderline
147 [3]	Butler, Not Servant: A Human-Centric Smart Home Energy Management System	2017	
148 [15]	A Non-Intrusive Cyber Physical Social Sensing Solution to People Behavior Tracking: Mechanism, Prototype, and Field Experiments	2017	Borderline
166 [26]	Driver Assistant in Automotive Socio-cyberphysical System Reference Model and Case Study	2016	
169 [32]	An Assistive Navigation Framework for the Visually Impaired	2015	
175 [27]	Online communities for agent collaboration in cyber-physical-social systems	2015	Borderline
188 [12]	Vita:A crowdsensing-oriented mobile cyber-physical system	2013	
191 [18]	Participatory cyber physical system in public transport application	2011	Borderline
202 [35]	Human-centred assembly: a case study for an anthropocentric cyber-physical system	2014	
212 [6]	Closing the Loop - From Citizen Sensing to Citizen Actuation	2013	
215 [20]	An Open Framework for Exploratory Visual Analysis of Geospatial Data for Winter Road Management	2013	
216 [10]	A Study for Human Centric Cyber Physical System Based Sensing Toward Safe and Secure Urban Life	2013	
234 [28]	Socio-cyberphysical System for Proactive DriverSupport	2015	

work together to achieve a ubiquitous system by using social and physical data. The concrete example mentioned is named Wi-City-Plus which takes care of systems and events in a city to provide better services for people living there as a smart city. Beside the general models and approaches of how such a system could be implemented, the SPARQL query language is used to give readers a real world example.

Paper 41: Dynamic Social Structure of Things: A Contextual Approach in CPSS (2015) [14]. In this article a smart services framework for CPSS – the Dynamic Social Structure of Things (DSSoT) – is proposed to narrow down the computational and networking contextual complexity based on situational awareness. To prove the concept, the Airport Dynamic Social System is introduced. It aims to connect smart objects in and around an airport, like weather sensors, temperature sensors in the airplane or lightning sensors in the waiting lounge, to the user and their needs. Therefore a mobile app is used to form a network of social nodes for direct interaction and service provisioning. The users can also subscribe to social objects in order to receive updates, such as the airplane's interior temperature or the number of boarded passengers.

Paper 45: A CPSS Approach for Emergency Evacuation in Building Fires (2014) [13]. This paper presents a CPSS for emergency evacuation in building fires. The system uses smoke, heat and video detectors to observe information from the buildings. The system consists of an artificial evacuation system to select the best evacuation strategy. Building structures, fire scenarios, and evacuees are taken into account. A computational experiment platform is used to evaluate and quantitatively analyze various factors to further improve the system.

Paper 65: A Real-time Complex Event Discovery Platform for Cyber-Physical-Social Systems (2014) [7]. Data from multiple sensors, events, situations, actuators and organizations is collected and then stored in a data structure called information object. Using the framework EventShop, situation recognition is performed on the data and the detected events are stored in EventWarehouse which can be used for future detection of events. The goal of the example in the paper is warning people with asthma about dangerous areas.

Paper 66: A System-Level Modeling and Design for Cyber-Physical-Social Systems (2016) [36]. This paper describes a model for CPSS interaction with their environment based on hierarchical Petri nets for control flow improvement and social flow for modeling the interaction with multiple personas. The system can recognize the context from social interactions and provide the supporting device services, such as automatically open the projector for presenting among the multiple users. Multiple sensors, actuators, and computation nodes proactively augment the social interaction behavior. For example, the video sensors provide the images of user interactions, the computation nodes process sensor data, sending the social recognition, the recognized originated context, to the central control node which then reacts and controls the physical objects, such as a projector, printer, scanner, plotter and fax. Improved is the design flow, objects placed and users satisfied under the social scenario needs.

Paper 79: Incorporating Social Sensors and CPS Nodes for Personalized Production under Social Manufacturing Environment (2016) [8]. This paper describes a CPSS platform that aims to facilitate personalized production under the social manufacturing environment conditions, bringing together customers, enterprises and other stakeholders for interactions and collaboration. Mass production of a product that does not satisfy the customer's needs leads to a massive financial and resource loss in a production company. To prevent it, the enterprises need to enable the customers to share their personalized opinion in advance and include these opinions into the production process. The platform provides web services for social sensors, CPS nodes and other physical objects, enabling the connection between the enterprises and the customers, and collecting social and industrial big data. The system allows the customers to track and trace the manufacturing process regarding their own orders, and provides enterprises with feedback for optimizing their product launch processes.

Paper 86: A framework to design a human-centered adaptive manufacturing system for aging workers (2017) [23]. The adaptive manufacturing system described in this paper aims to improve the working conditions for aging workers by improving the human-machine interaction. The work demands are to be reduced, the workers well being improved, down times, delays and production rate decrease avoided. Optimization of the manufacturing leads to higher quality production, increased energy efficiency and safer environment. The monitoring system gathers the information with machine control devices and environmental sensors, such as accelerometers, microphones, laser sensors, RFID tags and thermal and dust probes. Analyzing collected data results in defining the adaptation rules and system behaviors and implementing the correlations on UI that is accessible by web-based and mobile devices. Based on the collected process data in the real time, the machines and the interfaces can adapt their behaviour, also including the individual user requirements when interacting with the system as well.

Paper 126: Consumer-Centered Energy System for Electric Vehicles and the Smart Grid (2016) [4]. The system described in this paper proposes a consumer-centered energy system, which aims to smartly distribute energy. To achieve this, a network consisting of energy providers and energy users, is created. In this network data from every participant is collected to reach the best possible energy distribution.

Paper 147: Butler, Not Servant: A Human-Centric Smart Home Energy Management System (2017) [3]. In this paper a "smart home" system is proposed, which aims to comfort the user and optimize the energy consumption. This is achieved by collecting data from smart phones, social media and sensors, placed in the house. Afterwards the system generates an optimal scheduling strategy.

Paper 148: A Non-Intrusive Cyber Physical Social Sensing Solution to People Behavior Tracking: Mechanism, Prototype, and Field Experiments (2017) [15]. This paper describes a non-intrusive wireless fidelity (Wi-Fi)-based tracking method, which aims to predict the behavior of the user. The system collects data from wireless points and calculates with an algorithm the user's behavior.

Paper 166: Driver Assistant in Automotive Socio-cyberphysical System Reference Model and Case Study (2015) [26]. This paper describes an automotive socio-cyber-physical system for assisting a vehicle driver. It aims to warn drivers if they are tired or drowsy. This is achieved by collecting data from sensors in the vehicle and the driver's smart phone. As a result the system warns the user with a sound notification.

Paper 169: An Assistive Navigation Framework for the Visually Impaired (2015) [?]. This paper presents a system that consists of wearable sensors (i.e., GPS, pedometer, camera, IMU, and RGB-D sensor), feedback devices (i.e., bone headphone and vibro-tactile device), human interface hardware (e.g., voice input/output and touch pad), and a wearable computer with network connection. This system should be able to help visually impaired persons to navigate indoor and outdoor and find nearby social events to engage with.

Paper 175: Online communities for agent collaboration in cyber-physical-social systems (2015) [27]. In this very generalized paper two examples of CPSS are proposed. The first one describes how online collaboration can be enhanced by providing the members of an online meeting room services such as automatic data analysis and smart prediction where missing information could be found. The second example is implemented as smart traveling system to predict a driver's route or suggest events the driver could be interested in.

Paper 188: Vita: A crowdsensing-oriented mobile cyber-physical system (2013) [12]. This paper describes a CPSS which makes various crowd and mobile sensing applications possible. A concrete example named "Vita" shows how this approach is implemented using a mobile CPSS approach. Additionally, various problems and proposals of how the services are designed and should be used is topic of this paper. Finally, it is explained how Vita could be used as CPSS in a smart city environment.

Paper 191: Participatory Cyber Physical System in Public Transport Application (2011) [18]. This paper presents ContriSenseCloud, an extensible cyber physical system that manages grass-roots participatory sensing in public transportation. The system can help commuters to plan their bus journey by detecting traffic congestion on the roads during peak hours and allows them to contribute data via smart phones back to the system when they are on the road.

Paper 202: Human-centred assembly: a case study for an anthropocentric cyber-physical system (2014) [35]. The system described in this paper should help factory workers in the production process. The system stores all the information of the production systems (machines, tools, etc.) in the factory and all the necessary product design knowledge to manufacture a product. When the worker wants to manufacture a product he has to put on a VR-device (Google Glass, etc.). The system then analyzes the data of the worker coming from the VR-device (location, etc.) and the information about the product which should be manufactured. The steps that the worker has to perform one after the other, are displayed over the VR-device.

Paper 212: Closing the Loop - From Citizen Sensing to Citizen Actuation (2013) [6]. This paper describes a CPSS that aims to improve energy usage. The system collects data mainly from user requests and status updates, analyzes them and searches for energy issues. If any issue is identified, where energy usage can be optimized, an actuation request to check the issue is sent over social networks to a user of the system, who is located near to the issue. The user can then resolve the issue.

Paper 215: An Open Framework for Exploratory Visual Analysis of Geospatial Data for Winter Road Management (2013) [20]. In this paper a CPSS is described which should manage the snow removal. Beside weather data from meteorological sensors, it also analyzes call center requests as well as social media. After analyzing the information about the actual conditions and where snow removal is needed, the system displays the locations on a map.

Paper 216: A Study for Human Centric Cyber Physical System Based Sensing - Toward Safe and Secure Urban Life (2013) [10]. This paper describes two CPSS. The aim of the first one is to monitor the health data of patients and analyze them. Whenever the data is critical or the system thinks it is necessary to take action, the medical staff is alerted, so it can perform necessary steps. The aim of the second system described in the paper is efficient energy management. The system collects data, such as the number of people in a room, via sensors and regulates the energy (lights, etc.) depending on the data.

Paper 234: Socio-cyberphysical System for Proactive Driver Support (2015) [28]. This paper describes a CPSS that aims to proactively support drivers during the parking process. The system collects data from a variety of data sources including the driver's car, neighbouring cars, smart parking spaces, as well as driver data and preferences from the driver's smart phone. This data is integrated with semantic technologies based on ontologies. Behavior analysis techniques are used to model driver behavior. Recommendations for parking are suggested to the driver via the AppLink screen and the in-car navigation system.

3.2 Borderline Papers

When reading the papers in detail, a number of papers selected for the study were judged as having limited relevance for the study and were marked as "Borderline" papers (see Table 2). We hereby provide a justification of why these papers were considered as borderline.

Paper 1: This paper is unclear since no real CPSS is implemented. There is a small CPSS example, but not elaborated in depth (parallel parking). The main model is a calculation model, with no social part in it (iHorizon with Speed Predictions). The human element is a model of the driver behavior, i.e. whether an aggressive driver. Additionally, the main contribution of the paper is not clear.

Paper 126: Although the paper's introduction and conclusions suggest that the paper describes a CPSS, the presented system is a CPS (the social component is not described).

Paper 148 The main focus of this paper is on sensor-based people tracking. This is linked to the notion of CPSS, but the paper does not present a CPSS per se.

Paper 175: This paper does not describe a physical or social component, only an information system that retrieves information from a database. Therefore, we consider it as definitely not a CPSS. **Paper 191:** In this paper a system is described, but many details are not clear.

3.3 Bibliographic Analysis of the Collected Papers

This section provides an analysis of the bibliographic information of the collected papers, shown in Table 2.

Keywords

The most used keywords describing the collected papers refer to the term CPSS in different spellings. Besides *cyber-physical social system*, they used terms like *social Internet of Things*, *intelligent system*, *social cyber physical system*, *passive cyber physical social sensing*, *cyber-physical-human space*, and *cyber-physical-socio space*. Other keywords often mentioned are *social objects*, *navigation*, and *visually impaired*. Most keywords can be classified as one of the following two types: The first class of keywords describes the system type like *intelligent system*, *social objects*, *cloud* or *decision support system*. The second class of keywords describes the purpose of the system like *navigation*, *visually impaired*, *mobility*, *emergency management*, *parking assistance* or *electric vehicle*.

Publication Date

As shown in Fig. 4, papers discussing CPSS were published since 2011 and most of them in 2015.

