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Sustainability in Modelling of Cyber-Physical Systems: A Systematic Mapping Study

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Abstract

Supporting sustainability is becoming an active area of research in Computer Science. This work offers the first Systematic Mapping Study (SMS) on sustainability of Cyber-Physical Systems (CPS) to provide an overview of the research area by identifying the associated relevant primary studies, research results, and limitations. Specifically, the goal of this study is to search for modelling approaches to build CPS, approaches for sustainability, modelling approaches considering sustainability of CPS, and reported application domains.

Our search queries were build based on a PICOC analysis and updates of the search queries offered by relevant related work. These queries were thoroughly tested in the chosen digital libraries and validated in a workshop with experts of the NOVA LINCS research centre with significant experience in performing and evaluating systematic reviews. These search queries were executed in four reliable and commonly used digital libraries, particularly, the ACM, IEEE, SPRINGER and Science Direct. We assessed the results of the automatic searches in each database in the period of 2011 to 2017, retrieving a total

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of 1262 candidate primary studies. After reading the abstracts we selected 489 papers to be fully read. The full-text analysis and application of the inclusion, exclusion, and quality criteria resulted in removing 223 papers and selecting 266 for final data extraction. Its output is a set of modelling approaches, methods, tools, and application domains. Our analysis identified limitations and research gaps, which form the base for a future research agenda. We end the paper with a call for academics and practitioners for further investigation in four major topics: modelling of CPS, tool support, deeper understanding of the five sustainability dimensions, and modelling of sustainable CPS.

1. Introduction

Industry 4.0 is a growing technological revolution towards automation impelled by Internet of Things (IoT) devices, cloud computing, artificial intelligence, and Cyber-Physical Systems (CPS). This work focuses in the particular case of CPS, defined as those systems that integrate computation, networking, and physical processes [1]. CPS monitor and control complex physical processes and are formed by large communicating networks with possibly heterogeneous sensors and actuators. One of the key concepts of CPS is to manage complex feedback loops between the physical and the cyber worlds with specific intents considering their physical environment [2]. An example would be a smart office where the system aims at improving the energy consumption of the room [3].

Despite the growth of CPS, lead time and cost efficiency continue to be essential for industry competitiveness. Extensive use of modelling and simulation throughout the value chain and system life-cycle is one of the most important ways to effectively target those challenges. Nevertheless, dealing with the increasing complexity and multidisciplinary nature of CPS development is also challenging [4]. Thus, it is paramount to understand the current state of the art of modelling methodologies for CPS.

The systems that are being developed have increasing demands of sustainability, dependability and usability. On the other hand, large-scale and in-

creasingly software-defined systems in power-grid and factory automation are long-lasting, which requires their sustainability. It is thus also important to understand the current techniques that address the sustainability of CPS. A *sustainable CPS* is a system capable of enduring without compromising requirements of the system while renewing the system's resources and using them efficiently [5]. In fact, sustainability is one of main challenges for CPS [5]. Note, however, we are not focused on the definition of sustainable development proposed by the United Nations [6] which refers to the need of considering the economic, social and environmental dimensions when solving problems of the present, while guarantying that the needs of the future generations are not compromised. Although this is a very relevant problem for the humanity, it is not the purpose of this work. Instead, our goal is to offer an overview of the existing sustainability approaches that can be used in CPS modelling.

In this work we present a Systematic Mapping Study (SMS) that identifies a set of modelling approaches, methods, and tools, as well as a list of the considered application domains and usage limitations. Although there are many systematic mapping studies and literature reviews on different topics of software engineering, so far none has been conducted to investigate the relation between sustainability and modelling of CPS. This is relevant as sustainability is becoming a key concern in system development in general and CPS in particular [5].

Our mapping study objective is divided into four research questions. The first research question is about the existing modelling approaches for CPS. We document tools, (meta-)models, and processes that can be used to characterise CPS modelling approaches, independently of their consideration for sustainability. We then search for approaches to handle sustainability that can be applied to CPS. We record methods, metrics and models used to address sustainability of different kinds of systems. This allows us to report approaches for sustainability that may be used for CPS. With the third question we want to distinguish between domain-specific and general-purpose approaches, registering the different domains addressed. This is an important aspect as many

approaches related to CPS are domain specific and may not generalise. The final research question serves to identify existing modelling approaches for addressing sustainability of CPS. Although these primary studies may already appear in the previous questions, highlighting them gives us a clear picture of the combination of modelling and sustainability of CPS.

We found several works proposing modelling approaches for CPS, but many were not properly validated, raising doubts regarding their usefulness. Therefore, it is clear from our study that more validation and validation methodologies are necessary. It is interesting to confirm that UML-like and dataflow models are the most common for modelling CPS, and that Simulink, Modelica and UP-PAAL are the preferred tools. There are only a few modelling approaches for sustainability, and the results show that the technique most commonly used is automata and the modeling approach is life-cycle analysis. This, this is definitely a topic deserving further attention from the research community. The sustainability sub-characteristics mostly addressed are efficiency and resilience. Regarding application domains, the most common are smart manufacturing, critical infrastructure and building automation, and about 89% of the domain-specific studies address at least one of the main application domains. Our study identifies several other gaps and limitations, which were the base for a research agenda, challenging academics and practitioners for further investment ranging from modelling of CPS and tool support, to a deeper understanding of the five sustainability dimensions and their impact on modelling of sustainable CPS.

This paper is structured as follows. Section 2 introduces CPS and their sustainability, as well as related work. Section 3 describes our research method, and Section 4 presents and analyses the results. Section 5 discusses threats to validity, and Section 6 proposes a research agenda that emerged from the weaknesses and gaps identified during our study. Finally, Section 7 concludes the paper.

2. Background and Related Work

As the goal of this work is to offer a broad understanding of the existing modelling approaches addressing one or both topics of cyber-physical systems modelling and sustainability, this section starts with an overview of the base concepts and follows discussing the secondary studies focusing on these topics.

2.1. Background

Cyber-Physical Systems. Cyber-physical systems are systems that integrate computation, networking, and physical processes [1]. CPS monitor and control complex physical processes and are formed by large communicating networks with possibly heterogeneous sensors and actuators to achieve that. The key idea of CPS is to manage complex feedback loops in between the physical world and the cyber world with specific intents considering their physical environment [2].

Dealing with the increasing complexity and multidisciplinary nature of CPS development is challenging [4]. Typically, these systems require heavy simulation before implementation, for prediction, and for design and run-time decision support. Different disciplines such as Electrical Engineering, Mechanics, Physics, Software Engineering use different approaches, tools and modelling techniques to cope with this complexity. Examples of CPS include smartphones or wearables, industry 4.0 (e.g. with the massive introduction of robots for assisting humans in production lines), society 5.0, or smart buildings (e.g., smart offices, living assistance).

Recent research efforts such as the ones taken by the project Multi-Paradigm Modelling for Cyber-Physical Systems (MPM4CPS) [7] are focused on tackling the inherent complexity of large-scale and complex systems into different levels of abstraction and views. This should be addressed with rigorous models, expressed in an appropriate modelling formalism. Model-driven development (MDD) is a widely used approach for software engineering, where the system to be implemented is first abstracted into a model that can be (formally) verified and eventually used to simulate the system. Currently, most of the software sys-

tems developed can be thought of as CPS as most of them consider the physical world as first-class citizens in their implementation.

Sustainable Software and CPS. There are two ways of defining *sustainable software* [8]: *i)* the software code being sustainable, agnostic of purpose, and *ii)* the software purpose being to support sustainability goals, that is, improving the sustainability of humankind on our planet. Ideally, both interpretations coincide in a software system that contributes to more sustainable living. Therefore, in our context, sustainable software is energy-efficient, minimises the environmental impact of the processes it supports, and has a positive impact on social and/or economic sustainability. These impacts can occur directly (energy), indirectly (mitigated by service), or as rebound effect [8].

A *sustainable CPS* is a system capable of enduring without compromising requirements of the system while renewing the system’s resources and using them efficiently [5]. A highly sustainable system is a long-lasting system which has self-healing and dynamic tuning capabilities under evolving circumstances [5]. Gunes et al. address sustainability as one of main challenge for CPS [5].

2.2. Related Work

This related work section discusses the existing secondary studies addressing sustainable CPS (or software in general) and modelling of CPS. These studies were found during the planning phase where we collected general information about the topics and discovered some of these works. They were also gathered during the classification phase, where secondary studies relevant to the topics were grouped specifically to construct this related work section. In the end, we collected 46 paper potentially discussing related work. These papers were then distributed by 3 authors who analysed them to decide if indeed they were related work. In this phase, we were looking for secondary studies discussing at least one of the following topics: CPS (e.g. technologies, application domains), CPS modelling, sustainable software, sustainable CPS, sustainable software/CPS modelling. From these 46 papers, 2 focus on CPS (not necessarily their modelling), 3 focus on modelling CPS, 3 discuss CPS while also

discussing some perspective of modelling CPS, 6 study sustainable (software) systems, and 3 papers discuss particular kinds of CPS and their sustainability, making a total of 17 papers. In fact, none of these works approached modelling of sustainable CPS as we do, this reinforcing the need for our work. Table 1 summarises our findings, which we discuss in the next paragraphs.

Table 1: Classification of found secondary studies with similar aim to ours

Paper	CPS	CPS Modelling	Sustain.	Summary: focus of the study
[9]	X			IoT, CPS, and cloud computing in the intelligent manufacturing.
[10]	X			Maintenance in industrial context, and the challenges of CPS maintenance.
[11]		X		The use of modelling in Industry 4.0.
[12]		X		Challenges and current developments for sensing, smart and sustainable enterprises.
[13]		X		Modelling of critical physical and information systems.
[14]	X	X		Challenges and corresponding technologies for designing CPS.
[15]	X	X		Design and development methodology of CPSs.
[16]	X	X		Modeling Cyber-physical-socio-intelligence.
[17]			X	ICT of urban forms.
[18]			X	Digitisation of a food package's life cycle.
[19]			X	Sustainability in manufacturing operations scheduling, focusing on Energy Efficiency.
[8]			X	SE methods for sustainable software.
[20]			X	Resilience of IT and Computer Systems.
[21]			X	Sustainability in manufacturing scheduling.
[22]	X		X	Smart grids and aspects of sustainability.
[23]		X	X	Sustainable interoperability in networked enterprise information systems.
[24]	X	X	X	Multi-agent management of distributed energy resources.

CPS and CPS Modelling. The first two studies in Table 1 address CPS only. Zhong et al. [9] provides a review of CPS associated topics (e.g. intelligent manufacturing, IoT-enabled manufacturing, and cloud manufacturing) and reviews the key technologies used to enable intelligent manufacturing (e.g. IoT, CPS, cloud computing, big data analytics (BDA), and information and communications technology (ICT)). Roy et al. [10] discusses existing work on maintenance in an industrial/hardware production environment. Given the rise of Industry 4.0, it also discusses the implications of looking at industry through the lenses of CPS. In this context it mostly discusses open challenges of the use of IoT in industrial contexts, including sustainable issues as security.

The next three studies, [11], [12], and [13], focus on CPS modelling only. The work presented by Wortmann et al. [11] extends their previous mapping study of modelling languages in Industry 4.0, completing it with more recent works. Chen et al. [12] present the challenges and current developments for sensing, smart and sustainable enterprises, termed S^3 enterprises. The discussion is based on five viewpoints, namely enterprise, information, computational, engineering and technology. For each of these viewpoints they present existing modelling approaches. As S^3 enterprises can be seen as a CPS, a common solution for modelling CPS is to divide the system and use different methods to model each part. Svendsen et al.'s work [13] reviews the modelling approaches for critical infrastructures including physical systems and information systems.

The following three papers address CPS, but also address the topic of CPS modeling. The intent of [14] is to contribute to a model-based research agenda in terms of design methods, implementation technologies, and organisation challenges for the design and operation of CPS. The paper focuses on the challenges of modelling CPS and corresponding technologies. The study [15] reports on a survey overviewing different types of systems and the associated transition process from mechatronics to CPS and cloud-based (IoT) systems. Also, challenges related to CPS-design are considered from the perspectives of the physical processes, computation and integration.

Sustainable Systems. The following six papers in Table 1 address some form of sustainable systems, but not necessarily CPS or even modelling sustainable systems. Bibri et al. [25] present a literature review addressing the ICT of computing for sustainable urban forms. Even though they consider the models of sustainable cities, their focus is not on embedded systems, CPS, and their modelling. The Systematic Literature Review (SLR) by Vanderroost et al. [18] focuses on the food packaging life-cycle to improve efficiency in terms of food loss, material usage and operational costs. It mentions and revises CAD/CAM approaches and identifies the lack of the sensing part in the CPS, such as using image recognition. In [19] it is discussed the steps to solve sustainable manufacturing operations scheduling problems, concentrating in off-line scheduling and ignoring the system's reactivity. It discusses the still wide gap between research and industrial needs. The works analysed are essentially focused on energy efficiency. Penzenstadler et al. [8] present a SMS on software engineering methods for sustainability. The authors consider sustainable software the artefacts that fit in both categories: (i) software (code) that is sustainable itself and (ii) software which purpose is to support sustainability goals. There is a some intersection between this work and ours, as the authors answer the question how is sustainability supported and in application domains. However, the previous work reports studies only up to 2013. Moreover, our focus is on sustainable CPS while theirs is on software engineering methods. The next study [20] provides a condensed description of a roadmap for research in technologies for assessment, measurement and benchmarking (AMB) of the resilience of information, computer and communication systems. The last paper [21] of this group presents an SLR on scenario-based evaluation methods for sustainability support and metrics according to design principles for the sustainability of the system's architecture. The study identifies the need for more empirical studies on architecture evaluation that combine metrics and methods to determine its applicability.

Sustainable CPS. The final three studies from Table 1 focus on the combination of CPS and sustainability. Camarinha-Matos [22] presents a survey on smart grids, discussing several aspects of smart grids, including some aspects of sustainability as security, resilience and self-healing. Contrary to our work, his focus is on a particular kind of CPS, in this case, smart grids. In [23], the authors present a review of the research effort in enterprise information systems (EIS) (not necessarily CPS) interoperability and MDD for the purpose of network interoperability sustainability. They conclude that the future of EIS needs to be properly monitored and controlled to enable a sustainable innovation and highlight models and model-driven as a means for improved support for reasoning over semantics. Finally, in [24], the authors present review work on models taxonomy, with ontologies, of urban and smart-grid concepts, while discussing the possible architectural choices. The study compares recent energy management research, components and structures. The concerns are related to capacity and energy efficiency. It identifies future research areas to make the transition to this future energy management systems.

3. Research Method

To create a comprehensive overview of a given research area, Evidence Based Software Engineering (EBSE) provides two core tools for evidence-based studies: Systematic Literature Reviews (SLRs), focusing on identifying the best practices on a given topic based on empirical evidence, and Systematic Mapping Studies (SMSs), aiming at creating a comprehensive overview of a given research area [26, 27]. The goal of this paper is to perform a SMS to **identify and analyse modelling approaches for CPS and their sustainability**. To achieve this goal, we systematically investigated the existing research literature on both topics in the period 2011-2017. The quest is to identify model-driven methods and implementations that lend themselves to a more systematic change tracking, self-healing, dynamic tuning and well-use of resources of CPS, to summarise the state-of-the-art research trends, and to categorise the selected approaches,

techniques, tools and methods for assessing and improving the sustainability of CPS.

3.1. Search Design and Process

The design process suggested by Kitchenham [27] was preceded with a *pre-planning* step to search for existing systematic studies and surveys related to sustainability or modelling of CPS to (i) confirm the need for our SMS and (ii) analyse the protocols from the related studies to strengthen and complement our own study. This complete process is summarised in Figure 1.

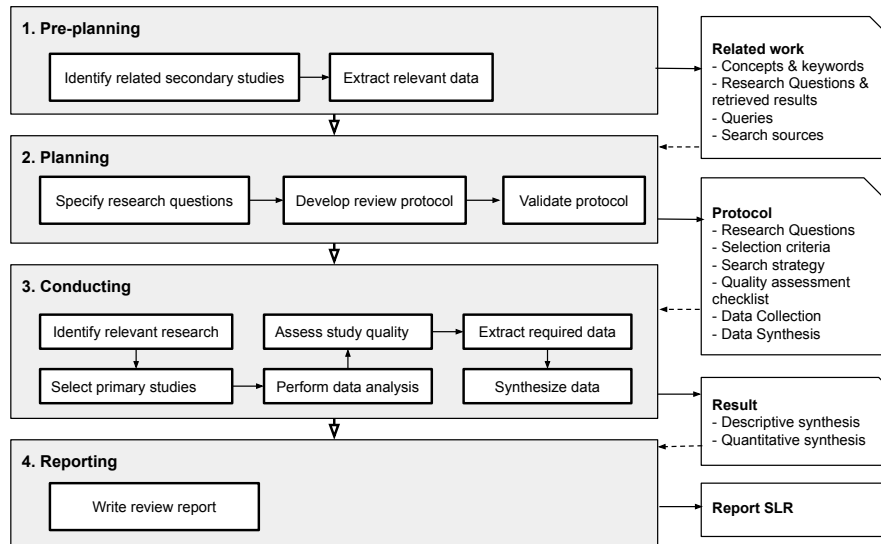


Figure 1: Review process overview based on [27]

In the *planning phase* we specified research questions and performed a PICOC (Population, Intervention, Comparison, Outcome, Context) analysis. Then, we developed the review protocol by defining the search strategy, selection criteria, quality assessment checklist and data extraction strategy. Finally, the protocol was validated in a closed workshop with seven experienced researchers in executing SLRs and SMS, which ended with a survey. During the *conducting phase*, the study selection process was executed by automatically searching for relevant primary studies. One reviewer read the titles and abstracts to decide

on their inclusion or exclusion according to a set of pre-established selection criteria. In case of doubt regarding a study’s admissibility, more of its content was read until a decision was made, always aiming at increased inclusiveness. The selected articles were distributed further among seven reviewers to be fully read, classified based on a quality assessment checklist, and their content was recorded according to the data extraction strategy. Papers not conforming to the inclusion criteria would be excluded from the data extraction process. If a reviewer was unsure about a paper, this would be reassigned for assessment to another reviewer. Finally, the *reporting phase* was fundamental for reasoning about the findings and performing a thorough evaluation of the extracted data from the previous phase in order to validate the fitness of the obtained results. Indeed, the inputs provided from the reviewers during the data analysis were re-validated. The process ended with the analysis of the threats to validity of the study. The comprehensibility of the report resulting from this phase reflects the quality of the performed systematic review.

3.2. Pre-Planning: Existing Work Shaping our Research Questions

The goal of the pre-planning phase was to identify existing systematic studies on our topics of interest. To accomplish this, we performed a thorough search in Google Scholar using a combination (and variants) of the keywords “sustainability”, “cyber-physical systems”, “energy-efficiency”, “modelling of cyber-physical systems”, “systematic literature review”, “systematic mapping” and “survey”. The first useful result from this activity was to confirm that no systematic reviews investigating the relation between sustainability and modelling of CPS existed. The second result was a list of seven systematic studies [21, 28, 8, 29, 30, 31, 5] (in Table 2) that were used to extract relevant research questions, fundamental keywords and concepts, a set of queries that were used to strengthen and complement our own, and the digital libraries more relevant for our search.

Table 2: Existing systematic studies on topics of interest

Paper	Year	Topic	Type
[21]	2011	Sustainability of software architectures	SLR
[28]	2012	Sustainability in software engineering	SLR
[8]	2014	Sustainability in software engineering	SMS
[29]	2013	Software sustainability measures	SLR
[30]	2015	Energy-efficient networking solutions	SMS
[31]	2016	CPSs security	SMS
[5]	2014	Applications and challenges in CPS	Survey

Table 3: Research questions from related studies

Paper	RQ	Research Question	Data Retrieved
[21]	RQ1	How do scenario-based architecture evaluation methods used in industry support sustainability evaluation?	Method
	RQ2	Which architecture-level metrics have been proposed to analyse the sustainability of software architectures?	Metric
	RQ3	What implications can be derived for the industrial and research communities from the findings?	Suggestions
[28]	RQ1	How much activity was there in the last 20 years (1991-2011)?	List of relevant studies by year and publication type
	RQ2	What research topics are being addressed?	Taxonomy with dimensions based on the degree of domain specificity
	RQ3	What are the limitations of current research?	High complexity and domain specificity, missing SE reference framework
	RQ4	How is sustainability support performed?	Models, methods and metrics
	RQ5	Which methods are in use?	Categorization
	RQ6	Are there case studies available?	List of case studies
	RQ7	Which domains are already considered?	Taxonomy of application domains
[8]	RQ1	What research topics are being addressed?	Topics by knowledge areas
	RQ2	How have these research topics evolved over time?	Boost from 2011
	RQ3	How is sustainability support performed?	Models and methods