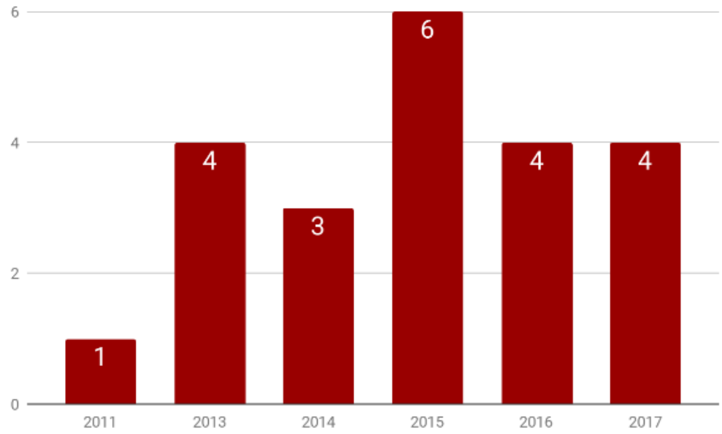

Figure 4: Publication year of papers

Since the first paper of the study form 2011 is a borderline paper, the real beginning of published research on CPSS can be dated in 2013. While in 2013 a paper (ID: 215) used the term *social cyber physical system* in its keywords, since 2014 the terminology used by the scientific community changed to *cyber-physical social system* in the title and keywords, if mentioned. The decrease of papers after 2015 is amplified by the fact, that one of the papers from 2016 and two from 2017 are marked as borderline papers, while none of the papers from 2014 and 2015 are. If these papers would be excluded, only two papers would be left in 2017, which would indicate a decrease of papers over the last years. For data from 2017, it should also be taken into account that this SMS started in November 2017. Therefore, papers that were published later in 2017 could not be considered.

Authors and their Affiliations

In total, the 22 papers of the study have 82 different authors. Most of the papers were written by different authors. Only four authors have contributed in more than one of the collected papers including *Alexander Smirnov and Nikolay Shilov from ITMO University in Saint Petersburg*, *Fei-Yue Wang from Chinese Academy of Sciences* and *Xiwei Liu from the Qingdao Academy of Intelligent Industrie*.

In total, the papers were published by authors from 35 different universities and other research institutes. Only three research institutes have published more than one of the collected papers including *the Chinese Academy of Sciences*, *the Xi'an Jiaotong University* and *the Russian Academy of Sciences*.

The authors of the papers are affiliated with research institutes from the following 14 different countries as illustrated in Fig. 5: *Canada*, *China*, *France*, *Germany*, *Hong Kong*, *Ireland*, *Italy*, *Japan*, *Portugal*, *Romania*, *Russia*, *Singapore*, *the United Kingdom and the United States*. To better compare the United States (2) and China (8) with the European Union, we counted up the number of papers from the EU resulting in a total publication number of 8. Fig. 6 shows the distribution of the countries on a world map.

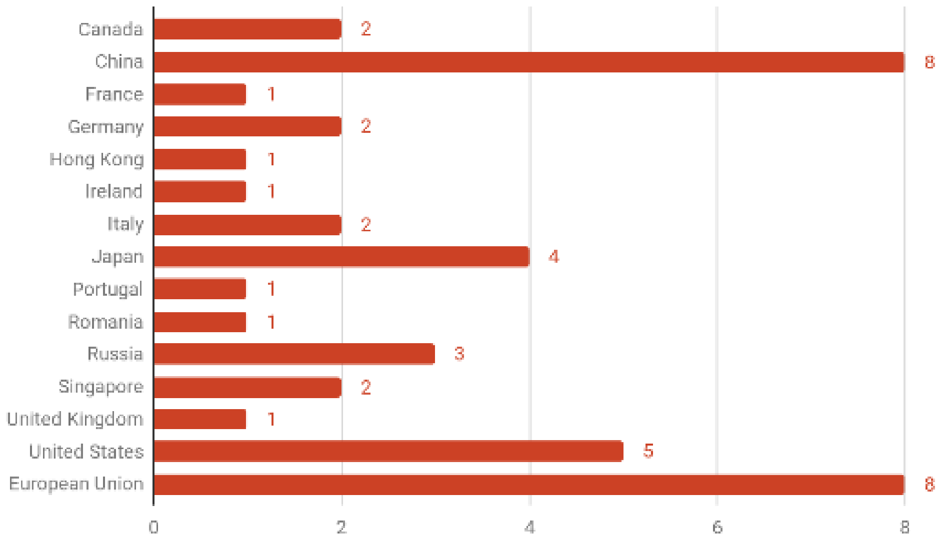

Figure 5: Countries in author affiliations

The most publishing group of researchers on the CPSS topic includes *Alexander Smirnov and Nikolay Shilov form ITMO University in Saint Petersburg* who published together three papers in the scope of this study. The titles and keywords of these papers show their focus on transportation. The most publishing single country in research of CPSS is China. 8 papers of the study were contributed by authors from Chinese universities, more than a third of the analyzed

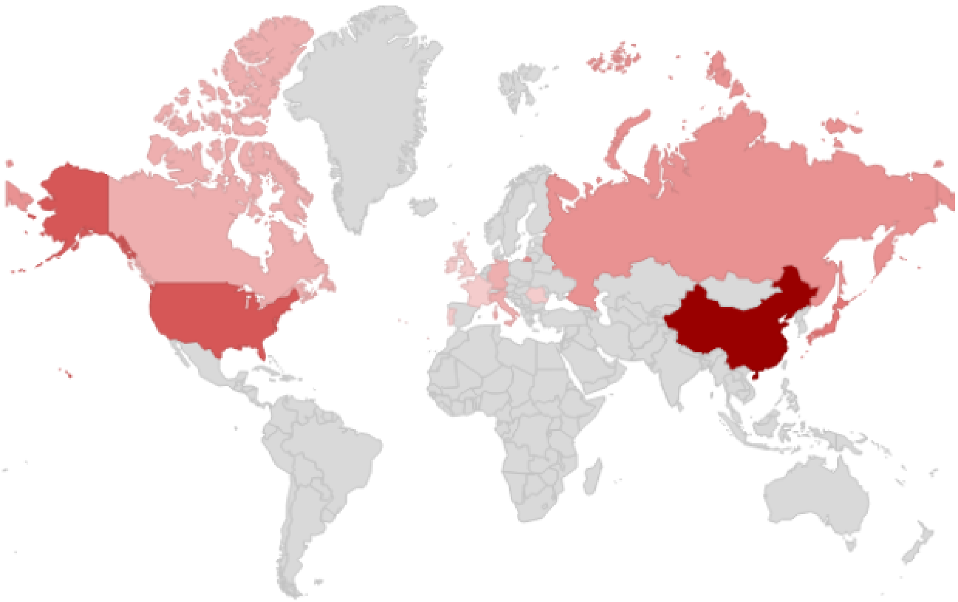

Figure 6: Distribution of countries in author affiliations

papers. Other authors with more than one paper from China are *Fei-Yue Wang from Chinese Academy of Sciences* and *Xiwei Liu from Xi'an Jiaotong University*. The Chinese papers seem to cover a wide variety of CPSS types, for instance the keywords include phrases like *social manufacturing*, *transportation* or *emergency evacuation*. Furthermore, the European Union should also be mentioned as a driving factor with 8 papers as well. In difference to China, all EU papers come from different authors and research institutes. In comparison to their population, also Japan with 4 and Singapore with 2 papers should be mentioned as other driving countries. However, the origins of these papers seem rather scattered across different universities and authors in the countries. But the results show that the Asian area has a particular interest in research of CPSS. Although more than half of the collected papers were published from Asia, CPSS is not a local research topic as the papers come from three continents. There is also a strong division of the papers among the authors. Only less than 5% of the authors have worked on more than one paper and about 9% of the universities were involved in multiple papers. In general, CPSS seems to be a global research topic, but there is no main research focus of any research group in CPSS.

Publication Types and Venues

In the study we used five categories to classify the publication type which are *book chapter*, *conference paper*, *journal article*, *workshop paper*, and *other venues*. As shown in Fig. 7, the papers cover three publication types: conference papers (7), workshop papers (4) and journal articles (12). The publication venues of the papers are widely distributed. Only four venues published more than one of the selected papers including the journals *IEEE Intelligent Systems* (2), *IEEE Transactions on Human-Machine Systems* (2), *IEEE/CAA Journal of Automatica Sinica* (2), and the proceedings of the *7th International Workshop on Information Search, Integration and Personalization* (2).

Generally, the distribution of the selected papers on publication types shows a picture of high-quality output in the CPSS research area since more than half of the papers were published in IEEE journals, which represents reputable venues in the computer science research

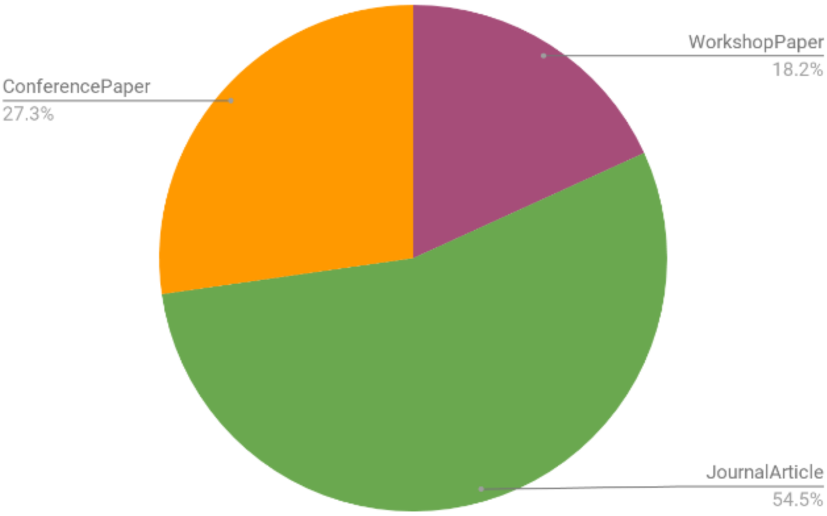

Figure 7: Publication type

community. The journal *IEEE Transactions on Human-Machine Systems* covers the areas of human systems and human organizational interactions including cognitive ergonomics, system test and evaluation, and human information processing concerns in systems and organizations. In particular, this publication venue fits the descriptions of CPSS very well, therefore this journal should be of interest for further research work studies.

The results of the bibliographic analysis presents interesting insights into the current trend of increased research work in the area of CPSS, mostly performed in the Asian region, but also in the European Union. The analysis shows that there has been a consistent interest in this research field which is not yet in its final phase since a large number of challenges are still open research topics. In principle, the number of published papers discussing CPSS has increased in recent years. While the publication output appears to be scattered across different publication venues, mainly journals, and in particular the *IEEE Transactions on Human-Machine Systems* journal, are most relevant venues for publishing CPSS papers.

4 Defining a CPSS

In this section we discuss the development of an overarching definition of CPSS and alternative terms. In addition, we present different subcategories of CPSS and notions which can be used to describe a CPSS. Finally, we summarize identified main differences between CPS and CPSS based on the analysis of the collected papers.

4.1 Comparison of CPSS Definitions

To analyze the differences between CPSS definitions found in the literature, we first extract all used definitions which are presented in the following.

Paper 1 - Parallel driving in CPSS: a unified approach for transport automation and vehicle intelligence [30]: "Cyber-physical systems (CPS) has been gaining increasing concerns in the past two decades, while CPSS augments the CPS capacity by integrating an additional dimension-human and social characteristics, so as to achieve more effective CPS design and operation. This augmentation also has a philosophical implication for being in line with Karl Popper's theory of reality, which states that three interacting worlds coexist in our universe: the physical world, the mental world, and the artificial world [...]. These three worlds are coupled by physical space and cyber space respectively, so as to conceive the cyber-physical-social space (CPSS). Rapid development in ICT enables us to exploit more in the artificial world so as to design and optimize the systems in the physical and mental world. Rapid development in ICT enables us to exploit more in the artificial world so as to design and optimize the systems in the physical and mental world."

Paper 23 - Cyber-physical-social system in intelligent transportation [34]: "[...] a kind of common complex system that is constituted by a physical system, and its social system including human beings, and the cyber system that connects both of them [...]. Normally, sensor network connects physical system and its cyber system, social sensor network connects social system and its cyber system, and then the physical and social system can be mapped equivalently to their cyber systems. On this basis, physical & social system and their cyber systems can understand each other, their stepwise interaction helps improve each other, and gradually the effective control and safe, reliable and efficient operation of CPSS will be realized."

Paper 31 - An ontological ubiquitous city information platform provided with Cyber-Physical-Social-Systems [5]: "[...] data on traffic and weather and on the user health status as well as social data, also known as Cyber- Physical-Social-Systems (CPSSs), are taken into account by the DSSs, thus supporting user decision using both system and user centric data [...] the elements dealing with CPSs and social data are recollected in a class named CPSS"

Paper 41 - Dynamic Social Structure of Things: A Contextual Approach in CPSS [14]: "Cyber-physical-social systems (CPSS) regard humans and their interests, needs, and motives as part of the broader system, not as additional aspects lying on its boundaries. In this sense, intelligence and reasoning about the social aspects of humans ﬃ including their activities, preferences, emotional states, and various other subjective elements embedded from human communities – act as the core for realizing the integration between virtual, physical, and social worlds. CPSS goes beyond the vision of cyber-physical systems (CPS), in which the latter aim to realize the integration between abstract computational artifacts with communication, monitoring, and control facilities; CPSS further incorporate and reason about extracted knowledge hidden in human behavior with the goal of bridging human-to-device perceptions."

Paper 45 - A CPSS Approach for Emergency Evacuation in Building Fires [13]: "CPSS is the extension of cyber-physical systems (CPS), which integrate with human and social characteristics and bridge the physical world, cyberspace, and human society together."