Continued on next page

Table 3 – continued from previous page

Paper	RQ	Research Question	Data Retrieved
	RQ4	Which of those models and methods are used in practice?	Evaluation and experience reports
	RQ5	Which research type facets have been considered in the contributions?	Correlation of knowledge areas and research types
	RQ6	Which application domains have been considered?	Studies by application domains
	RQ7	Which research groups are the most active and what is the distribution between academics and practitioners?	Author network sub-graphs
[29]	RQ1	How much activity was there in the last 20 years?	Boost from 2011
	RQ2	Are there software sustainability measures and indicators proposed in the literature?	Measures per quality characteristics
	RQ3	What sustainability aspects have been paid more attention?	Measures per product quality characteristics
	RQ4	What are the limitations of current research?	Limited number of measures, especially for sustainability in use
	RQ5	Are there measures proposals that fit on the 25010+S model?	Keyword cloud
[30]	RQ	What are the energy-efficient networking solutions in cloud-based environments?	Lists of solutions per strategy, Technologies per scale and Evaluation methods per scale
[31]	RQ1	What are the publication trends of research studies on CPSs security?	Distribution of studies by years, type of publication and institution
	RQ2	What are the characteristics and focus of existing research on CPSs security?	Distribution of studies by application area, point of view, security attributes, system components, process and measurement noise
	RQ3	What are the validation strategies of existing approaches for CPSs security?	Distribution of studies by research type, research method and simulation test system
[5]	Q1	Application domains	Categorisation and definitions
	Q2	Challenges	Categorisation and definitions

3.2.1. Research Questions from Related Studies

We extracted all the keywords and definitions of the concepts from the above related studies. Furthermore, we collected all the research questions from those studies together with the major highlights, as shown in Table 3. Five studies address sustainability concerns in software engineering in general [21, 28, 8, 29, 30] or, more specifically, software architectures [21] or networking solutions in a cloud-based environment [30]. These studies retrieve methods and metrics for sustainability. These methods were used as the categories in our protocol and the metrics are further analysed in the result analysis section of Section 4 in relation to their appropriateness to be used in a context of CPS.

Koziolok et al. [21] retrieve two scenario-based architecture evaluation methods and over 50 architecture based sustainability metrics. Penzenstadler et al. [28],[8] find that approaches supporting sustainability are limited as they miss software engineering reference framework and have a tendency to be domain-specific and are highly complex. They provide a categorisation of 14 sustainability methods and models and highlight a boost of the sustainability-related research from the year 2011. The authors conclude that there is little research coverage on the different aspects of sustainability in software engineering while other disciplines are already more active. Calero et al. [29] also confirm boost of sustainability research after the year 2011. The study found 82 sustainability measures defined in the literature of which 17 fit in the 250101+S quality model and the top-five sustainability-related quality characteristics: Performance efficiency, Maintainability, Portability, Usability and Reliability. Moghaddam et al. [30] reports 11 strategies, 10 solutions, 10 technologies and 4 evaluation methods for energy-efficient networking solutions in a cloud-based environment. The remaining two studies are related to CPS. Lun et al. [31] lists publication trends, characteristics and validation strategies for CPS security. Gunes et al. [5] provide a categorisation of application domains for CPS. This work highlights sustainability as one of the important challenges to be addressed within the CPS field, thus supporting the need for our work.

3.2.2. Search Queries and Sources from the Related Studies

The related studies queries were analysed and used to complement our own. Table 4 summarises the findings and the covered period.

Table 4: Search strings from related studies

Paper	Search string	Period
[21]	software architecture AND (evolvability OR evolution OR maintainability OR maintenance OR ‘qualitative evaluation’ OR ‘quantitative evaluation’ OR ‘scenario-based evaluation’ OR metrics OR modifiability OR modularisation OR sustainability)	till 2011
[28]	(sustainab* OR environment* OR ecolog* OR green) AND (software engineering OR requirement OR software system)	1991-2011
[8]	(sustainab* OR ecolog* OR green) AND (software engineering OR requirement* engineering OR requirement* specification OR software specification OR system specification)	1989-2013
[29]	(sustainab* OR environment* OR ecolog* OR green) AND (software measure* OR software metric* OR software indicators)	2003-2014
[30]	routing ‘data-center’ network cloud (intitle:energy OR intitle:power) -intitle:mobile -intitle:telecom -intitle:wireless -intitle:hoc -intitle:radio -intitle:smart	2008-2013
[31]	((('cyber physical' OR 'cyber-physical' OR cyberphysical OR 'networked control') AND system*) OR CPS OR NCS) AND (attack* OR secur* OR protect*)	2006-2015

The query defined by Koziolok et al. [21] was found to be very general and tight to the term of software architectures, relating to ours with the term ‘*sustainability*’. Regarding Penzenstadler et al.’s [28] and [8], their search string ‘(sustainab* OR environment* OR ecolog* OR green)’ is very complete for sustainability search. The same set of keywords was used by Calero et al. [29]. Penzenstadler et al. [28] also use the search string ‘(software engineering OR requirement OR software system)’ to restrict obtained studies to the topic of software engineering. We target to obtain the subset of software engineering topics related to modelling of CPS, so we can reuse the same search string to restrict our results. Moghaddam et al. [30] use a general query oriented to network-based cloud solutions, which is out of the scope of our study. Finally, Lun et al. [31] use ‘(‘cyber physical’ OR ‘cyber-physical’ OR cyberphysical OR

‘networked control’), from which we did not use ‘networked control’ as it was found too general.

Finally, the search sources are listed in Table 5. Most of the studies performed an automatic search in the ACM Digital Library (ACM), IEEE Xplore (IEEE), Science Direct (SD), Springer Link (SL) and Web of Science (WS). Koziolok et al. [21] also considered Google Scholar (GS) and Elsevier (EL) indexing systems, while Penzenstadler et al. [8] took into account DBLP, INSPEC, JSTOR, arXiv, Wiley and Citeseer. Manual search was performed following some venues (ICT4S, GREEN, RE4SUSy, HiCoNS, IJCIP and ISRCS) that did not show in the indexing systems.

Table 5: Search sources from related work

Used in	Automatic search	Used in	Manual search
[21], [28],[8],[29], [31]	ACM	[8]	ICT4S’13,
[21], [28],[8],[29], [31]	IEEE	[8]	GREENS’13
[21], [28],[8], [31]	SD	[8]	RE4SuSy’13
[21], [28],[8], [31]	SL	[29]	GREENS’12
[21]	GS	[29]	RE4SuSy’12
[21]	EL	[31]	HiCoNS
[28],[8], [30], [31]”	WS	[31]	IJCIP
[8]	DBLP	[31]	ISRCS
[8]	INSPEC		
[8]	JSTOR		
[8]	arXiv		
[8], [31]	Wiley		
[8]	Citeseer		

3.3. Planing: Protocol Construction

In addition to establishing the need for performing a mapping study on sustainability for modelling of CPS, in this phase, we defined our main research questions and produced a well-defined and detailed review protocol. The produced protocol has been further evaluated and refined according to the obtained feedback.

3.3.1. Research Questions

Our research questions were derived from the PICOC analysis (Table 6).

Table 6: PICOC analysis

PICOC	Definition
Population	The set of studies reporting on works for modelling CPS and/or approaches for sustainability, preferably applied to CPS. No specific industry, system or application domain was considered.
Intervention	Reports of methodologies for sustainability assessments, namely reporting on CPS, and software products applicable to CPS. We also search for supporting methodologies, tools, technologies, and procedures for CPS modelling while taking in consideration sustainability concerns (e.g. energy efficiency, resilience, accessibility, etc.).
Comparison	Not applicable
Outcomes	Techniques, methods and metrics that can be used to address the sustainability of CPS during their modelling/design phase.
Context	All practitioners: Academy and Industry

The overall objective of our study is to **offer an overview of the current state of the art of approaches supporting the modelling of CPS regarding the sustainability concerns**. Thus, our goal is to *identify the major contributions regarding modelling approaches, processes, metrics, tools and case studies*. This is synthesised in the following research questions:

RQ1 Which modelling approaches exist for building CPS?

RQ2 Which approaches for addressing sustainability exist?

RQ3 Which application domains have been considered?

RQ4 Which modelling approaches for addressing sustainability of CPS exist?

The objective of **RQ1** is to analyse and classify primary studies reporting on modelling of CPS. We expect to retrieve the type of models used to describe the approach or system, the list of modelling languages and tools developed to support the approach or used by the reported approach, and the systematic process, if any, supporting the given approach. The objective of **RQ2** is to analyse and classify all the existing approaches for addressing sustainability and to identify those that are (or can be) applied to CPS. We expect to retrieve the methods (techniques) used by the approach, as well as metrics and sustainability models. The objective of **RQ3** is to retrieve the application domains and then

analyse the coverage of specific case studies addressed in the primary study. We distinguish approaches to be domain specific if they are developed just for a concrete application domain; otherwise we find it to be general purpose. Finally, the **RQ4** objective is to identify existing model-driven approaches for addressing sustainability of CPS, representing an intersection of approaches for modelling of CPS (RQ1) and approaches for addressing sustainability (RQ2).

3.3.2. Search Strategy

We performed automatic searches from 2011 till 2017 in the ACM Digital Library (ACM), IEEE Xplore (IEEE), Science Direct (SD) and Springer Link (SL). These search sources are found to be the most popular, and were used by most of our the related studies discussed in Section 3.2.2 [21, 28, 29, 30, 31, 5, 8].

We defined the three following queries reusing search strings from the identified related work, and performed a test obtaining the results in Table 7.

Q1 - *(sustainab* OR environment* OR ecolog* OR green) AND (('cyber physical' OR 'cyber-physical' OR cyberphysical OR smart) AND system*) AND ('modelling' OR 'modeling') AND ('software engineering' OR requirement OR 'software system')*

Q2 - *(sustainab* OR environment* OR ecolog* OR green) AND (('cyber physical' OR 'cyber-physical' OR cyberphysical OR smart) AND system*) AND ('modelling approach' OR 'modeling approach' OR 'integrate modelling' OR 'integrate modeling') AND ('software engineering' OR requirement OR 'software system')*

Q3 - *(sustainab* OR environment* OR ecolog* OR green OR 'energy efficien*' OR 'energy-efficien*') AND (('cyber physical' OR 'cyber-physical' OR cyberphysical OR smart) AND system*) AND ('modelling approach' OR 'modeling approach' OR 'integrate modelling' OR 'integrate modeling' OR 'model driven' OR 'model-driven') AND ('software engineering' OR requirement OR 'software system')*

Table 7: Testing search queries on digital libraries (April, 2017)

Library	ACM			IEEE			SD			SL			Sum		
<i>Web</i>	dl.acm.org			ieee.org			sciencedirect.com			link.springer.com					
<i>Query</i>	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3
2011→	103	1	4	44704	15	54	3139	284	447	4439	347	414	52385	647	919
2001→	169	2	6	49188	17	58	4072	329	555	5856	449	518	59285	797	1137

Q1 retrieved a large number of papers due to the use of the word ‘modelling’. Prior to the protocol evaluation workshop, Q2 was our proposed query. One recommendation was to include variations of both ‘energy efficiency’ (for the sustainability part) and ‘model-driven’ (for the modelling approaches), resulting in Q3, which was further used in this systematic study.

Table 8: Inclusion Criteria

Id	Criteria
I1	Publication date from 1/1/2011 to 1/1/2018.
I2	Explicit mention of sustainability or sustainable system.
I3	Explicit mention of modelling approach for CPS.
I4	Papers that report a methodology, metric or model for a sustainable software system.
I5	Papers that report a methodology, metric or model for CPS.

3.3.3. Inclusion and Exclusion Criteria

To select relevant publications answering our research questions, we defined the Inclusion Criteria in Table 8. We include peer-reviewed articles, reporting on modelling of CPS or/and sustainability assessment reported 2011-2017. The Exclusion Criteria in Table 9, exclude informal literature, secondary studies, duplicated work or its extension, and works in languages other than English. The inclusion and exclusion criteria are applied during the screening phase of the titles, keywords and abstract of the primary studies. The studies selected at this stage were read fully and these criteria were applied again for the final selection of primary studies.

3.3.4. Quality Assessment Criteria

The Quality Assessment Criteria in Table 10 was used to assess the quality of the studies after the data analysis. We did not define any exclusion criteria

Table 9: Exclusion criteria

Id	Criteria
E1	Informal literature (powerpoint slides, conference reviews, informal reports) and secondary/tertiary studies (reviews, editorials, abstracts, keynotes, posters, surveys, books).
E2	Duplicated papers.
E3	Papers that do not apply to research questions i.e. do not report the method for sustainability or modelling approach for CPS.
E4	Papers with the same content in different paper versions.
E5	Papers written in other than the English language.
E6	Purely hardware, or electrical engineering perspective papers.
E7	Purely application of sustainability in environmental domains (e.g. agricultural papers).
E8	Environmental used only in the context of technical (operational) environment of CPS, and not the impact on the environment.

regarding the quality of the study, but we find it meaningful to present statistics and observe the impact of the study. Therefore, the list serves as a complement to the extracted data.

For Quality Assessment 1 (QA1) we used *CORE*², and SCIMAGO³ as secondary source. Venues not listed in these were marked as ‘Not so relevant’. For QA2 we took the number of citations reported by *Google Scholar*⁴. As the data extraction process was expected to be time consuming, the primary studies were ranked according to these two criteria at the end of the process, for efficiency. The QA3 to QA7 were criteria reflecting the quality of the approach based on the content presented in the primary study. Finally, to reflect the confidence of the reviewer, we defined two self-assessment criteria: S1 (regarding answers provided in the data extraction form in Table 11) and S2 (regarding the answers to quality assessment questions). In cases where the reviewer was not confident on a primary study, an additional reviewer was asked to make a revision and the assessment scores was discussed.

²<http://portal.core.edu.au/>

³<https://www.scimagojr.com/>

⁴<https://scholar.google.pt/>

Table 10: Quality assessment and self-assessment criteria

Id	Assessment Criteria	Scale
QA1	What is the relevance of the paper according to the conference/journal where it was published?	1 = Very relevant (A) — 0.5 = Relevant (B) — 0 = Not so relevant
QA2	What is the relevance of the citation according to its related citations?	Number of citations
QA3	How clearly is the problem of study described?	1 = Explicitly — 0.5 = Vaguely — 0 = No description
QA4	How clearly is the research context stated?	1 = With references — 0.5 = Generally — 0 = Vaguely
QA5	How rigorously is the method evaluated?	1 = Empirical foundation — 0.66 = Case study — 0.33 = Lessons Learned — 0 = No evaluation
QA6	How explicitly are the contributions presented?	1 = Explicitly — 0.5 = Generally — 0 = No presentation
QA7	How explicitly are the insights and issues for future work stated?	1 = With recommendations — 0.5 = Generally — 0 = No statement
SA1	Reviewers confidence about content of the study	1 = Very confident — 0.5 = Confident — 0 = Not very confident
SA2	Reviewers confidence about quality of the study	1 = Very confident — 0.5 = Confident — 0 = Not very confident

3.3.5. Data Extraction Strategy

After selecting the relevant primary studies by reading the title and abstract, the reviewers initiated the data extraction using a predefined and validated extraction form. The form is divided into three parts. The first part serves to collect meta-data regarding the publication (Authors, Title, Year, Venue, CitationKey (which served as a unique identifier) and URL), hence storing general information about the selected study. The reviewers' name was stored for each paper. The second part collects information that will help answering the research questions (see Table 11). Each question, except Q3.1, was expected to be answered with 'Yes' or 'No', and an extra text field was provided to extract meta-information if the question is answered with 'Yes'. For RQ1, we are identifying if the primary study reports a modelling approach for building CPS, and if it does, we register if it offers a model/meta-model, a tool or a process. For RQ2, we identify if the primary study reports an approach for addressing sustainability and if it does, we want to know if it offers a technique or method,

a metric, or a sustainability/green model. Further, we indicate which sustainability sub-characteristic is addressed by using the categorisation provided by Gunes et al. [5] or which types of sustainability technique/method was addressed for Q2.1 by using findings from Pezenstadler et al. [28] (see Table 12). For RQ3, we register if the approach is domain specific and which application domain was considered in a study, for both domain specific and general purpose approaches. We categorise the application domains according to Gunes et al. [5] (see Table 12). Finally, for RQ4 we explicitly register if a primary study reports on modelling approaches for addressing sustainability of CPS.

Table 11: Data Extraction Form for addressing the research questions

RQ1	Q1	Does the paper report modelling approach for building CPS?
	<i>Q1.1</i>	Does paper report a model/meta-model?
	<i>Q1.2</i>	Does paper report a tool?
	<i>Q1.3</i>	Does paper report a process?
RQ2	Q2	Does the paper report approach for addressing sustainability?
	<i>Q2.1</i>	Does the paper report technique/method that is used?
	<i>Q2.2</i>	Does the paper report metric?
	<i>Q2.3</i>	Does the paper report sustainability/green model?
RQ3	Q3	Is approach domain specific?
	<i>Q3.1</i>	Which application domain is addressed?
RQ4	Q4	Does the paper report modelling approach for addressing sustainability of CBS?

Table 12: Special categorisations and their mapping to some of our RQs

	Q2	Q2.1	Q3.1
1	Adaptability	Entity-relationship	Smart Manufacturing
2	Resilience	Neural networks	Emergency Response
3	Reconfigurability	Cost calculations	Air Transportation
4	Efficiency	Life-cycle analysis	Critical Infrastructure
5			Health Care and Medicine
6			Intelligent Transportation
7			Robotic for Service
8			Building automation

The third part of the extraction form collects information about the quality of the primary study and the confidence of the reviewer as specified in Table 10.

3.3.6. Protocol Validation

Prior to the SMS conducting step, we performed a protocol validation task with two goals in mind: check that the protocol addresses the goals of the SMS; solicit suggestions for improving the protocol. The protocol pre-validation was performed in a workshop meeting with the Automated Software Engineering (ASE) research group of the NOVA LINCS research centre from University NOVA of Lisbon. The protocol was presented to the group participants and the informal feedback received resulted in small changes in the protocol. The validation was then performed online using a Google survey form, with questions that required single-choice and free-form responses. In total, seven reviewers were involved. All reviewers were from academia, and they were at least knowledgeable in SLRs. Four of those reviewers authored published mapping studies and SLRs.

The reviewers agreed that the need for this SMS is justified, and that the venues, keywords, and inclusion/exclusion criteria were sufficient for performing the SMS. Furthermore, the reviewers strongly agreed that the quality assessment criteria are complete enough to achieve the SMS objectives. The reviewers agreed that the research questions cover the work objective, and suggested several clarifications that led to a better alignment between the study's goals and the research questions. Similarly, the reviewers analysed the research questions and proposed small improvements. Finally, they agreed that the data extraction form included all the necessary fields to achieve the SMS objectives. The outcome of this validation was that the SMS protocol is adequate for its goals. More details about the protocol validation can be found in Appendix A.

3.4. Conduction

In this section we detail how the primary studies were selected and how we validate the quality of the extracted data.

3.4.1. Obtaining the Data

During the conduction phase we had three main sub-activities: Query search, Abstract Review, and Classification (see Figure 2). During the Query search

activity, we execute the search string on each digital library. The first set of papers was obtained in April 2017. A second search to retrieve the papers published after this date was executed one year later, in April 2018. After removing the duplicates, we obtained 1262 papers, with Springer (SL) contributing with almost half of all papers (49.29%), followed by ScienceDirect (SD) with 44.61%. With a significantly smaller number of papers is IEEE database (5.71%) and finally ACM database (0.40%).

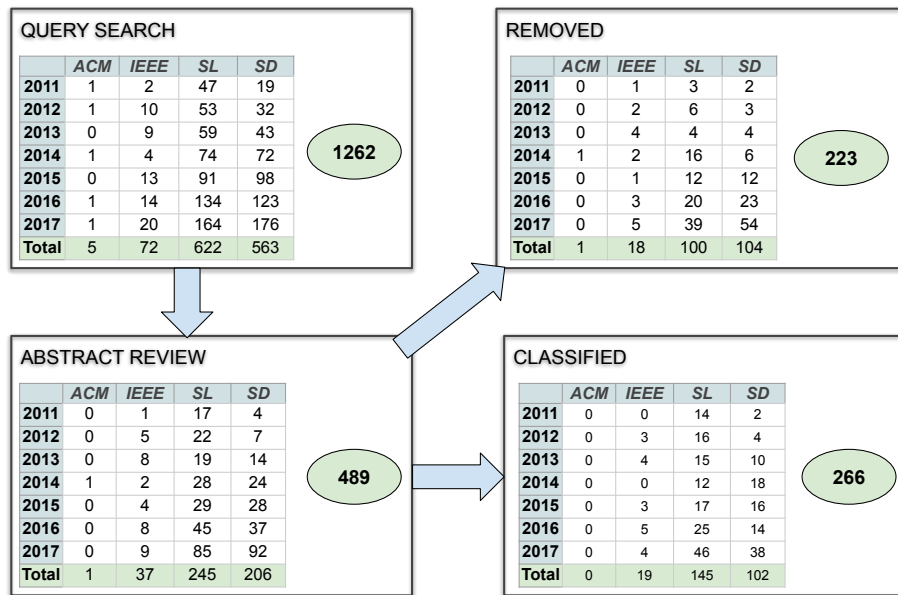


Figure 2: Conduction process and primary studies by year and library

The papers were added to an Excel workbook and their abstracts and conclusions copied there. By reading abstract and conclusions it was decided to include/exclude the study for the classification phase based on criteria presented in Tables 8 and 9. The number of papers marked for exclusion were 377 for Springer, 357 for SD, 35 for IEEE, and 4 for ACM. The rest of the papers were imported to the Mendeley library and their full text was downloaded. After abstract review, 489 primary studies were selected for classification. In the second iteration we prepared a separate individual data extraction sheet and assigned each paper randomly to one reviewer. The researchers read their papers and

decided if the paper contributed to answer Q1 (from RQ1) or Q2 (from RQ2). If the paper did not present a modelling approach for CPS (Q1) or a sustainability approach for CPS (Q2) it was excluded. Papers with ‘Yes’ for at least one of the questions were classified based on the quality assessment checklist and their contents extracted and added to the data extraction sheet (structured according to data extraction form). In total, reviewers excluded 223 papers during this iteration and classified 266 papers (145 papers from Springer (54.51%), 102 from ScienceDirect (38.35%), 17 from IEEE (6.39%), and, surprisingly, none from ACM).