Paper 66 - A System-Level Modeling and Design for Cyber-Physical-Social Systems [36]: "Cyber-physical-social systems (CPSS) as a novel emerging paradigm has gained popularity within the research community and industry due to the fact that it enables deep fusion among humans, computers, and things. Differing from the internet of things (IoT)/cyber-physical systems (CPS), which merely focuses on linking the objects in physical space, CPSS integrates human social characteristics and can bridge the gap among cyberspace, physical space, and social space [...]. Technically, CPSS can be seen as the extension of IoT/CPS and be enabled to leverage the combination of current IoT/CPS technologies, socio-technical systems, and cyber-social systems."

Paper 79 - Incorporating Social Sensors and CPS Nodes for Personalized Production under Social Manufacturing Environment [8]: "CPS/CPSS, IoT, and Cloud Manufacturing all involve a certain level of resource virtualization and emphasize the combinational applications of cyber technologies in the physical domain. CPS/CPSS give rise to the IoT or Industrial Internet and endow them with new characteristics such as self-configuration, self-control, and social interaction. As to the relationship between CPSS and Cloud Manufacturing, CPSS can be viewed as an implementation form of Cloud Manufacturing which applies cyber technologies in inter-enterprise collaborative manufacturing systems and provides manufacturing services with the premise of cyber-physical- social interconnection and Internet of Services (IoS)."

Paper 126 - Consumer-Centered Energy System for Electric Vehicles and the Smart Grid [4]: "However, EVs and smart housesplay an important role in the current energy system, so we should not ignore the human and social dimension in a CPES, because these energy unitsfftti behaviors depend highly on human and social. Therefore, we further extend CPESs to CCESs by introducing human knowledge and sociocultural elements as an integrated part of CPES design and operation."

Paper 148 - A Non-Intrusive Cyber Physical Social Sensing Solution to People Behavior Tracking: Mechanism, Prototype, and Field Experiments [15]: "CPSS is designed to operate in conjunction with and in service of people. It leverages the sensed information collected by sensing nodes and aggregates it for recognizing people's behaviors (e.g., mobility pattern), and in turn provides people with a higher level of combined information or services, which simplifies people's lives. The rapid development of mobile devices with various sensors is the catalyst to promote CPSS to form a context-aware or social-aware mobile wireless sensor network."

Paper 166 - Driver Assistant in Automotive Socio-cyberphysical System Reference Model and Case Study [26]: "Driver, vehicle, smartphone, and software services partly integrated in the mobile application and partly accessible in the cloud are considered as a socio-cyberphysical system that integrates physical space (driver and vehicle), social space (driver), and information space (smartphone with mobile application, software services, and vehicle infotainment system)."

Paper 175 - Online communities for agent collaboration in cyber-physical-social systems [27]: "A CPSS consists of cyber space, physical space, and mental space. These spaces are represented by sets of resources. The physical space consists of various interacting information and computational physical devices. These devices united on the communication basis organize the cyber space. The mental space is represented by humans with their knowledge, mental capabilities, and sociocultural elements. All the three spaces are tightly related. Information from cyberspace interacts with physical space (physical devices) and mental space (humans)."

Paper 188 - Vita: A crowdsensing-oriented mobile cyber-physical system [12]: "Similar to traditional CPS, which are integrated computing and communication systems that process and react to sensing data from the external physical environment, and transform the way humans interact with the physical world, mobile CPS could be considered as a prominent subcategory of CPS with inherent mobility features. Mobile crowdsensing refers to a broad range of social and community-based sensing paradigms employing mobile devices and wireless networks."

Paper 191 - Participatory Cyber Physical System in Public Transport Application [18]: "The system can be extended into cyber-physical-human space or cyber-physical-socio space. Cyber-physical-socio space or cyber physical society implies merging of social interaction between humans with physical processes and digital computation whereas cyber-physical-human space lacks the interaction."

Paper 202 - Human-centred assembly: a case study for an anthropocentric cyber-physical system [35]: "Some recent studies are trying to give a more comprehensive view over CPS that, besides the classical computational and physical dimensions, includes the social one as an integral part of a CPS. This may be observed in the new emerging concepts (e.g. cyber-physical-social systems, human system integration, smart environments, etc.) that are paving the way towards the old vision of symbiotic man-machine systems."

Paper 215 - An Open Framework for Exploratory Visual Analysis of Geospatial Data for Winter Road Management [20]: "Social Cyber-Physical Systems (SCPS) feature a close integration and coordination between the systemffttıs computational and physical elements in large social systems."

Paper 216 - A Study for Human Centric Cyber Physical System Based Sensing - Toward Safe and Secure Urban Life [10]: "As pervasive sensing progresses, Human centric Cyber Physical System (HCPS) will receive much attention where effects of human activities are taken into consideration for designing and developing CPS based social systems."

Different papers of the study used different definitions of CPSS and described different aspects which the system should implement in order to be considered as a CPSS. Those identified main aspects are summarized in Table 3.

Table 3: Identified CPSS definition aspects

Aspect of a CPSS Definition	Paper ID/Ref
1. CPSS extend CPS with a social aspect	1 [30] , 45 [13], 66 [36], 126 [4], 188 [12], 202 [35], 216 [10]
2. CPSS include three parts: (1) physical, (2) social, (3) cyber	1 [30], 23 [34], 31 [5], 41 [14], 45 [13], 66 [36], 79 [8], 126 [4], 166 [26], 175 [27], 191 [18], 202 [35], 215 [20]
3. CPSS must based on social aspects	41 [14], 148 [15]
4. No definition provided	65 [7], 86 [23], 147 [3], 169 [32], 212 [6]

We use these four aspects to categorize the collected papers, because they show the influence of the social aspect on these different systems. The influence of the social aspect is also the major difference between the definitions, as some only require that data is collected from a social network, while others envision a user interaction with the system or more. This is also the difference between aspect one and three. For the first aspect, any sort of social interaction is enough. The third aspect requires more action from a human. All aspects are described in more detail in the following.

4.1.1 Distribution of CPSS Aspects

From the analyzed 22 papers, 5 (22,68%) of them do not contain any definition at all. 7 (31,82%) papers use the definition of a CPSS as an extension of a CPS. For 14 (63,63)% papers a CPSS consists of three different parts, i.e., a physical, cyber, and social part. 2 (9,09%) papers describe a CPSS as a system based on social aspects. Figure 8 illustrates these results.

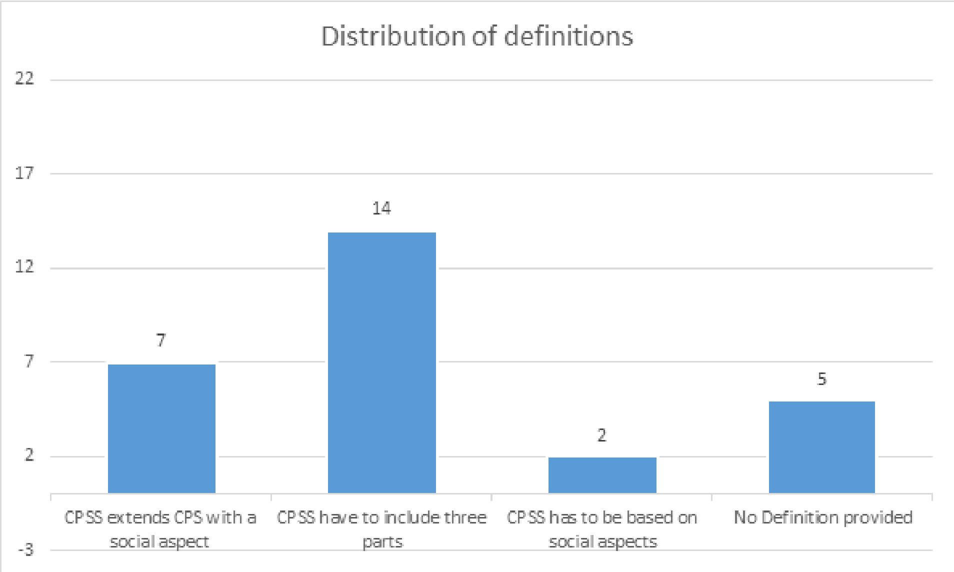

Figure 8: Distribution of different CPSS aspects

Figure 9 shows the overlap of the different aspects. We excluded the last aspect as it is not relevant for this figure. There cannot be an overlap between the first and third aspect, as they exclude each other. However, we can see most of the papers describe a CPSS as a system with three different parts and additional with some sort of social aspect, but a more detailed definition of this social aspect remains missing.

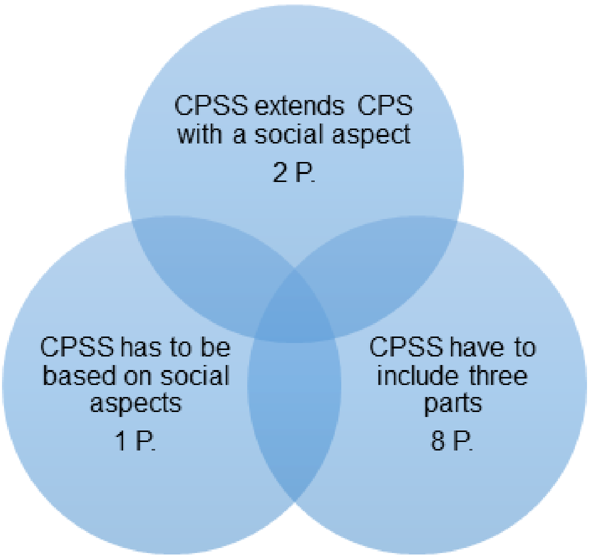

Figure 9: Overlap of different CPSS aspects

4.1.2 Explanation of Different CPSS Aspects

The first aspect – *CPSS extends CPS with a social aspect* – describes a CPSS as a CPS with an additional social aspect. This aspect can be collecting data from a social network or assisting a human in a specific situation. Overall, they describe a CPS as a CPSS as soon as some sort of human interaction is involved.

The next aspect, which we referred to as *CPSS have to include three parts*, states that a CPSS must implement three different parts:

- physical: some sort of physical component in the physical world, e.g., sensors
- cyber: a computational system that operates in a network
- social: a system which includes a human in some way, either as a data source, an actuator or as a decision maker

These three parts have to interact with each other in order to constitute a CPSS. With regard to the definitions, a human has to play a major role in the system. It is not a CPSS if the social aspect is a side effect.

For the third aspect – *CPSS has to be based on social aspects* – a CPSS is a system which is built around a social aspect. The human has to be the main actor and everything else is built around the human and his/her actions. A good example is given in the definition of paper 41 [14].

We assigned the last aspect – *No definition provided* – to papers which discuss a CPSS, but do not provide a clear used definition.

4.1.3 Reflection

Most definitions include a cyber-physical aspect and a social aspect in order to refer to a CPSS. As described above the major difference is the level of influence of the social aspect on the system. To conclude, we propose a definition combining the knowledge gained from the analyzed papers. A CPSS includes different aspects. First, it has to include a social part, like social media data or an interaction with the user. Furthermore, it should implement typical components of a CPS meaning it includes a physical interaction with the real world.

4.2 Alternative Terms for CPSS

By analyzing the collected study data, we identified a number of alternative terms that were used to describe a CPSS. In the following, we summarize and discuss these synonymous terms for CPSS, which are presented in Table 4.

Every term used to describe a CPSS consists of three or four parts, which describe the same thing in a different way. Only one of the terms misses the physical part, i.e. *Cyber-social system*. The *social* part of the term refers to the social aspect of a CPSS. Possible phrases for this part are:

- social
- socio
- human-centered/human-centric
- human-in-the-loop

Table 4: Identified terms that are used for a CPSS

Term	Paper ID/Ref
Cyber-physical-social system	most papers as it was the main term we were looking for
Cyber-physical-social interconnection	79 [8]
Cyber-physical-social system-related applications	148 [15]
Human-centric-cyber-physical system	216 [10]
Human in the loop cyber-physical system	169 [32]
Socio-cyberphysical system	166 [26]
Cyber-social system	66 [36]
Anthropocentric cyber-physical system	202 [35]

- human
- anthropocentric

For the *cyber-physical* part, the same phrase is always used and we could not identify any other synonym. A potential explanation of this fact could be that the scientific community already agreed to use this term and created a naming standard which is used in all research work to refer to this kind of systems.

In the last part, the terms describe the overall name of the application it is used for. We found the following words in the previous mentioned terms:

- system
- interconnection
- system-related-application

Most often the term CPSS is used. All the other terms are only used once or twice in all papers included in this study. As for now, we conclude that CPSS is the most frequently used term across current status of research.

4.3 Subcategories of CPSS

In some of the papers we identified subcategories of CPSS, which are used in specific application areas. In the following we discuss these subgroups of CPSS and explain how these are used. Table 5 gives an overview of the identified subcategories with the corresponding papers.