We could observe the boost in the number of publications on modelling and sustainability for CPS by each year. For instance from query search we obtained 5.47% of the total 69 of papers retrieved for year 2011, this getting to 11.97% for year 2014 and, while for 2016 we had 21.55% and for year 2017 28.61%. The classified papers showed a similar trend, with 6.02% of papers for 2011, 11.28% in 2014, 16.54% in 2016 and the number almost doubled for year 2017 with 33.08%.

3.4.2. Data Quality Control

Since the process of data collection was an error-prone combination of automated and manual steps, we developed the data quality control process in Figure 3. This process involved collecting quality control information about our review process and implementing multiple checks for data integrity at each step of data collection and extraction. The process relies on the publication database (Mendeley) and three Google sheets:

- *The Library Sheet* contains a full list of papers downloaded from an external database, along with the tags of inclusion, review classification, and the reviewer’s name. This sheet serves as an initial storage of primary studies information, which is also uploaded to Mendeley along with the full text of the paper.
- *The Validation Sheet* contains meta-information about the review process that enables data validation over the data extraction sheet. The validation

sheet indicates whether individual papers, grouped by reviewer, pass the quality checks (outlined below) and whether the counts of reviewed papers match the counts of downloaded papers.

- *The Data Extraction Sheet* contains data extraction forms for each paper included in our study, as discussed in the previous sections. This information is checked by the validation sheet.

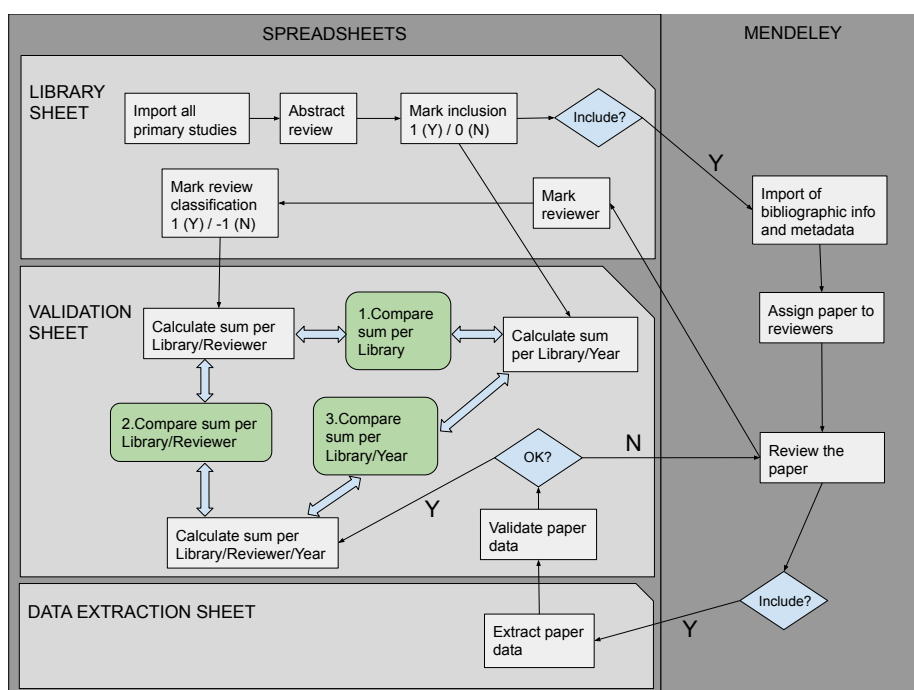


Figure 3: Data quality control process. Grey boxes are tasks, green boxes are checks, and blue diamonds are choices.

In this section we focus on the validation sheet, which served two purposes:

1. Ensure that the numbers of primary studies are consistent across multiple sheets. The validation sheet checked that every study was assigned to some reviewer, and that every study is eventually included or excluded from the review.
2. Ensure that each extraction form is complete and internally consistent.

That is, the format of each data extraction form follows the expected data schema, and that this information follows certain logical rules.

For the first purpose, the validation sheet counted the number of papers that were split into groups of papers by reviewers, years, and external libraries, as follows: papers that marked for inclusion were split based on their publication year and source library; papers marked by review classification were split by libraries and reviewers; papers from which data had been extracted were split by libraries, reviewers, and years. This resulted in multiple groups of papers. To ensure that the groups consistently split all the studies, the validation sheet compared the counts of studies by libraries, years, and reviewers, as shown in Figure 3. Once finished the review process, the validation sheet indicated that the counts of primary studies added up correctly across the sheets and Mendeley. The agreement between counts in the library sheet, the extraction sheet, and Mendeley led us to believe that all the papers were processed consistently, with a minimal risk of error or omission, due to the redundancy of our data storage.

For the second purpose (completeness and consistency of extraction forms), the validation sheet implemented several automated quality checks, which were applied to every data extraction form. All of these checks were encoded as rules on the existing data guaranteeing that the data is present and contains no contradiction within each data extraction form:

- No question (RQ1-4) or data field has an empty answer.
- No question answered with ‘Yes’ has empty answers to sub-questions.
- At least one of RQ1 and RQ2 is ‘Yes’ (otherwise, the study would have been excluded).
- If RQ1 is ‘Yes’, then at least one of its sub-questions should be ‘Yes’. Same applies to RQ2 and its sub-questions. (Otherwise, the answers should have been ‘No’.)

The result analysis phase began once all the studies were either included or excluded, and each included study passed all the above validation checks. This

approach ensured that our analysis was based on the complete data that adheres to the intended data schema. Additionally, the second reviewer performed the analysis of the papers marked with ‘not confident’ by the first reviewer, after which both reviewers made a final decision regarding the extracted data. Therefore, for all the extracted data, we have the level of confidence: Confident or Very Confident. Finally, during the analysis, one reviewer focused on the classification results for a single question, and if she/he had doubts regarding the paper classification, she/he rediscussed inputs with the original reviewer.

4. Discussion of the Study Results

The goal of this section is to detail and discuss the findings of our systematic mapping study.

4.1. Quality of the Studies

In this subsection, we present an analysis regarding the overall quality⁵ of the 266 studies classified following our quality assessment criteria shown in Table 10. For the first quality assessment question regarding the relevance of the paper according to the conference or journal where it was published (QA1), we can see in Figure 4 that over half of the articles (52.3%) were published in not so relevant venues. This may be due to the fact that the research in the area of modelling of CPS and sustainability is relatively new. Therefore, the research presented, in many cases, is not mature enough to be published in high ranked venues. However, 27.8% of the selected articles were published in conferences ranked as CORE A or higher.

In Figure 5, we present results related to the relevance of citations obtained from Google Scholar in November and December of 2018. We highlight the details concerning the performed analysis in Table 13. We register both maximum and average number of citations per year, as well as the number of pa-

⁵Note that we are not evaluating the quality of the papers. The classification is that of the event where it was published, according to the Scimago Journal & Country Rank (SJR) index for journal papers and the Computing Research and Education Association of Australasia (CORE) for conference papers.

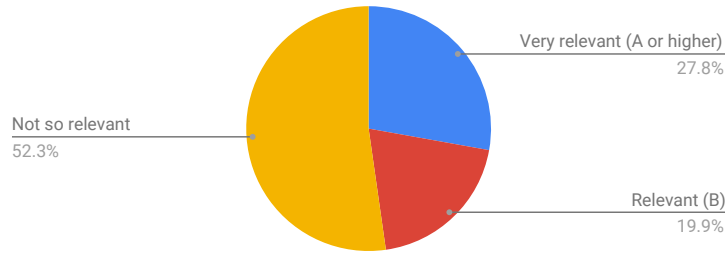


Figure 4: Percentage of articles relevance according to the venue where they were published

pers which did not have any citations. Moreover, we defined the scales dependent on the year the articles were published as **Low**: ($Year < 2016 : [0 - 5]$, $Year \geq 2016 : [0 - 1]$), **Med**: ($Year < 2016 : [6 - 12]$, $Year \geq 2016 : [2 - 6]$) and **High**: ($Year < 2016 : [> 12]$, $Year \geq 2016 : [> 6]$), and counted the number of articles per year which fit in each of these categories. We can note that around one-third of the classified articles have a low citation number, while a similar number of papers can be ranked as medium or highly cited.

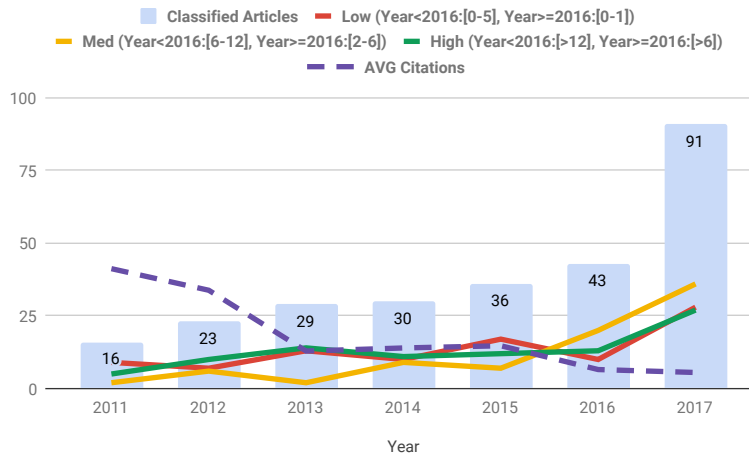


Figure 5: Relevance of papers according to their citations

In addition to the observed citations, we performed a quality assessment that considered: *i*) the content of the papers, namely the clarity of motivation and research context for the approach presented in the papers; *ii*) the completeness

of the evaluation of the presented approaches; and, *iii*) the explicitness of how contributions and future work were stated. Figure 6 a) shows the results of classifying the papers when answering to the question of how clearly the problem of the study is described (QA3). From those figures, we can observe that almost three-quarters of the selected papers (73.7%) clearly and accurately describe the problem and only 25.9% of them describe the problem vaguely. Only one article does not present the problem description in a clear way. The conclusion is that the reviewers found that all primary studies not only presented the motivation for their approach, but also this motivation was clear and specific to the problem which the study claim to address.