Table 5: Identified subcategories of CPSS

Subcategory of CPSS	Paper ID/Ref
Transportation cyber social physical system	23 [34]
Human-centred adaptive manufacturing systems	86 [23]
Mobile cyber-physical systems	188 [12]

The term *Transportation cyber social physical system* is used for CPSS, which enable the transportation of people or goods. This kind of CPSS is introduced to increase the efficiency of sensing and improve the control of such transportation systems. Other terms used to describe such systems are *intelligent transportation system* or *social transportation* [34].

The term *Human-centred adaptive manufacturing systems* describes a system, which takes human factors, e.g., age, into account and adapts the system, such that no worker has to exceed his limits. Other terms used to describe such systems are *personalized production*, *social manufacturing* [8], smart production [23], smart factory [35].

Even though *Mobile cyber-physical systems* does not contain a social aspect in its name, it denotes a CPSS. These systems take information from multiple mobile resources, e.g., smart phones, and use these to make suggestions to a user. A common term to describe this functionality is *crowd sensing* or in particular *mobile crowd sensing*.

4.4 Notions Related to CPSS

We extracted different notions which are used with respect to CPSS and describe different parts and characteristics of the system. To categorize these notions, we use three different types: *social*, *cyber-physical* and *overall used notions*.

Figure 10 shows the distribution of different terms. In summary, there are not a lot of notions relating to single aspects of CPSS (7,26%), but we identified a lot of different terms for CPSS overall (13,48%). To conclude based on our investigation, there is not yet a broadly-accepted description of CPSS.

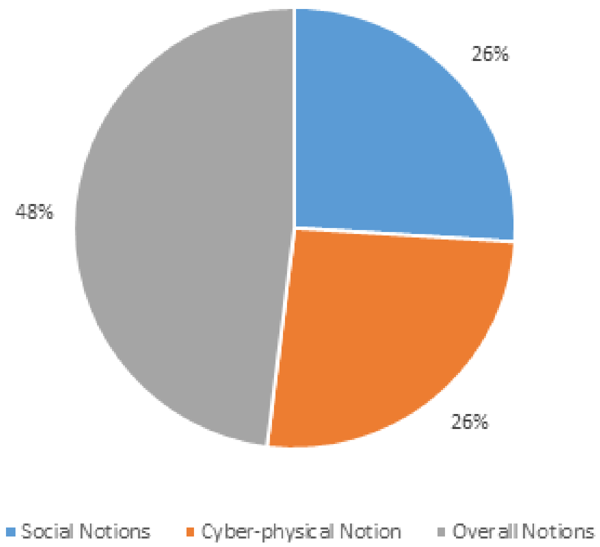

Figure 10: Distribution of different CPSS-related notions

Table 6 summarizes identified terms used to describe the social aspect of a CPSS. This is important as it shows the main points, which have to be taken into account when designing and engineering a CPSS.

Table 6: Notions to describe the social aspect of a CPSS

Notion	Paper ID/Ref
Social environment	66 [36]
Mental space	175 [27]
Human system integration	202 [35]
Human-in-the-loop	169 [32], 212 [6]
Human behavior	216 [10]

Table 7 summarizes identified terms which describe the cyber-physical part of a CPSS, meaning it describes parts without social interaction. These terms can also be used to improve the CPS definition.

Table 7: Notions to describe the cyber-physical aspect of a CPSS

Notion	Paper ID/Ref
Cyber-physical system	45 [13], 79 [8]
Internet of Things	65 [7], 147 [3], 169 [32]
Predictive learning	1 [30]
Artificial systems	23 [34], 45 [13]
Self-aware and self-adapting systems	86 [23]
Computing for human	41 [14], 45 [13]
Ubiquitous sensing	147 [3]

Finally, we collected notions which are often used in connection with a CPSS which are presented in Table 8. These can also be used to describe other systems than a CPSS.

Table 8: Notions often used in connection with CPSS

Notion	Paper ID/Ref
Smart services	41 [14]
User centric data	31 [5]
Decision Support Systems	31 [5]
Human-centered computing system	212 [6]
Human-centric framework	147 [3]
Human-centric computing	169 [32]
Human-centered system	23 [34]
People centric Internet of Things	147 [3]
People-centric applications	148 [15]
Cyber-physical-social space	1 [30]
Cyber physical social sensing	148 [15]
Cyber-physical-socio space	191 [18]
Cyber-physical-human space	191 [18]

4.5 Differences between CPS and CPSS

Several papers describe a CPSS as a CPS with a social aspect. Therefore, the main difference is the missing social aspect in CPS. Consequently, it is important to clearly understand what is meant by social aspect and in which intensity the social aspect has to be implemented so that it implies a CPSS. For some authors it is enough to provide a user benefit. An example for this sort of paper is paper 166 [26]. This paper describes a warning system for tired car drivers. In this example the user only gets warnings based on sensor calculations. The human has no real interaction with the system and no active role. Other definitions require an active interaction with a user to consider a CPS as a CPSS. A good example for this kind of paper is paper 169 [32] which discusses a tool to help visually impaired people navigating. In this system the user provides data via social media, interacts with the system during the processing and benefits from the results (find the right door or get notified about a public event).

5 Domains, Goals and Stages of CPSS

This section discusses in detail the application domains, goals and the stages of CPSS, collected from the selected papers in this study. Answering RQ 2 *"What domains, goals, and stages are specific to CPSS?"* and its sub-questions illustrates the purpose of CPSS in general. It is crucial to get familiar with the human roles, needs and benefits in each example domain to better understand their focus and solution contributions in order to collect parts of the big picture of CPSS in the scientific community. The following sub-sections will first introduce the domains and the specific goals in each domain and then discuss the stages and activities of CPSS in general.

5.1 Application Domains and Goals of CPSS

According to the analysis of the selected papers, these papers belong to five application domains. Table 9 lists the application domains and the paper IDs. From 17 selected papers, 4 (24%) address applications in the smart transportation domain, 3 (18%) in the smart building domain and 5 (29%) in the smart city domain. Again 3 (18%) papers focus on the smart factory and only 2 (12%) on the other dynamic social systems and their smart services.

Table 9: Overview of application domains covered by CPSS

Application Domain	**Paper ID/Ref (share of papers in %)**
Smart transportation	23 [34], 166 [26], 215 [20], 234 [28] (24%)
Smart building	45 [13], 147 [3], 212 [6] (18%)
Smart city	31 [5], 65 [7], 169 [32], 188 [12], 216 [10] (29%)
Smart factory	79 [8], 86 [23], 202 [35] (18%)
Other dynamic social systems	41 [14], 66 [36] (12%)

Figure 11 provides a graphical overview of the main application domains and scenarios covered by CPSS described in the the papers of this study.

5.1.1 Smart Transportation

Four papers focused on the application domain of *smart transportation* [34, 26, 20, 28]. Their main common goal is providing the drivers with proactive recommendations on the road. The variations between the papers are the reasons for the recommendations, e.g., supporting the parking process, by recommending a parking space based on the time left before an appointment, some specific driver requirements, or a combination thereof.

The social component in CPSS focuses on actively analyzing the user behavior in the context by collecting information and providing recommendations to the driver. Sources of information are previous driver behavior, social input from open social networks, or the driver's private schedule. In smart transportation scenarios, this context information helps optimize the traffic control and safe driving.

Traffic behavior analysis can provide useful information for all drivers, considering the conditions of the road and individual social requirements. The system will repeat the learning process every time it is used, to gather the new information, compare it to the useful old situations, and support the driver proactively in the current conditions.

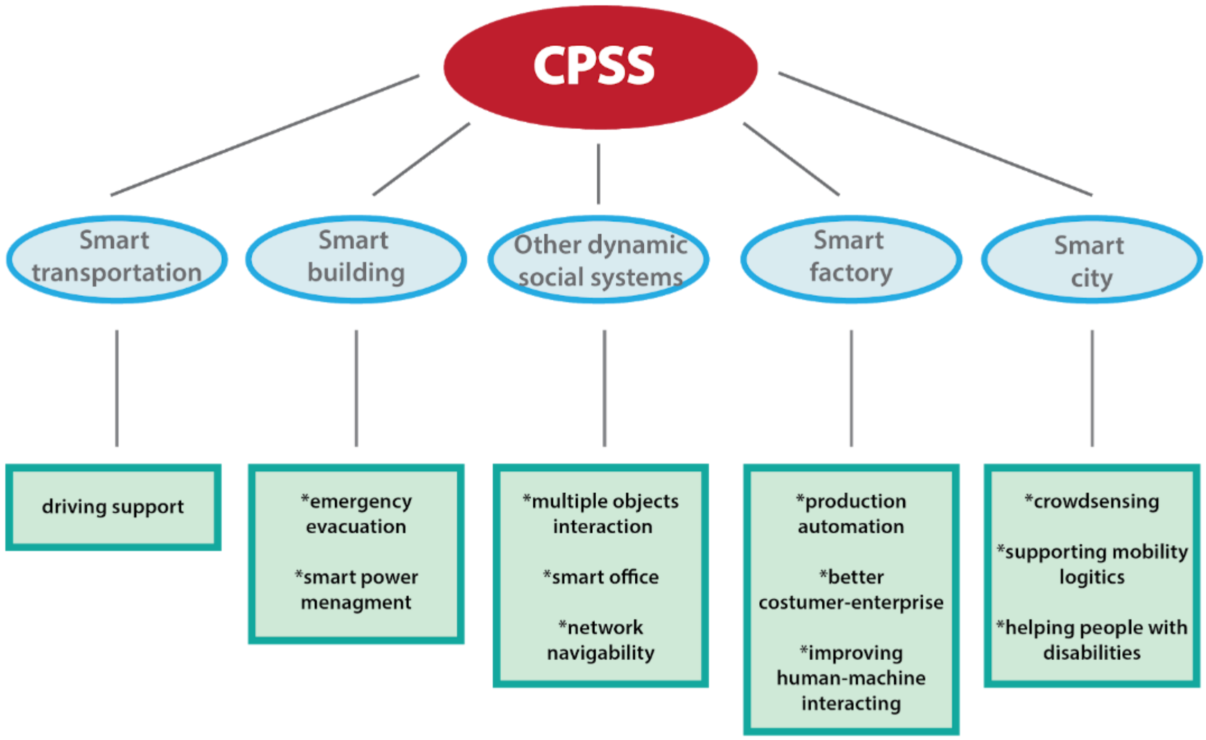

Figure 11: CPSS application domains and typical goals in those domains

5.1.2 Smart Buildings

The three papers in the application domain of *smart buildings* [13, 3, 6] focus on two main scenarios: emergency evacuation of a building and smart power management for a building. The building emergency evacuation scenarios proactively model the users behavior in case of fire in a building. The pre-arranged evacuation plans are evaluated to effectively guide humans in real time during the emergency. Therefore, the system has to combine prepared evacuation plans in real time with dynamically changing situations to effectively guide the building occupants to safe ground in a timely fashion. Guaranteeing the users' safety is the main purpose of the system.

Power management for buildings focuses on efficient use of energy. Reducing the average energy consumption should be combined with similar or better comfort for the users. A major concern of reducing energy consumption are electricity cost savings by reducing expensive peak loads. Simulated experiments with users showed the potential for significant reduction of the average energy consumption in the selected scenarios.

5.1.3 Smart City

Smart city is the domain most often analyzed in the selected papers [5, 7, 32, 12, 10]. These papers focus on crowdsensing, on supporting mobility and logistics, and on helping people with disabilities. The goals in medical area, such as monitoring the patients behaviour and current state, individual warning for specific patients about the possible danger on their way, classification of the emergency cases to the hospitals, etc., are very important and helpful systems that support these scenarios are always needed. Classification of patients in emergency hospitals based on the severity of their condition or warning people with asthma about dangerous areas for them are both of greater purpose to every city.

Modern mobile devices offer interesting private sensor capabilities. These sensors and devices play a major role in collecting the social networking data and are also efficient for crowdsensing applications. Users can be quickly informed about critical mobility conditions, and receive recommendations based on personal information. Location based applications capable of providing the users with the personalised dining information, regarding the request the user posts in the app, uses the crowdsensing to detect the others who could possibly help with the request, who have been at that specific location and have posts about it, contacts them, analyses their social data, and replies to the primal request within just a few minutes. Crowdsensing opens up a wide range of possibilities, such as improving the navigation for visually impaired people or for urban pedestrian flows, guidance in shopping malls and for evacuation planning in underground cities, which is similar to the evacuation of a building in this case, where testing environment simulation requires pedestrian behavior models.

5.1.4 Smart Factory

The three papers with the application domain of *smart factory* focus on production automation, better customer-enterprise interaction, and improving human-machine interaction [8, 23, 35]. Many interesting scenarios between customers and enterprises improve the customer's ability to reach the enterprises, to receive news and updates, and to receive advice on products. The interaction between them opens the possibility for collaboration on personalized orders, such as co-creation and quality monitoring. Co-creation is made possible via social media. All these scenarios aim at improving customer satisfaction and further exposing market offers and trends.