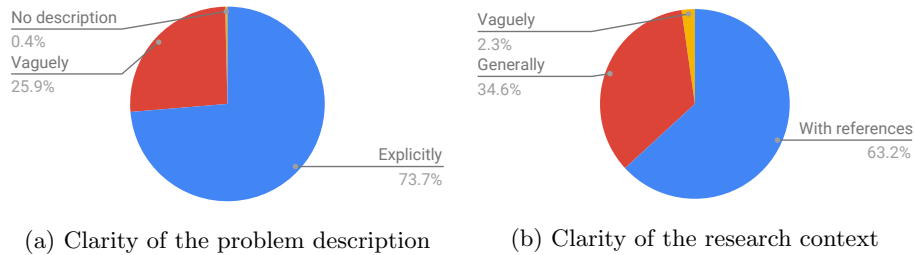


Figure 6: Classifying the clarity of the analysed papers.

Regarding how clearly is the research context stated (QA4), we can see in Figure 6 b) that the vast majority (63.2%) presents the research context with references, while 34.6% is showing it generally. The reviewers found that a negligible number of studies introduced a vague research context (2.3%). The small number mentioned means that in most of the studies not only the related

Table 13: Citations statistics

Year	2011	2012	2013	2014	2015	2016	2017	Total
<i>COUNT (articles)</i>	16	23	29	30	36	43	89	266
<i>MAX citations</i>	565	402	197	194	207	168	170	
<i>AVG citations</i>	41.25	33.83	12.9	13.97	14.72	6.53	5.53	
<i>COUNT (0 citation)</i>	2	0	3	2	3	8	12	30
<i>COUNT (Low)</i>	9	7	13	10	17	10	28	94
<i>COUNT (Med)</i>	2	6	2	9	7	20	36	82
<i>COUNT (High)</i>	5	10	14	11	12	13	27	92

work was reported, but also the lacks and advantages of the related work were identified and compared with the proposed approach.

We judge the rigour of the evaluation method used in the primary studies (QA5) based on their evaluation types. Figure 7 shows the evaluation types used to validate the proposed solution. More than half primary studies (61.3%) offered solutions that are evaluated by applying their proposal to small case studies. However, 19.2% of the papers do not report any evaluation. Additionally, only 10.9% of the presented work is evaluated empirically, although it is commonly known that those are necessary to make the proposed approaches better understood and accepted. The remaining 8.6% of the papers show the applicability of the proposal using some illustrative examples.

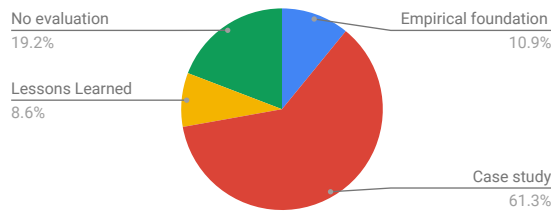


Figure 7: Rigour of the evaluation method

The quality of the contributions claimed by the selected primary studies was measured based on how explicit these same contributions address the problem (QA6). It is possible to observe that 48.5% of the papers contribute with a concrete solution and highlight the scope of their contribution clearly in the conclusions. A negligible number of papers does not present contributions (4.1%), while the remaining (47.4%) vaguely describe their contributions. Figure 8a shows these results.

Regarding mentions to future work, as we can see in Figure 8 b) one-quarter of the studies does not present any future direction (QA7), 46.2% emphasised future directions in a general way, and the remaining (28.6%) provide concrete recommendations.

From the previous figures, we can conclude that most of the primary studies motivate their problems and provide the research context. Most of the ap-

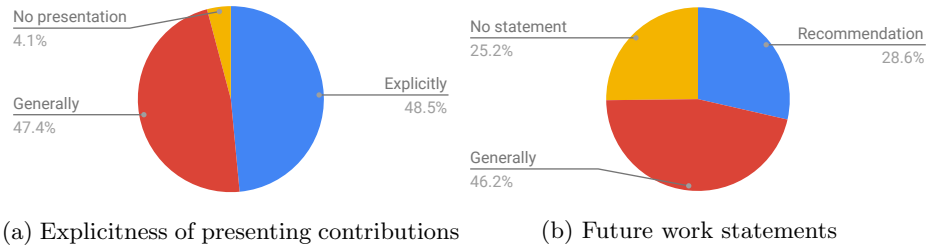


Figure 8: Analysis of the section of conclusions in the selected papers.

proaches reported by primary studies are evaluated by a case study or empirical foundations. Although in most cases the contributions are explicit, the future work is either very general or rarely reports a concrete road-map.

4.2. Modelling Approaches for Building CPS (RQ1)

The results presented in this section are related to “RQ1 – Which modelling approaches exist for building CPS?”, and sub-questions “Q1 – Does the paper report modelling approach for building CPS?”, “Q1.1 – Does paper report a model/meta-model?”, “Q1.2 – Does paper report a tool?”, and “Q1.3 – Does paper report a process?”.

A total of 233 studies (out of 266, 88.6%) introduced or used some modelling approach to CPS. From those, 199 (85.4%) used and reported explicit models, and 34 (14.6%) did not (on which we comment at the end of Section 4.2.1).

Most modelling approaches enable rigorous and automated engineering of CPS. The differences between those modelling approaches are best explained by the following two characteristics:

- *Specific purpose*: most modelling approaches are meant for simulation of CPS, analysis of CPS (including verification), or supporting engineering activities (such as defining a DSL).
- *Aspect of the system modelled*: some modelling approaches targeted the high-level interactions, whereas others focused exclusively on the physical part (e.g., modelling a plant differential equations) or digital part (e.g., modelling a software protocol behaviour with a Petri net).

Further details about the models, tools, and processes in the primary studies are presented next.

4.2.1. Approaches Reporting Model and/or Meta-Model

To identify the prevalent models and meta-models, we assigned a code (label) to each model or meta-model explicitly reported and used in a primary study, with some studies being annotated with several codes due to several models. The code represented the category of the model; for instance, we assigned the finite state machine category for primary studies that used a state machine or a state chart. In our initial coding, each study’s model was assigned the most specific label; for example, a study that relies on hybrid automata would be tagged with a “hybrid automaton” label, not a “finite state machine” or “differential equation”. The categories were iteratively merged with each other, without losing the level of specificity. To determine the higher-level categories of models, we performed axial coding over the model codes, which resulted in 11 mutually exclusive high-level categories of models:

- UML-like models are based on UML, its profiles (most prominently, MARTE) and similar languages (most prominently, SysML). This category is the largest, accounting for 18.1% of all models. The examples from primary studies include using SysML-sec for safety and security of CPS [32] and UML activity diagrams for developing industrial automation [33].
- Dataflows include models focused on data exchange, such as block diagrams, synchronous dataflow models, and Simulink models. This category accounted for 14.3% of all models. The examples include integrating multiple Simulink models for experimenting with smart grids [34] and functional units for designing automation systems [35].
- Component models include any architectural or component-based models, excluding UML-like models (which form a separate category). These models account for 13.8% of all models. The examples include using AADL as a basis for timing analysis with Polychrony [36] and using architecture

descriptions for design space exploration [37]. Together with UML-like models, the component models would be the largest category, comprised of 31.9% of all models in primary studies.

- Automata include finite state machines, hybrid automata, probabilistic state machines, and other types of automata. This category accounted for 12.3% of all models. The examples include using customised state machines called RoboCharts for verification of timed robotic controllers [38] and using stochastic hybrid systems for modelling CPS resilience [39].
- Meta-models include language syntax models, data schemas, meta-models for agent descriptions, and other models of models. This category accounts for 11.9% of all models. The examples include a meta-model of planning specifications for Industry 4.0 [40] and a netlogo meta-model of smart home devices [41].
- Equational models included explicit equation-based modelling with differential equations, optimisation problem constraints, and structural equations in bond graphs. This category accounted for 10% of all models. The examples include equational mechanical models of self-driving cars [42] and constraints between CPS components in the FORMULA language [43].
- Process models include formalisms that focus on the process of the system's evolution, such as Petri nets and process algebras, but excluding the dataflow and UML-related models from other categories. This category accounts for 4.6% of all models. The examples include the use of stochastic Petri nets for representing gas distribution networks [44] and using Timed CSP for modelling distributed real-time systems [45].
- Custom graphs include specialised graph-based models that do not fall into the UML-like, component, and process categories. This category accounts for 4.2% of all models. The examples include logistic task graphs for modelling supply networks in Industry 4.0 [46] and dependency graphs

in critical infrastructures [47]. It is worth noting that most of the other model categories can be seen as graphs.

- Specifications include declarative system descriptions such as Z and UTP that do not fall into any other groups. This category accounts for 3.4% of all models. The examples include using the Clock Constraint Specification Language (CCSL) for analysing a wind turbine [48] and using goal requirements specifications for holistic security analysis in socio-technical systems [49].
- Program-like formalisms include imperative languages similar to high-level programming languages. This category is the smallest among the named categories (i.e., except for the Other models) and accounts for 2.7% of all models. The examples include using the ABS language for railway specifications [50] and Fortran simulation models for a water reservoir system [51].
- Other models include all other types of explicitly reported models that did not fit into the above categories, and did not merit creation of another high-level category. This category accounts for 4.6% of all models. The examples include queuing theory models to maximise data centre revenues [52] and 3D geometry models for thermal analysis of multi-core systems [53].

The categories of models and their percentages among all models are shown in Figure 9. As this figure shows, the most common static models are various component and object models (including structural versions of UML-like models), and the most common dynamic models are dataflows and automata (including the behavioural types of UML-like models). The references to the primary studies can be found in Table 14.

By analysing the citations of model types (Figure 10), we found that the highest impact (average citations per study) comes from studies that use equations (mostly, differential equations). The second and third most impactful types

Table 14: Model types in primary modelling studies. Percentages are of the total count of models in all studies.