One paper focuses on actively supporting the workers to reduce work demands, such as if the worker has some specific personal issues, to adapt the system individually so that it does not make it harder to finish the given task. The idea of smart, adaptive, and collaborative manufacturing environment resulted with improving the human-machine interaction. Not only is the interaction improved, but also the workers' well being, health and the working atmosphere. The purpose of smartly adjusting the production patterns is to avoid delays, down times, and production rate decrease due to disruption and maintenance. It is necessary to adequately deal with the new working conditions, whether the changes came from the firm or from the workers, new machine or specific health issue, or both, all is to be considered and adapted in order to reach higher quality and mass production.

5.1.5 Other dynamic social systems

Other dynamic social systems are presented in papers referenced with 41 and 66 [14, 36]. One of them describes the airport dynamic social system scenarios and the other a smart office scenario.

The goal of these systems is to interact with multiple objects at the same time in order to combine their capabilities and reach a new user experience. The dynamic airport scenario enables the user to send multiple requests from one device, for example, the airplane's interior temperature and the lighting level in the waiting room for reading the book, and the sensors reply directly to the user. The combination of devices, services, and web applications generates a better experience and greater user satisfaction. The purpose of improving network navigability is reaching adequate alliance between CPSS components. The replies to the various user requests are faster and the navigation much more efficient.

5.2 Main Stages of CPSS

17 analyzed papers in this systematic mapping study presented a CPSS or a model of a CPSS involving three main stages/activities: *data collection*, *data analysis*, *and proactive recommendations*. The systems differ from each other in how they perform these activities, and even extending some activities. Table 10 lists the stages found in the analyzed systems.

Table 10: Papers categorized by identified stages/activities

Stages / Activities	Paper ID/Ref (number of papers)
Data collection	23 [34], 31 [5], 41 [14], 45 [13], 65 [7], 66 [36], 79 [8], 86 [23], 147 [3], 166 [26], 169 [32], 188 [12], 202 [35], 212 [6], 215 [20], 216 [10], 234 [28] (17)
Data analysis	23 [34], 31 [5], 41 [14], 45 [13], 65 [7], 66 [36], 79 [8], 86 [23], 147 [3], 166 [26], 169 [32], 188 [12], 202 [35], 212 [6], 215 [20], 216 [10], 234 [28] (17)
Proactive recommendations	23 [34], 31 [5], 41 [14], 45 [13], 65 [7], 66 [36], 79 [8], 86 [23], 147 [3], 166 [26], 169 [32], 188 [12], 202 [35], 212 [6], 215 [20], 216 [10], 234 [28] (17)
Data integration	147 [3], 234 [28] (2)
Data storage	31 [5], 65 [7], 234 [28] (3)

Figure 12 depicts the main stages of a typical CPSS and its dependencies.

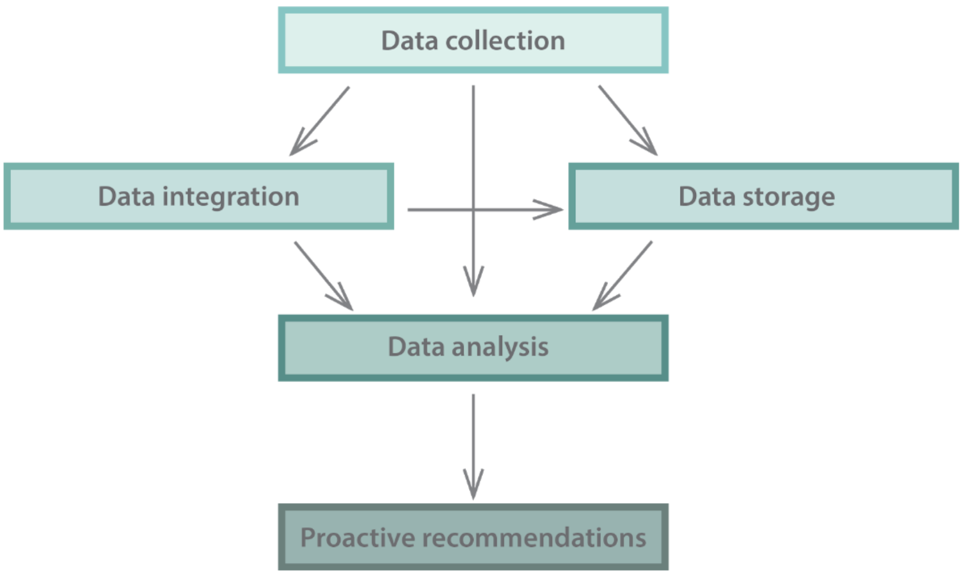

Figure 12: CPSS stages

5.2.1 Data Collection

All 17 analyzed papers include a data collection stage. The difference is in the way how to collect the data. Some systems use sensor collected data only, others social networking data only, or a combination of sensor and social networking data. The systems that store the data, include data storage activity, are also in collection stage using the stored information if relevant and useful for the current scenario. One system uses agent-based modeling methods to imitate the users and based on performed experiment collects the necessary data. The extended Petri net model captures the modelled relations between physical objects and cyber actors. Crowd-sensing applications, such as removable private sensors, collect real time data. And medical area collected data are also monitored in real time.

5.2.2 Data Analysis

Data analysis occurs in all analyzed papers. Depending on the domain, differently collected data are processed in various ways, as different data aspects are relevant for reaching diverse goals. For example, social networking data collected for parking assistance purpose go through location-based analysis while the social data collected for personalized production purpose are analyzed more individually for statistical customers relevance. Analyzed are user behaviors, the repeating patterns and the results of each decision previously made and the reaction afterwards. Smart services are mapped to a certain smart object. In the evacuation purposes, various emergency strategies are stored in databases and then applied to the artificial system to analyze their influence. Diverse scenarios have a diverse impact on evacuee psychology and physiology, and it is necessary to analyze the behavior in each case. Behavior analyses helps to model the user behavior. Individual and group collected aspects differ, whether on humans or machines, objects or processes, etc. Individually analyzed behaviours can not be applied to a whole group without analyzing the group and comparing the aspects. The individual analysis is more specific and follows more details, while group analysis gives a brighter picture more oriented on similarities.

5.2.3 Proactive Recommendations

The third stage of CPSS found in every analyzed paper is proactive recommendations. After collecting and analyzing the relevant data, the system makes suggestions to the user in terms of active recommendations based on the results of the previous stage. The recommendations are usually presented through the user interface. Typical types of recommendations are textual notifications and map navigations. In the medical area, if the monitored patient state has concerning changes the medical staff is notified via the system. Driving assistance systems notify the drives about the possible danger, using visual or sound options. The warnings about the dangerous areas for people with asthma are popping up in the user's personal devices. The users get the status updates in the smart energy usage case, and the generated virtual instructions in the smart factory case.

5.2.4 Other Stages and Activities

Other stages and activities of CPSS mentioned in the analyzed papers are *data integration and data storage*. Data integration combines the data collected from different sources, connecting the collection and analysis part, and data storage stores the collected data. These activities come in between the data collection and analysis, connect them, further extend the CPSS, but not all cyber-physical social systems include them.

The data is usually integrated with the semantic technologies based on ontologies. Stored data from databases are applied in analysis stage to compare the current state with the previous and recognize the patterns. In the case of dangerous areas for people with asthma, modelled and stored are the information objects, used to warn the users about possible danger.

6 The Role of Humans in CPSS

Humans' roles in CPSS varies depending on the nature of the system of interest. Either they provide the system with data to operate on making them to social sensors, they could use services and recommendations provided by the system to make decisions making their role to decision makers, or they could be social actors (also referred to as actuators) where they operate the system and help with driving the decision-making mechanism in the CPSS. In many CPSS the overall role of humans can be a combination of many roles. In order to better illustrate possible roles of human, we use the example of the intelligent parking assistance system proposed by Smirnov et al. [28].

This CPSS uses the driver's needs and preferences beside situation detection methods to serve better recommendations on a pre-trip as well as an on-trip bases. The system builds a profile for the diver by analyzing his/her behaviour to predict future actions as well as implicit preferences provided by the driver (preferring free parking, parking next to the door, etc.). One way to perform behavior analysis is the functional behavior analysis technique, which builds a conditional behavior model (how a user would act in a given situation). In the proposed system four techniques are used to reveal the user's behavior patterns:

- revealing the user's behavior for problems with similar structure and different parameters
- revealing the user's behavior for different problems that were solved by the same person
- revealing the user's behavior based on optimization criteria the person follow/avoid
- applying the previous techniques to multiple users with similar profiles

With these four techniques the user's behavior can be predicted even for situations in which the user was not put before. The system also relies on social media networks to aggregate customers' rating for parking facilities and access the driver's schedule from the smart phone to serve better route and parking recommendations. The used recommendation system is a group recommendation system, which groups users with similar interest together and then serves recommendations to a user based on what others in that group have chosen before.

As we can see from the above scenario, the human's role in the CPSS involves providing social data to the system (e.g., personal preferences and the schedule) making the user to a social sensor, reacting to the system's recommendations and deciding where to park illustrates the decision maker role, and finally using the behavior of other drivers with similar interests to serve better recommendation shows the social actor aspect in a CPSS.

Table 11 provides an overview of the different roles humans can play in a CPSS.

Table 11: Overview of roles which humans can play in a CPSS

Role of humans in a CPSS	**Paper ID/Ref**
Social sensor	23 [34], 31 [5], 41 [14], 45 [13], 66 [36], 79 [8], 86 [23], 147 [3], 166 [26], 169 [32], 175 [27], 188 [12], 202 [35], 215 [20], 216 [10], 234 [28]
Decision maker	23 [34], 31 [5], 79 [8], 147 [3], 166 [26], 169 [32], 175 [27], 188 [12], 234 [28]
Social actuator	31 [5], 65 [7], 79 [8], 166 [26], 169 [32], 188 [12], 212 [6], 234 [28]

6.1 Social Sensor

Social sensing can be described as the process of data acquisition and data fusion in a CPSS. Such data acquisition can be performed by using physical sensors and social apps installed on smart phone devices, e.g., Twitter. In general, social sensors consist of four components:

- A sensing unit that collects both social data using social apps and data related to the user's environment using physical sensors in the smart phone.
- A preprocessing unit that normalizes the collected data and prepare it for transmission.
- A transmission unit that sends the collected data to the cloud.
- An assistant unit that provides the above three components with assistant services.

In this role of interaction, humans provide the system with data from their physical and social environment. The social data can include the user's interests, preferences, knowledge and behavior. Other types of social data can be inferred from the social interactions humans have with each other where people with similar interests tend to rely on the same services when they are in the same physical environment, meaning shared interests. The physical data collected by humans can include accidents details, traffic congestion, weather condition and other types of information. In the following we provide some examples of CPSS where humans play the role of social sensors.

Xiong et al. [34] introduce *Transportation 5.0* in their work which is a urban social transportation system that integrates passengers, drivers and pedestrians as social sensors. In this system humans can share their knowledge among each other such as emergency events (traffic accidents), guidance info (traffic congestion), travel-related information (marketplaces and travel tips that might interest new travelers) and information about sharable travel resources (car sharing services).

In the airport dynamic social system proposed by Hussein et al. [14] the user would like to interact with services and objects provided by the airport's network to achieve a goal. Once the user makes a request, the system will provide a list of all the services currently available that can help the user achieve his/her goal (e.g., finding the right gate), while also considering the user's profile preferences (service ratings, user's history, travel destination, etc.). The system then builds a structure of the returned social services/objects (coffee shops, boarding gates, shops, etc.). The user can interact with each object using the smart phone or an object gets triggered proactively by an event such as the user's schedule or based on the user's physical location. Each social object can push back notifications to the user about any updates (e.g., delay in boarding).

Hu et al. [13] presented a CPSS to model human behaviors during evacuation processes to come up with effective strategies for evacuating buildings during fire accidents. The social aspect in modeling such scenarios is the psychological and physiological behavior of the evacuees during fire scenarios, where considering the physical and psychological characteristics for everyone can have a great impact on predicting the crowd's behavior and movement during evacuations. Also the environment information will influence the evacuees' behaviors and movement during fire situations. Physical sensors will be used to collect accurate measurements for the evacuees' behavior during evacuation drills to calibrate the system.

6.2 Decision Maker

Humans interact with CPSS to achieve a goal that meets their interests. In this role, when a CPSS provides services and recommendations, the user uses these services and react with them by providing his/her feedback to the system. Such a reaction at this stage means the user becomes a decision maker in the system, regardless of whether making a decision only affects the state of the system or the end user. Now humans become both service consumers and collaborators, they provide data, make decisions and act based on the systems output.

In many of the described CPSS of this study, the user's interaction with the system involves decision making. In the following we illustrate some examples.

In the social transportation system described by Xiong et al. [34], the knowledge which other users of the system choose to share will affect the travel decisions the end user will make, which road to take, or what restaurant to visit. In the social manufacturing system introduced by Ding and Jiang [8], the customer can monitor the manufacturing process and provide real time feedback to the manufacturer, which will change properties of the final product dynamically. An additional advantage of that system is that it allows a human-to-machine interaction (customer or manufacturer), sending commands and instructions to the machine using mobile devices. The smart traveling system explained by Smirnov et al. [27] collects the driver's feedback, analyzes the decisions made by the driver and other drivers with similar interests/habits (whether the proposed solution was followed, and which was picked if many were recommended) to increase the system's reliability. This shows how humans engage with the system as a data consumer (following the system's recommendations) and a data provider (providing feedback and ratings). The CPSS presented by Smirnov et al. [26] illustrates the decision maker role of a human in the system, where the user reacts according to the system's feedback, such as slowing down or pulling over to take a nap.

6.3 Social Actuator

In the role of a social actuator, humans can change the behavior of the system either explicitly or implicitly using the influence they have on the system with their knowledge and cognition. A synonymous term of social actor is citizen actuation, where the data collected by citizen sensing is used to drive the system and make decisions. One way to think of social actuation in CPSS is of systems that involve citizen sensing. The sensing activity is performed by the community using their mobile devices, and humans in such systems are actuators as they move the sensors (their smart phones) around the physical environment. With the following examples we explain the role of social actuator in more detail.

In the social manufacturing system outlined by Ding and Jiang [8] the users can provide the machines with manufacturing instructions using their smart devices. In the Wi-City-Plus smart city system described by Costanzo et al. [5] the drivers and the pedestrians can provide traffic data to the system while they are on the move, meaning they are moving the sensors around. In the CPSS named Vita described by Hu et al. [12] different tasks are assigned to users of the system. One user can post a request and other users in the system can process the request. The tasks required to process the request are distributed among those users based on the resources and knowledge they have (their location, their mobile devices' availability and computation capabilities, battery level, etc.).

After analyzing the roles humans can play in a CPSS, we can conclude that the role of humans in these systems can be described as a feedback loop. The system presents the user with some kind of information, the user reacts based on this information (input, behavioral data, etc.), the reaction is then pushed back to the system and the loop starts again. This loop can be shared among multiple users and the knowledge learned from one user can be used to serve others with similar requests/interests. That is why in most of the investigated CPSS the role of decision maker and actuator occurred together.

6.4 Collecting Human Input

Multiple techniques are currently implemented in CPSS to collect the humans' data. In the following we present the identified data collection techniques in the papers of the study.

Crowdsensing is a sensing activity performed by the community using mobile devices and wireless networks instead of the conventional sensing using stationary sensors. Crowdsensing leverages human intelligence to collect, process, and aggregate sensed data. Crowdsensing can be deployed on the roads to build vehicular social networks (VSNs), where drivers can collect information about the road conditions (congestion, accident) and exchange these information with the network using their mobile devices. Another application for crowdsensing could be environment monitoring. Mobile devices are used by humans to take readings of their physical environment such as air quality and accidents and then share the results with the community. An example represents the work by Hu et al. [12] where a traveler would like to find a restaurant. He/she posts a crowdsensing request on Vita's social network. The system analyzes the request based on the traveler's location and stored preferences and then pushes the request to other human participants that are capable of processing the request based on their social vector (are currently in restaurants that meet the criteria of the user's request). Finally, Vita pushes the results back to the user. According to the work by Higashino and Uchiyama [10], crowdsensing technologies can be used to collect data about humans' behavior and social activities in urban areas using humans' mobile devices. The CPSS described by Dao et al. [7], beside physical sensors that sense the air quality, can rely on crowdsensing techniques to build an accurate understanding of the weather condition. Tweets for people talking about asthma is crawled from Twitter and, if many people from a specific area are talking about asthma, this usually suggests that the situation in that area is not very friendly to asthma patients.

Citizen sensing is a concept of collecting, analyzing and mining information about events. In the era of Internet of Things everything can become a sensor, including humans. This leads to the concept of citizen sensing where humans are actively observing and collecting data from their surrounding environment and then reporting their findings back to a system. The backbone for such a sensing technique are usually social networks and smart phone devices.

User profiling is applied in systems which can access the user's preferences, history, activities, behaviors and other personal data from a profile associated to that user. In most systems, such a profile exists on a social network and/or on the mobile device of the user. An example for this technique is the smart city system presented by Costanzo et al. [5] which can provide the users with recommendations and services based on their personal data and social profile. Another example is the assistive navigation framework for the visually impaired described by Xiao et al. [32] where the system can use the user's profile to find the home and working place address.

Social media platforms are driven by large online communities which can constitute the bridge between the cyber, physical and social spaces of a CPSS. Online communities are virtual communities where humans interact with each other, share their interests and knowledge. In such networks humans are both service consumers and providers (information posted by people on social networks is an example for services provided by humans to CPSS). As stated before, in most cases the user's profile data are stored on and accessed from social networks.

We observed that sometimes crowdsensing and citizen sensing are used interchangeable. Social networks (commercial networks or private ones) are the infrastructure for accessing and distributing collected information in crowdsensing systems. The user can post a request on the social network and then access the result from the same network.

6.5 Social Data and Their Sources

Different types of social data are collected in a CPSS to be used by the social actuator to make decisions and by the system to provide recommendations. Examples of collected social data include:

- *ambient condition*: information about the surrounding environment such as traffic accidents and congestion, weather condition, air quality
- *user's emotional and physiological state*: information to reflect the user's satisfaction with a service
- *service ratings*: public and private service providers such as restaurants can receive ratings of service quality and price ranges from users
- *online activities*: user's activities on social networks like check-ins, posts (text, audio, video and pictures), tweets on Twitter and accepted social events can be used by the CPSS to extract the user's schedule and preferences
- *physical behaviors and activities*: information about human behavior during evacuation processes, workers activities in an assembly line and pedestrians' paths
- *quantifiable information*: complaints and requests from citizens to call centers, subway passenger records, driving speeds on the roads

Social media platforms and social networks are the most used examples of sources for social data. They are very popular for two main reasons: (1) the public react to events on social networks faster than from news or government organizations, (2) it is easier and faster to obtain such information from social networks than from private sources due to various restrictions, in particular privacy issues. Twitter is the most commonly used social network for social information exchange due to its available public API, ease of posting and lack of barriers. A CPSS uses tweets posted on Twitter by the public and analyzes them to detect social events, accidents and crowded places. Other social networks were used for similar purposes. Users' opinions about products and ratings for services can be published to social networks, e.g., on Yelp or Tripadvisor. Social networks are also used to access the user's preferences, interests and upcoming events he/she is going to attend. In addition, the user's emotional status is measured based on his/her collected social data. Some of the CPSS we investigated operate on top of custom/unspecified social networks.

7 Main Data Sources in CPSS

CPSS have to deal with big amounts of data to perform operations such as decision making or behaviour recognition. As this kind of systems make a lot of computations and analysis to provide the best results possible, it is important to better understand which data is needed for the systems' operation and where the data is collected from, i.e., what is the data sources. To get a better understanding of how CPSS could be used in the real world we will look at first approaches in this area and how they handle the usage of data. By analysing some examples of CPSS we will get to know what typical data sources are and how these systems rely on a specific kind of data.

To get a brief overview of the properties and classifications of data and their data sources we will first discuss a few aspects of this topic.

As the name implies, everything which provides some kind of data could be called a data source but it is possible that a data source is not needed or causes an effect. To make data and their sources relevant there are a few properties which need to be mentioned:

- Interface: we have to communicate with the data source or even have to know how we get the data
- Understanding: we have to know what kind of data we get and what the data is telling us
- Actuality: the data has to be up-to-date, otherwise we would calculate on static data and nothing would change.

Another aspect is the importance of data related to a system and its decisions. These decisions often depend on real time data and the use of legacy or historic data to also take advantage from already passed events.

In the following sections we will focus on the classification of data and data sources used in CPSS.

7.1 Most Used Data Sources

Although the analyzed systems are different, it is possible to detect some similarities by abstracting the data sources that they rely on. In Table 12 the five most used data sources are listed and which papers refer to this abstracted group of data sources.

Table 12: Overview of most used abstracted data sources in CPSS

Data Source	Paper ID/Ref
mobiles	31 [5], 41 [14], 79 [8], 166 [26], 188 [12], 212 [6]
social networks	41 [14], 65 [7], 79 [8], 147 [3], 175 [27], 188 [12], 212 [6], 215 [20]
web services	31 [5], 41 [14], 65 [7], 212 [6]
special sensors (extra sensors which are not already part of another system)	1 [30], 23 [34], 31 [5], 41 [14], 45 [13], 65 [7], 66 [36], 79 [8], 86 [?], 126 [4], 147 [3], 166 [26], 169 [32], 191 [18], 202 [35], 216 [10]
legacy data & history data	126 [4], 147 [3], 169 [32], 215 [20], 216 [10]

It is not surprising that sensors, social networks and mobiles are often used when it comes to the question of data sources. Most of the papers use the fact that everybody is carrying a mobile phone and provides an easy way to collect data all the time. Beside the constant data flow of mobiles, it is also a big advantage to make use of the modern technology installed in smart phones and get data from an big amount of sensors everybody has.

As we are talking about CPSS, the social part requires some social data. This is often achieved by the use of social networks which provide a centralized hub for many interactions between people and the resulting amount of social data. (Examples of specific platforms are covered in later sections.)

When it comes to an abstract view of the system, it is not relevant where the data is coming from. In most of the cases, web services are mentioned but not explained in detail. These kind of services are often used to get information about public data like traffic news or weather reports.

As seen in Table 12, the most used group of data sources are sensors. Sensors are omnipresent and can not be left when we are talking about a CPSS. All the physical data which a system needs to know what is going on in the world is collected by sensors such as car sensors or heart rate sensors. These data sources cover the "physical" part of a CPSS.

The last big area are legacy data or historic data sources. Many CPSS use past events to get a broader knowledge about the processes they are trying to analyze. Often systems learn and change their behavior based on historic data to develop new strategies which increase their efficiency.

7.2 Social Data Sources

As it is very difficult to abstract the social part of a CPSS, this topic claims to be one of the hardest in this section. By grouping the social data sources in the three classes seen in Table 13, we can consider all typically used data sources which collect social behaviour or an interaction of several persons.

One possible way to collect social data is the usage of sensors such as cameras or microphones. In this case the recorded data is analyzed and people's interactions are extracted for further usage. Another kind of data source uses customer feedback where the users are explicitly asked about their interaction with other people. As it is not clear how much customer feedback are valued to the area of social data we come to the next data source where the social value gives their name: social networks. The most used source of social data is coming from social networks and is mentioned in nearly every paper.

Table 13: Overview of most used social data sources in CPSS.

Social Data Source	Paper ID/Ref
sensor readings	66 [36], 79 [8]
customer feedback	31 [5], 215 [20]
social networks	41 [14], 65 [7], 79 [8], 147 [3], 175 [27], 188 [12], 212 [6], 215 [20]
Twitter as a social network	65 [7], 79 [8], 147 [3], 169 [32]
Facebook as a social network	79 [8], 147 [3]

As we can see in Table 13, many scenarios rely on contemporary social networks such as Twitter and Facebook. Often system architects miss a feature of social networks or simply do not want to use an already existing system. In this case a few CPSS approaches make use of their own social network tailored to the concrete use case, but do not mention concrete details about implementation and other usage of those custom social platforms.

7.3 Physical Data Sources

As seen in Table 14, physical data can be grouped in three big classes which are data from physical sensors, data from mobile devices and environment data. Physical sensors are only part of the system and would not exist otherwise. As most of the CPSS use their own physical part, there are a lot of different physical sensors like proximity, light or medical sensors. Another sensor which is used as single physical sensor or in a smart phone is the GPS sensor. Many CPSS use the embedded sensors like GPS or NFC to get physical data from probands.

Table 14: Overview of most used physical data sources in CPSS

Physical Data Source	Paper ID/Ref
physical sensors	1 [30], 23 [34], 31 [5], 41 [14], 45 [13], 65 [7], 79 [8], 86 [23], 147 [3], 166 [26], 169 [32], 175 [27], 191 [18], 202 [35], 215 [20], 216 [10]
mobile devices	41 [14], 79 [8], 147 [3], 169 [32], 188 [12], 212 [6]
environment data	31 [5], 41 [14], 86 [23], 126 [4], 202 [35], 215 [20]

Beside location data, it is also common to make use of environment data which is typically collected from two different data sources: (1) weather station/service in papers 31 [5] and 41 [14] or (2) the public infrastructure service (papers 23 [34], 31 [5], 202 [35]). Most CPSS use their own services and sensors to gather environmental data or do not give a concrete example where the data is coming from.

Human sensors - Besides social data, humans are also able to produce physical data which CPSS can track. This data, named biometric data, can be used in a widespread of areas. Most of the systems use medical sensors to take care of humans and classify the health state of a person. The second used data source are video sensors to record movements of persons.

7.4 Historic Data

When it comes to the question of legacy or historic data, most of the systems assume to use already collected data to predict future events or make advanced user suggestions. The concrete process of how the data is being converted or where the legacy data is coming from is not mentioned in the papers we read. Historic data which is already collected and needs no conversion is assumed to be already in the right format and is being used without additive explanation. Typically used historic data includes: weather data (paper 215 [20]), medical data (paper 65 [7]), power consumption (paper 147 [3]) or other legacy data (papers 175 [27], 215 [20], 216 [10]).