Model type	#	%	Primary studies
UML-like models	48	18.1	[54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 32, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 33, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99]
Dataflows	38	14.3	[100, 101, 102, 36, 103, 104, 105, 106, 107, 108, 109, 35, 110, 111, 48, 62, 112, 113, 114, 115, 116, 117, 37, 118, 119, 120, 33, 121, 80, 82, 122, 34, 123, 124, 125, 126, 91, 127]
Component-based	37	14.0	[128, 129, 130, 131, 36, 132, 133, 106, 134, 135, 136, 110, 48, 137, 138, 139, 37, 140, 141, 142, 75, 143, 144, 145, 122, 85, 146, 147, 34, 148, 149, 150, 151, 152, 153, 154, 155]
Automata	33	12.5	[100, 156, 131, 157, 158, 55, 159, 160, 40, 161, 38, 48, 162, 163, 62, 164, 117, 39, 165, 166, 44, 140, 167, 168, 169, 170, 80, 171, 172, 173, 95, 154, 99]
Meta-models	31	11.7	[131, 174, 175, 176, 107, 24, 159, 40, 177, 162, 178, 41, 179, 180, 118, 181, 182, 183, 184, 185, 78, 186, 187, 188, 189, 124, 190, 191, 192, 193, 194]
Equations	27	10.2	[195, 196, 197, 102, 198, 109, 35, 199, 43, 200, 113, 42, 164, 201, 117, 119, 73, 168, 202, 203, 80, 123, 124, 91, 150, 204, 45]
Processes	12	4.5	[205, 54, 206, 207, 56, 180, 44, 208, 170, 209, 210, 45]
Custom graphs	11	4.2	[47, 211, 212, 213, 214, 215, 187, 216, 46, 217, 218]
Specifications	9	3.4	[219, 58, 48, 43, 49, 84, 147, 90, 91]
Programs	7	2.6	[220, 109, 199, 51, 50, 123, 149]
Other models	12	4.5	[55, 179, 201, 52, 221, 170, 222, 80, 223, 53, 224, 210]
<i>No model reported</i>	34	<i>n/a</i>	[225, 226, 157, 227, 228, 229, 230, 231, 232, 233, 138, 234, 235, 142, 33, 214, 145, 236, 21, 237, 238, 85, 209, 239, 223, 240, 241, 242, 243, 244, 127, 210, 245, 99]

of models are dataflows (mostly, Simulink) and program-like models. This finding suggests that either these model types are particularly successful in CPS modelling, or that other model types have not been explored yet.

The 34 modelling studies that did not report models explicitly turned out to have inferior quality characteristics, compared to those that reported models explicitly. In terms of the numeric scales of Table 10, the average citation relevance was 0.63 (vs. 0.8 for those reporting models explicitly), evaluation rigour was 0.41 (vs. 0.56), and explicitness of presentation was 0.64 (vs. 0.73) — all lower than the parenthetical averages for the studies with explicit models.

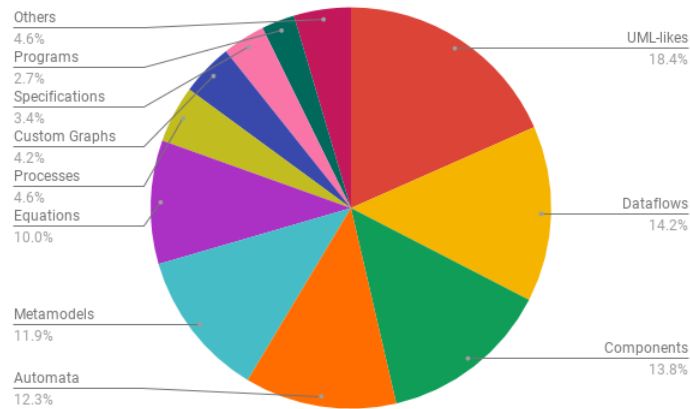


Figure 9: High-level categories of models. Percentages are of the total count of models in all studies.

These comparisons were all shown to be statistically significant with an unpaired t-test, $p < 0.001$. Our interpretation is that model-based studies benefit in quality from explicit reporting of models.

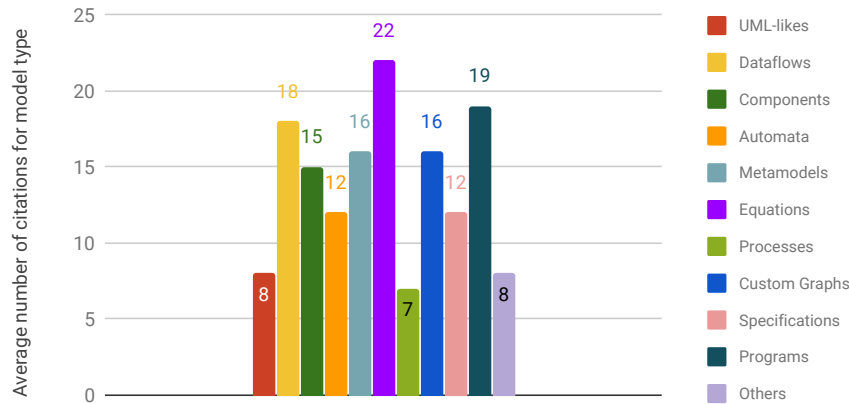


Figure 10: Average citations per model type

4.2.2. Tools Developed and Used in Modelling Approaches

Of the 266 total number of primary studies included in our analysis, 129 (48.5%) were reported using some tool, while in 139 studies (52.3%) authors did not report using a tool. Please note that we considered only papers in

which authors explicitly emphasised using some tool (whether developed by the authors or an existing tool). Thus, if a paper simply mentioned that a tool could be used, it was not included in our analysis and was marked as not reporting a tool. We were looking for papers that explicitly emphasised the use of tools in modelling some part of a CPS system.

Relative to the total number of studies that reported using some model, 200 studies (75.2%) were found and more than half of them, 121 studies (60.5%), reported both using models and tools. In 56 (46.2%) of those 121 studies, authors reported their developed tool or extension of some existing tool. These tools can be divided in 4 categories:

- Eclipse based/Papyrus based. This category contains the tools that are built based on the Eclipse platform. The smallest number of tools belong to this category with 12 (9.9%) of 121 papers that reported model and tool.
- SysML/UML/MARTE based. This category contains profiles that are developed as extension of SysML/UML/MARTE model. This category accounts for 13 (10.7%) of 121 papers that reported model and tool.
- Matlab/20-sim/Simulink/Modelica/UPPAAL based. This category contains tools that present some extensions or use general propose modelling tools like Matlab, Simulink, Modelica and UPPAAL. This category accounts for slightly more than the previous categories, 19 (15.7%) of 121 papers that reported model and tool.
- Custom tool. The largest group of tools is the one where a tool is developed either using some general purpose language (e.g. Java) or present an extension to some other custom tool. This category accounts for the largest number of papers (77 papers or 63.6%).

The references to the primary studies reporting both models and tools can be found in Table 15.

Table 15: Primary studies by tool type.

Tool type	Primary studies
Eclipse based/Papyrus	[171, 159, 95, 110, 135, 34, 121, 185, 190, 74, 79, 83]
SysML/UML/MARTE	[187, 113, 123, 103, 126, 73, 90, 63, 89, 93, 68, 246, 247]
Matlab/20-sim/Simulink/Modelica/UPPAAL	[168, 44, 162, 139, 37, 109, 127, 91, 124, 203, 71, 81, 72, 167, 48, 154, 164, 169, 154]
Custom tool (other)	[172, 38, 160, 80, 161, 62, 55, 170, 40, 165, 131, 140, 151, 147, 150, 148, 146, 152, 75, 136, 155, 134, 36, 143, 131, 140, 149, 137, 218, 216, 217, 115, 118, 116, 43, 180, 189, 183, 181, 176, 179, 175, 184, 177, 118, 41, 194, 186, 40, 188, 224, 221, 53, 50, 206, 56, 207, 170, 49, 58, 219, 32, 88, 248, 60, 99, 61, 66, 87, 67, 249, 250, 251, 252, 253, 254]

According to the reported tools, we can conclude that there is a large number of tools for modelling CPS systems. by the significant number of papers reporting developed tools.

Contrary to our expectations, only 15.7% of the papers use well-known tools for modelling CPS, like Matlab [168, 162, 113, 124], Simulink [126, 124], 20-sim [123, 71], Modelica [71, 203], or UPPAAL[154, 169, 48]. Instead, we found a many new proposed tools — almost one new tool per paper — such as Möbius [207], KeY-ABS [50], OpenMETA [149], SensorML modeling language [252], NetLogo [41], C2WT-TE [34], Polichrony [36], COMET [177], FUJABA [56], TTTech toolchain [155], RoZ [58], FLYAQ [175], OMiLAB [152], SGAM[216], PReSIC [218], COMPASS toolset [138], UncerTolve [99] and TTool[32].

4.2.3. Processes Reported by Modelling Approaches

Only 106 studies (39.8% of all studies, 45.5% of model-based studies) proposed or reported a process. This finding shows that processes are less popular than models or tools, at least among the included studies. The reported processes are suggested for two main purposes: *i*) organising the development and business processes, and *ii*) suggesting a workflow of a system’s operation. Among the reported processes, we noted the following three forms of presentation:

- *Rigorous graphical processes*: formalised graphical notations including

BPMN, activity diagrams, sequence diagram, and other notations with precise defined meanings of blocks and arrows.

- *Informal graphical processes:* general and abstract block-and-line diagrams indicating flows and orders of operations without precise or formalised meanings of the graphics primitives.
- *Informal textual processes:* textual descriptions of processes, including itemised lists and section-by-section breakdowns.

As Table 16 indicates, the most prominent way to represent a process is via an informal graph. The number of processes reported as informal text and formalised diagrams is similar. Therefore, processes in CPS works are largely informal.

Table 16: Primary studies by process presentation

Process presentation	#	%	Primary studies
Rigorous graphical	21	19.8	[235, 84, 243, 99, 189, 115, 168, 198, 60, 148, 255, 75, 179, 78, 219, 41, 194, 116, 68, 67, 236]
Informal graphical	62	58.5	[151, 241, 256, 32, 208, 237, 147, 248, 150, 101, 74, 182, 63, 113, 187, 114, 89, 79, 225, 216, 144, 123, 221, 107, 183, 213, 181, 125, 152, 92, 153, 201, 217, 139, 94, 227, 176, 110, 48, 80, 257, 178, 106, 258, 104, 87, 135, 192, 73, 95, 164, 251, 90, 252, 244, 40, 165, 240, 259, 118, 166, 47]
Informal textual	23	21.7	[180, 88, 172, 64, 93, 197, 185, 203, 204, 146, 117, 175, 38, 206, 58, 57, 66, 55, 159, 228, 122, 226, 91]

4.3. Approaches for Addressing Sustainability (RQ2)

The results presented in this section are based on “RQ2 – Which approaches for addressing sustainability exist?” and its sub-questions “Q2 – Does the paper report approach for addressing sustainability?”, “Q2.1 – Does the paper report technique/method that is used?”, “Q2.2 – Does the paper report metric?”, and “Q2.3 – Does the paper report sustainability/green model?”.