7.5 External Services

Many CPSS use external services to get relevant data. Most of the used services are services from public institutions everyone can use. For example a fuel station service could be used to collect the current fuel price or get information if there is a possibility to wash the car. Another example is the service of a restaurant to check the menu and suggest restaurants to the user. Combined with social data and user preferences new functionalities can be achieved.

8 Challenges and Open Issues

In this section we discuss and analyse the current challenges and described open issues in the area of CPSS identified in the different papers of this mapping study (RQ 8). In the following we provide a summary of the analysis results to answer RQ 8 and its subquestions. In the first place we will have a closer look on the current challenges related to CPSS and then we go on to the future research directions.

8.1 Challenges

A number of challenges related to CPSS have been identified and discussed in literature, which are analyzed and discussed in the following. Table 15 gives an overview of the challenges in terms of CPSS with the paper references where they are mentioned. They can be classified using 7 categories as shown in the table.

Table 15: Challenges in CPSS Research

Categories of identified Challenges	Paper ID/Ref
Different sources and formats of data	31 [5], 212 [6], 215 [20]
Effective processing of real time data	31 [5], 166 [26], 202 [35]
Finding metrics	23 [34], 215 [20]
Dealing with large scale of contextual data	169 [32]
Privacy and security	31 [5], 79 [8]
Other technical challenges	23 [34], 169 [32], 212 [6], 216 [10]
Not mentioned	45 [13], 65 [7], 66 [36], 86 [23], 147 [3], 188 [12]

We analyzed 17 papers in total, where some papers mentioned multiple challenges. 14.3% of the analyzed papers mentioned the challenge of the different sources and formats. Also 14.3% mentioned the challenge of effective processing from the real-time data. Finding metrics and topics regarding privacy and security were each discussed very rarely by only 9.5% of the papers. Also the large amount of data was mentioned only by 4.8% of the papers. Very often a very specific technical challenge was mentioned (19 %) in the papers and in 28.6% of the papers challenges are not even mentioned.

8.1.1 Different Sources and Formats of Data

From the studies reviewed, we can observe that one main challenge, which is mentioned in three papers (31 [5], 212 [6], 215 [20]), is that the data is coming from different sources and is represented in a wide variety of formats.

This has been already a challenge in CPS, because the data is provided by different physical sources in different formats and must be mapped to a format which the CPS understands. Nevertheless, because the data are coming from physical sources, the format of one source does not change from time to time and the conversion process is not as complex as in CPSS. The big problem with the data coming from the human respectively the social component is that it is very inconsistent and the format can change very quickly.

For example in one paper the data is gathered from status updates of people on social networks, so it is necessary to analyze the language. This is a very complex task, because beside the fact that every human is different and writes in another style (language, grammar, mistakes, dialect, etc.), the human itself also changes, for example because of his daily condition.

In another paper pictures and videos posted by people on social networks is used by the CPSS, therefore the system must know what is shown on the image or on the video what is also a very complex task. Most of the papers try to handle this challenge by using semantic web technologies based on ontologies.

8.1.2 Effective Processing of Real-time Data

We observed that there are many difficulties regarding the processing of real-time data also mentioned in three papers (31 [5], 212 [6], 215 [20]). This is a very important issue because in a CPSS the result has to be displayed in a timely manner for example in navigation systems or even more important in health-critical applications.

One problem in processing real-time data, as mentioned in the previous section, represents the large amount of data from different sources and in different formats which is very complex to analyze. Another problem is after the transformation and analysis of the data a result, which matches the users behavior, must be calculated. Therefore the system must additionally save and analyze data of the user as well as predict the behavior of the user.

This challenge is very hard to deal with, because as described the amount of data increased and the processing and analyses of the data is more complex compared to CPS but the time until the result is shown is the same. This problem depends very much on the performance of the algorithms and components used in the system. Therefore it can be solved by improving the algorithms and components used in the system. The improvement of existing algorithms or the development of efficient algorithms will be a topic in future studies.

8.1.3 Finding Evaluation Metrics

Metrics are functions a system uses to measure certain characteristics, so it is possible to compare them and use them in the analysis process. In terms of the social component of the CPSS the metrics are missing. Therefore many characteristics which would be relevant in the analysis process can not be integrated.

This challenge is mentioned in two papers (23 [34], 215 [20]) and like the development of the effective algorithms to improve the performance of CPSS it will be topic in future studies to find good metrics in relation to the social component of CPSS.

8.1.4 Dealing with Large Scale of Contextual Data

This challenge of dealing with large scale of contextual data is just mentioned by one paper (169 [32]), but it can be implicitly derived from other papers as well. For example, as we already described, the effective processing of real-time data is challenging and one reason for that is the large amount of data which is gathered from different sources.

The large scale of contextual data was already a challenge in CPS because the data can come from many different sources. In the most CPS the problem could be solved or handled technically, by introducing components more suitable for high amounts of data. For example using Big-Data or NoSQL databases instead of relational databases.

Most papers of this study also tried to solve this problem by introducing new components, but in many systems this is not enough as the problem often lies somewhere else, e.g., with the used algorithms or the transportation of the data over the network.

8.1.5 Privacy and Security

From the studies reviewed only two papers (31 [5], 79 [8]) mentioned the challenge of securing the system and protecting the privacy of the humans using the system. In general privacy and security of CPSS were very little discussed in the papers collected in this study. The problem here, compared to CPS, is the additional social component in CPSS. Because of this, data which is partially or mainly sensitive, comes into action and securing this data to protect the privacy of the human is very important to consider.

The fact that privacy and security is discussed very little in the papers of this study gives a hint that there are many topics not yet dealt with and it is important to create awareness about that situation. Users will probably not use systems that do not protect their data, such as health records or financial transactions, no matter how functional those systems are. The security of such systems to protect the privacy is a very important issue and will be a major research topic in the future.

8.1.6 Other Technical Challenges

Many papers (23 [34], 169 [32], 212 [6], 216 [10]) described very specific technical challenges of their systems which are not so interesting for CPSS in general. For example in one paper a challenge was the miscount of people, because the sensors used are imprecise in crowded regions and cannot detect people behind objects. Another challenge here was for example to reduce image blur when using head-mounted cameras.

8.1.7 Not Mentioned

The remainder of the reviewed papers do not mention any challenges with regard to CPSS. This could have different reasons. For example it could be the missing awareness as already mentioned in the section privacy and security. Another reason could be that in some papers a system is described but must be tested in a bigger experimental setup to run into the same problems and challenges as the CPSS in other papers.

8.2 Open Issues and Future Work

In the analyzed papers in this study many different open issues are mentioned, where future research is still necessary. These are analyzed and discussed in the following. Table 16 gives an overview of the open issues in terms of CPSS described in the papers. They can be summarized using 4 different categories. 29.4% of the papers mentioned the application of their approach in different areas as their future work topic. Also very often were specific technical extensions mentioned (29.4%) in the papers. Privacy and security is discussed very rarely by only 5.9% of the papers. The majority of the studies (35.3%) does not mention any planned future work in their paper.

Table 16: Future Work in CPSS Research

Categories of Open Issues and Future Work	**Paper ID/Ref**
Applying approach in different areas	23 [34], 86 [23], 147 [3], 212 [6], 216 [10]
Privacy and security	41 [14]
Other technical extensions (virtual reality, big data)	31 [5], 45 [13], 79 [8], 212 [6], 215 [20]
Not mentioned	65 [7], 66 [36], 166 [26], 169 [32], 202 [35]

8.2.1 Applying Approach in Different Areas

The main topic for future work is to apply the proposed approach in a different setting (e.g., different areas, domains, locations). This is mentioned in five papers (23 [34], 86 [23], 147 [3], 212 [6], 216 [10]). In some papers the approach should be applied in different application domains (transportation, manufacturing, etc.), in other papers they would like to broaden the experimental setup with more users and in more complex industrial scenarios.

8.2.2 Privacy and Security

The securing of the CPSS and the protection of the privacy of the humans using the system is only mentioned by one paper (41 [14]), but will be a major topic in the near future. As already discussed along the challenges of CPSS the awareness of privacy issues with the large amount of partially sensitive data is an open issue.

Because in a system where partially or even mainly sensitive data is used it is clear that securing this system and so protecting the privacy of the human has to be an important issue and the fact that this is mentioned in the papers so little gives a hint that awareness about this topic is missing and has to be improved. Besides that it is a note that there could be other important topics not even mentioned in the papers of this study.

8.2.3 Other Technical Extensions

In five papers (31 [5], 45 [13], 79 [8], 212 [6], 215 [20]) technical open issues and work for the future is described. Most of them deal with the improvement of data integration or data analysis approaches, be it by trying to implement other data storages, like big data, or by improving the data analysis algorithm. Other papers aim to improve the user experience and the modalities used for CPSS result distribution, for example, by adding virtual reality to their approach.

9 T2.1 CPSS Taxonomy

The goal of task T2.1 is to identify key characteristics and features of CPSS and based on them classify these systems in a pertinent taxonomy. A taxonomy consists of a set of dimensions to characterize different types of CPSS as well as of distinct values for these dimensions which allow describing the space of CPSS. For example, in the area of Human Computation, Quinn and Bederson [24] proposed a taxonomy of human computation systems including dimensions such as the motivation of human contributors (with values such as: pay, altruism, enjoyment or reputation), quality control mechanisms or aggregation techniques used. Their taxonomy was an important milestone and contribution to the emerging field of Human Computation. Today, research on CPSS is in a similar situation. Results of our systematic mapping study reveal that there is a wealth of papers that publish research work on CPSS. But yet these systems widely differ among themselves from several perspectives. Currently, there are no works that aim to better understand these variations and the axes along which they occur. Our work addresses exactly this critical gap for this research line.

Based on the preliminary analysis of the collected papers, we present first emerging elements of such a taxonomy as an initial version of the deliverable. These will be further investigated and the taxonomy will be developed for the next version of the deliverable.

We identified the following *initial* taxonomy dimensions:

1. Role of social actors:
   (a) sensing
   (b) decision making
   (c) user of the system
   (d) actuation: some CPSS entice humans to action and enable them to act as actuators (e.g., in congestion dissipation).
2. Methods for collecting information about the social element:

   (a) implicit (e.g., mood sensing through social media analysis)
   (b) explicit crowdsourcing (citizen sensing through dedicated apps or incentive mechanisms (e.g. gamification).

3. Adaptation and coordination model:
   (a) Feedback loop to physical and social sensors.
   (b) Self-adaptation methods
4. Data collection
5. Data integration and analytics approaches
6. Explicit representation of the social element - is only achieved in some of the papers.

Future work in this task will include:

- extending the dimensions of the taxonomy based on an in-depth analysis of the rest of the papers collected as well as based on taxonomies of related systems types, such as collective intelligence systems or CPS;
- categorizing the CPSS examples reveled in the study along the dimensions of the taxonomy to gain a better understanding of the landscape of the CPSS family.

10 T2.2 Social Actor Model

The overall goal of task T2.2 is to build a semantic model (ontology) that captures key characteristics of the social actors involved in the CPSS. The *Social Actor Model (SAM)* will both provide a better theoretical understanding of the role of social actors in CPSS while acting as a foundation for data integration through the methods developed in WP4.

Within the first months of this task, the focus was on collecting relevant ontologies which could be reused and adapted for CitySPIN's own Social Actor Model. These ontologies were identified as follows:

1. based on the results of the systematic mapping study which identified papers that used ontologies for representing the social actors in a CPSS (see 10.1);
2. based on earlier work within the Semantic Web area for representing personal information and data from online communities (see 10.2);
3. based on work for related research areas such as Human Computation systems (see 10.3).

10.1 Ontologies identified through the Mapping Study

During the literature study in T2.1, from the 22 papers inspected the following three made use of ontologies for representing CPPS social actors.

In paper 31 [5] the LinkedTV User Model Ontology (LUMO) is used to represent an user with her/his preferences and the main user context dimensions within the networked media domain. Additionally, the General User Model Ontology (GUMO) is employed to model the user data. GUMO relies on the UbisWorld Ontology that models the urban environment. The main feature of the proposed ontology is that it is centered on a limited set of basic level concepts and that the related decision support system can use a simple fuzzy engine implemented by

SPARQL queries able to find the right recommendations for supporting typical smart city scenarios with a satisfactory time performance.

Paper 175 [27] focuses on resource collaboration in cyber-physical-social systems. Technologies of ontologies, intelligent agents, and online communities are used to enable interoperability of human and non-human resources. An agent ontology and major principles of agent collaboration are proposed. The proposed ontology is based on the earlier developed ontology for resource self-organization. That ontology is specialized for agent collaboration empowered by online communities. The examples from smart room domain and smart travelling domain are concerned with scenarios of agent collaboration.

In paper 166 [26] a behavioral model is created in order to better understand the driver's behavior. The states of the model can be hierarchically organized to describe the short and long-term behaviours by using the driver ontology that includes visual cues and visual behaviours and determines relationships between them.

We plan to read more papers collected in the mapping study in order to extend this list of ontologies.

10.2 Ontologies from the Social Semantic Web

The Semantic Web community has already created a number of ontologies meant for representing and sharing social data. Some of these ontologies that are already widely adopted and will be considered for reuse include:

- **FOAF (Friend of a Friend)**[1] - was the first ontology offering an easy to use vocabulary for describing personal information as well as social relations between people (e.g., such as the *knows* relation);
- **SIOC (Semantically-Interlinked Online Communities)**[2] is a core ontology offering semantic structured needed for describing information in online communities such as message boards or social networks. This ontology is promising for describing data collected from the social actors in the CPSS. SIOC extends some of the FOAF concepts and can be used in tandem with FOAF and other ontologies[3].

10.3 Ontologies from other related areas

Within the related field of Human Computation, a line of work focuses on describing the workers involved in HC systems, their CVs and skills [1, 19, 25].

Next steps in task T2.2 include:

1. finalizing the collection of relevant ontologies based on a more focused inspection of the relevant literature;
2. clarifying the requirements for social actor representation of the project use cases (together with WP3);
3. creating the CitySPIN SAM by reusing relevant ontologies.

[1]FOAF project: http://www.foaf-project.org/
[2]SIOC Core Ontology Specification: http://rdfs.org/sioc/spec/
[3]SIOC/RelatedOntologies: https://www.w3.org/wiki/SIOC/RelatedOntologies

11 T2.3 Software Engineering Principles of CPSS

The goal of task T2.3 is to synthesize collected knowledge about CPSS into a catalogue of software engineering principles and architectural methods to support architects and engineers with the conceptual design, modelling and engineering of data-intensive CPSS. To achieve this goal, a first step is to analyze the preliminary results of the collected papers with regard to architectural principles that all CPSS share and thus constitute their design basis.

From a software architecture perspective a CPSS is a complex system that is constituted by three parts [34]:

1. A **physical space** that is interacting with the physical world. Physical components like vehicles, production systems, robots, road infrastructure, and smart meters, are used to monitor their environment, to collect information with sensors and take actions to influence the environment and react to uncertainties with actuators. This space is also part of the traditional CPS.
2. A **social space** that represents the significant extension to the common CPS architecture. Socio-technical systems are integrated into the CPS architecture to monitor social activities and collect information, knowledge, experiences, and observations shared by humans. These socio-technical systems provide specific mechanisms to humans, organizations, and societies so that they can contribute different kinds of information to other users and get feedback. By the combination of social and physical sensing information, CPSS can then achieve more intelligent and improved decisions than a CPS. These resulting decisions and recommendations of the CPSS are distributed back through these social channels so that humans can take actions based on this feedback. Examples of such socio-technical systems include collective intelligence systems [22] (e.g., Facebook, Twitter, Yelp, YouTube) and crowdsourcing systems [11] (e.g., Amazon Mechanical Turk, Crowd Flower).
3. A **cyber space** which represents the core of the CPSS and is in charge of the overall system control. It provides context-aware services and applications to integrate and store as well as process and analyze the collected data according to defined goals and purposes. Based on its resources and analysis results, the computational system makes decisions and recommendations which is sent back to the other two parts of the system in order to use the generated results for appropriate reaction and adaptation.

We identified that a main characteristic of the surveyed CPSS is that they collect and integrate large amounts of heterogeneous, poly-structured data from a variety of sources. Besides sensor data from physical devices, a hallmark feature of CPSS is that they also capture social data via mobile apps comprising customer feedback, social preferences, emotional status or personal schedule data, but also from social networking services (e.g., Facebook, Twitter), collective rating & review platforms, and information from websites such as safe-place or emergency support centre. We refer to these data sources as socio-technical systems. Findings show that CPSS typically disseminate consolidated information and triggers back to physical actuators and human users, so that ideally there is an optimization of the locally performed tasks, but also an optimization of system-wide processes and crowd/community needs. In the existing engineering of CPSS, this feedback, however, is mostly targeted towards sensors and actuators of the cyber-physical system and less on the actual users or crowds. Many systems use the socio-technical platforms only as passive data sources and only few of the surveyed CPSS actively disseminate triggers and feed results back to users or socio-technical platforms.

Examples of such "social actuation" are Twitter messages, which inform an appropriate user about identified abnormal energy use with a request to check this issue [6], or notifications about dangerous events via a car infotainment system which delivers information to the driver through invehicle screen, audio system or steering wheel vibration [26].

The study results revealed that a CPSS can be referred to a *system-of-systems* which is integrated with one or more socio-technical systems in the social space, but also can consist of various systems in the physical and cyber space depending on the CPSS goals and purposes.

Figure 13 presents an initial version of a CPSS architecture pattern comprising the identified process of (1) data collection from both social and physical space, (2) data processing and analysis in the cyber space, and (3) result dissemination for feedback and actuation.

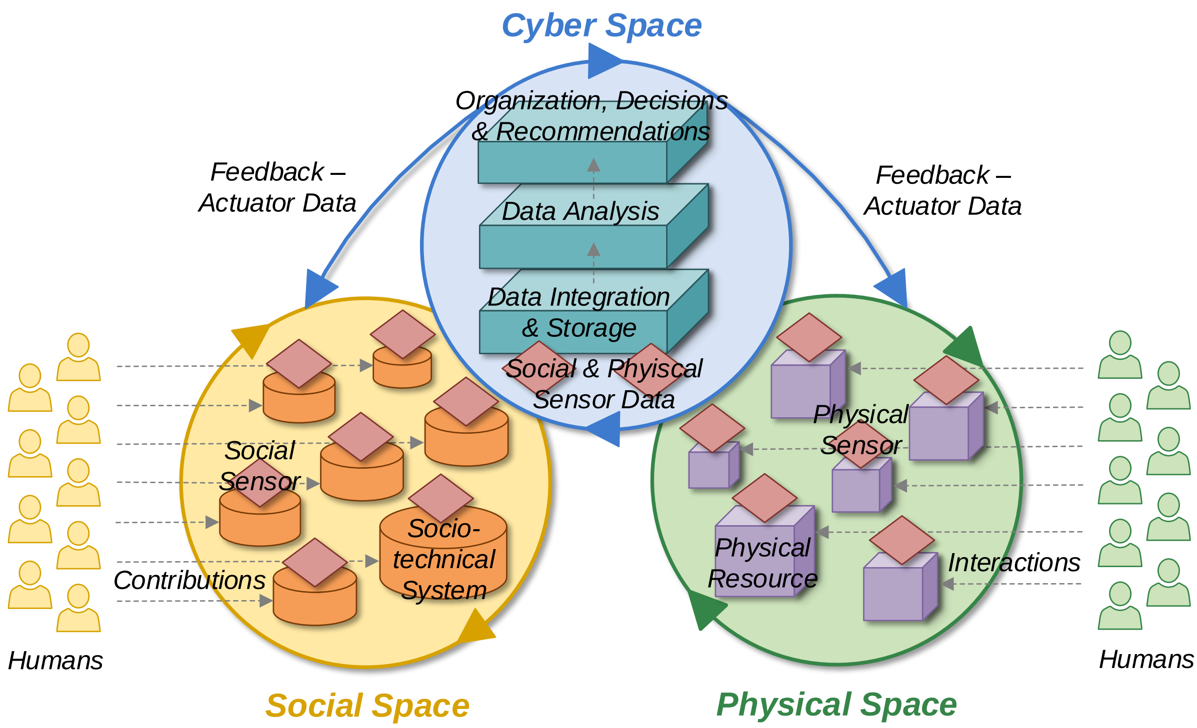

Figure 13: Initial version of a CPSS architecture pattern with data collection, data processing and analysis, and result distribution

Finally, the study results confirm that there is currently a lack of methods to explore and analyze the design of data collection and integration, result dissemination and actuation phases especially with respect to orchestrated machine and human interaction. The challenge is to integrate an appropriate mixture of socio-technical systems and different kind of data to enhance information collection and coordination capabilities of CPSS. Therefore, future work in this task will include:

- Formally describe a common architecture pattern which describes a CPSS architecture and highlights the difference to the traditional CPS architecture;
- Develop an architectural method (e.g., architecture viewpoint, framework) to support engineers in the decision making process with regard to the design of a particular CPSS of interest that addresses a set of defined goals and purposes as well as to produce a comprehensive system architecture description.

12 Conclusion and Future Work

This deliverable described preparatory work necessary for creating a CPSS blueprint which was performed in the first six months of the CitySPIN project. the major task performed was the execution of a Systematic Mapping Study which allowed collecting the relevant literature needed to accomplish the main outputs of WP2, namely the taxonomy of CPSS models (T2.1), the social actor model (T2.2) and the catalog of CPSS design patterns (T2.3).

12.1 Conclusions on main research questions

In the following, we summarize the major conclusions reached for some of the research questions that informed the systematic mapping study. Research questions 3, 6 and 7 will be addressed for the next version of the deliverable.

RQ 1: CPSS Definitions The biggest difference in the definition of CPSS is the influence of the social aspect. In some definitions of a CPSS it is enough to provide a social interaction through social media data or similar data. On the other hand, there are definitions, which require an interaction with the user-base of the system is that system is to be considered a CPSS. For example in paper 169 the user has to decide, if he already arrived at this final destination or not [32]. The analysis of the different terms and notions to describe a CPSS and synonyms for CPSS revealed, that the CPS part of a CPSS is already well established and defined. In contrast, however the social part is defined in a variety of different ways and there is no overarching consensus on the roles of this part in system. Based on the various definitions collected during the study, we combine them into one overarching definition as follows:

A CPSS includes different aspects. First, it has to include a social part, such as social media data or an interaction with the user. Furthermore, it should be based on a CPS, which means that it includes a physical interaction with the real world.

RQ 2: CPSS domains and stages The typical application domains of CPSS are *smart transportation*, *smart building*, *smart city and smart factory*. These domains provide a wide spectrum of scenarios where the overall goal is to achieve better effectiveness and efficiency of processes, and reduce the risks. Smart transportation focuses on proactive recommendations for safe driving and supporting the driver in the best possible way, making road transfer much more intelligent, improving traffic flow, or reducing accidents. Within the smart building domain, the focus is on effective and efficiently guided emergency evacuation and improving energy usage. The smart city supports efficient mobility and logistics, navigates the citizens and warns them about dangerous areas to reduce risks. Smart factory brings customers and enterprises together to collaborate, and actively supports the workers in improving the human-machine interaction and the workers' well being, health and the working atmosphere. Other dynamic social systems work on interaction with multiple objects at the same time, such as sending multiple requests from a device and gathering the information from different sensors in the same time.

The stages/activities identified in every CPSS analysed in this study are *data collection*, *data analysis and proactive recommendations*. Data collection is mostly achieved using diverse sensors and social networking data. Data analysis compares the current and stored data, analyses user behavior and results in active support via recommendations for a better user experience, improving the user's behavior, perception and reaction.

RQ 4: Role of human actors in CPSS A CPSS will always involve a human interaction, however this type of systems is focused on the social interactions of multiple users within a CPSS instead of a single user. This multiple users' interaction shows the importance of social networks (networks of people) in these systems. The main roles humans play in CPSS are: *social sensors*, *system users*, *decision makers*, *social actuators*. Several of the systems we reviewed in this study were related to smart buildings and crowdsensing, because CPSS can help with the exchange of knowledge between the human users efficiently thanks to the pervasive existence of mobile device. Using the social data by the CPSS to generate recommendations makes the human interaction with those systems more intuitive and more implicit.

RQ 5: CPSS Data sources As most of the explored CPSS provide only an abstract approach it is often difficult to predict which concrete data source will be used by an implementation. Examples for typical data sources are physical sensors from mobiles and social networks like Twitter. An overview about the different data sources shows that actual systems concentrate on the physical part and give the social part more possibilities for realisation. The role of historic data is difficult to identify because many systems rely on past events but do not explicitly mention where historic data is coming from or how it is collected. Because of the abstract view of the different approaches and many ambiguities in describing concrete implementations, future work should cover this topic again in more detail and analyse the concrete data and data sources used of the next generation of CPSS.

RQ 8: CPSS Challenges The biggest challenge discussed in the papers of this study is that by adding the additional social component in CPSS a high amount of data which is really complex to integrate and analyse is gathered. Despite the fact that it is not mentioned very often in the papers, a very big challenge in future will be to secure the CPSS and its data so that the privacy of the humans using the system is protected. Beside that, most of the papers plan to widen the experimental setup of their approach or to integrate it in other areas and domains.

12.2 Future Work

Future work will focus in completing the literature survey by reading the remaining papers and answering the research questions that are still open.

Also, work on the three components of the CPSS blueprint will be intensified by taking into account the lessons learned about the state of the art in CPSS.

Acknowledgements

We thank the six students who took part in the study: Nikolina Blagojevic, Matthias Deimel, Leonhard Esterbauer, David Hinterndorfer, Maximilian Medetz, and Hainoun Muhammad Mujahed.

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