A total of 86 papers (32.3%) of all the classified studies reported some approach for addressing sustainability concerns. These works are categorised ac-

according to the classification provided by Gunes et al. [5], as depicted in Table 17.

Table 17: Approaches addressing sustainability sub-characteristics

Category	%	Primary study
Adaptability	17.44	[260, 158, 261, 262, 219, 59, 112, 105, 263, 133, 251, 264, 131, 195, 225]
Resilience	29.06	[265, 266, 128, 107, 196, 255, 110, 163, 267, 175, 38, 268, 269, 270, 48, 160, 136, 205, 230, 271, 272, 47, 51, 211, 60]
Reconfigurability	2.35	[129, 273]
Efficiency	51.16	[109, 157, 101, 111, 156, 197, 198, 130, 274, 227, 35, 206, 132, 275, 276, 277, 278, 279, 280, 100, 24, 281, 282, 220, 258, 108, 283, 284, 285, 228, 286, 287, 288, 289, 290, 226, 40, 229, 231, 259, 102, 199, 291, 162]

More than half of the approaches of the selected papers address **efficiency**, i.e. ‘good use of resources’. In this context, it is considered that a highly efficient system operates properly with an optimum use of system resources such as energy, cost, time, etc. Most of the works presented target energy efficiency in the power grid. Over a quarter of the approaches of the selected papers address the **resilience** concern, i.e. ‘self-healing’ or the ability of a system to persist in its operation and delivery of services with acceptable quality when the system is exposed to any inner or outer difficulties. For example, those difficulties can be a sudden defect, some malfunctioning of components or rising workload, which do not exceed its endurance limit. 17.2% of the approaches address **adaptability**, i.e. ‘evolving circumstances’ indicating the capability of a system to change its state to survive by adjusting its configuration in response to different circumstances in the environment. Finally, only 2.3% of the selected approaches address **reconfigurability**, i.e. ‘dynamic tuning’ which is the property of a system to change its configuration in case of failure or upon inner or outer requests.

By relating sustainability to modelling approaches (RQ1), we discovered that, on average, non-model-based studies are more likely to contribute a sustainability approach less than the model-based studies. Supporting this finding

is the fact that the correlation⁶ between Q1 (whether a paper presents a modelling approach) and Q2 (whether a paper presents a sustainability approach) was moderately negative ($r = -0.54, p < 0.01$). The sub-questions of Q1 have minor negative correlations with Q2, corroborating this result. We interpret this finding as an indication of the disconnection between the CPS modelling community and the sustainability community.

The models are consistently used along with sustainability approaches: exactly half (43) of the sustainability approach studies (86) use one or several models. The most likely sustainability approach to have a model is resilience: 60% of studies with it (15 out of 25) use some model. The least likely approach is efficiency: only 43% of studies with it (19 out of 44) rely on a model.

4.3.1. Methods used to Address Sustainability

Among the studies reporting sustainability approaches, 82.6% of them (71 studies) report a method/technique used to address some sustainability concern (see Table 18). To characterise the methods and techniques used to address sustainability, we followed the categorisation given in Section 3.3.5.

Table 18: Methods used to address sustainability (ER = Entity Relationship; NN = Neural Networks; CC = Cost Calculations; LCA = Life-Cycle Analysis)

Method	%	Primary study
ER	18.31	[163, 175, 268, 269, 260, 206, 275, 279, 108, 228, 288, 131, 47]
NN	7.04	[266, 283, 289, 290, 195]
CC	15.49	[265, 274, 35, 267, 278, 282, 230, 284, 286, 226, 259]
LCA	59.16	[128, 101, 225, 111, 156, 272, 231, 102, 199, 162, 51, 211, 109, 157, 198, 107, 196, 255, 110, 38, 48, 276, 205, 158, 280, 100, 24, 281, 129, 262, 220, 219, 59, 112, 271, 285, 263, 133, 287, 251, 264, 229]

Figure 11 offers an overview of the addressed sustainability sub-characteristics and the methods used by the analysed studies reporting on sustainability. Most of the approaches (59.2%) use the *life-cycle analysis* approach, among which 10 studies [225, 158, 262, 219, 59, 112, 263, 133, 251, 264] address the adaptability

⁶We calculated Pearson’s product-moment correlation for a sample of binary answers for RQs, using 0 for “No” and 1 for “Yes”.

concern. These studies, for example, facilitate adaptation for enterprise network by performing goal analysis. Among other purposes, those provide methodological support for pollution, enterprise manufacturing, tracking diseases, people well-being focused on nutrition and physical activity observed thanks to different bio-sensors. Another 12 studies [128, 272, 51, 211, 107, 196, 255, 110, 38, 48, 205, 271] are concerned with resilience. For instance, the studies report on risk modelling and calculation of resilience metrics based on simulation or quality factors for an industrial facility, power grid, water reservoirs and supply chains. These studies are concerned with self-monitoring, self-awareness, self-prediction, self-optimisation, and self-configuration of systems, usually in domains like robotic for service and critical infrastructure. Only one study [129] reports a sustainability method to address reconfigurability. It presents a modelling approach for organisational control reconfiguration for a robust smart power grid protection. The remaining 20 studies address efficiency. Among those, we highlight the one concerning the good use of resources by building a theoretical framework for cyber-physical interactions supporting energy supply models [287]. Another [220] addresses the efficiency problems in cloud computing for e-Commerce. In [276] it is presented an approach for money saving and gas emission reduction by modelling crop production. Finally, [285] contributes to energy efficiency by lowering the thermal workload of data centre servers.

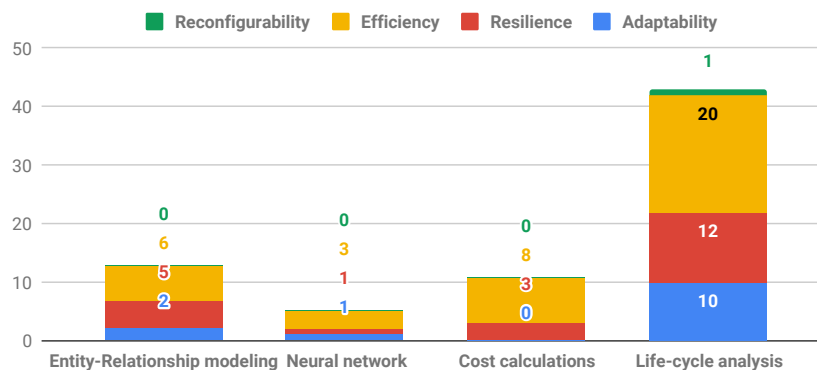


Figure 11: Methods used to support sustainability sub-characteristics

18.3% of the sustainability methods use *entity-relationship* modelling to represent their data, knowledge, or information models. Two approaches [260, 131] deal with self-adaptive systems, five [163, 175, 268, 269, 47] deal with resilience by analysing constraints and information dependency to find a vulnerability in the design of critical infrastructures and robotics for service, and the remaining six [206, 275, 279, 108, 228, 288] tackle efficiency by analysing trade-offs between energy consumption and other indicators relevant for business process management focused in smart manufacturing and building automation.

15.5% of the studies provide methods for *cost calculations*. Three of them [265, 267, 230] tackle resilience management of air traffic, networks and sustainability of data centres, while other studies [274, 35, 278, 282, 284, 286, 226, 259] deal with efficiency. The most highly cited approaches are: [274] that addresses pricing in retail competition model; [284] that tackles control for renewable energy integration in a smart grid; and [226] that deals with energy optimisation using graph theory for dynamic task scheduling in mobile cloud computing.

Finally, only 7% of the presented methods use *neural networks*, suitable for dynamic systems and simulation environments [28]. The work presented in [266] deals with resilience by developing dynamic data-driven learning approach for self-healing avionics using linear regression approach. In [195], the focus is on adaptability, concentrating on electricity demand planning by forecasting climate change. Finally, the remaining three studies [283, 289, 290] focus on efficiency by looking at the energy consumption of smart infrastructures using data mining and genetic algorithms.

The studies with sustainability approaches have an uneven distribution across model types (Q1.1, Figure 9). As Figure 12 shows, dataflows, automata, equations, and components are more likely to be used as part of a sustainability approach. On the other hand, UML-like models are substantially (approximately 6 times) less likely to be used as part of a sustainability approach. Therefore, we observe that while UML-like models are common in CPS literature, they are not commonly used in sustainability approaches.

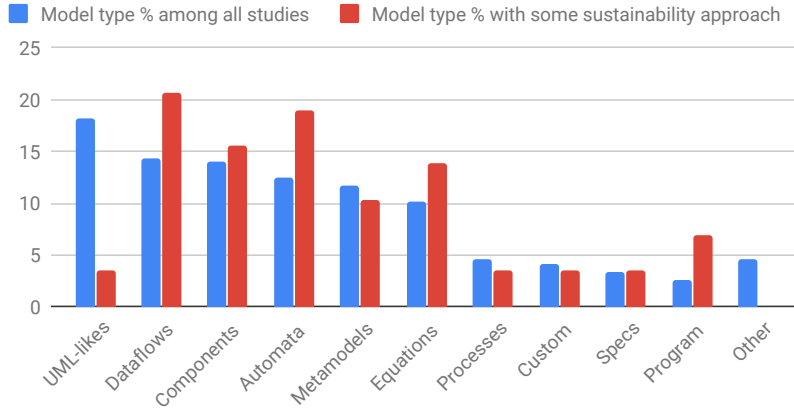


Figure 12: A comparison of prevalence of model types (RQ 1.1) in all studies with their prevalence in studies with some sustainability technique (RQ 2). Each model in a study is counted separately.

4.3.2. Metrics for Sustainability

We found 32 studies addressing metrics for sustainability or sustainable systems. These range from different uses, to different scenarios, to different types. Table 19 lists the primary studies reporting these metrics. Note that a paper may appear in more than one category as it may discuss more than one kind of metrics.

Table 19: Categories of metrics

Category	Primary studies
Energy	[197, 274, 206, 282, 285, 286, 287, 288, 289, 290, 226, 231, 102, 199, 291, 162, 195]
Resilience	[265, 196, 272, 47, 211, 51]
Efficiency	[267, 275, 136, 279, 199]
Well use of resources	[275, 279, 264, 220, 267]
Generic formulation/Framework	[271, 286, 102, 162]
Reliability	[206, 160, 51]
Environmental impact	[267, 276]

We can see that most works (17) propose energy-related metrics (e.g., cost, usage, power). Resilience is also addressed, but only by 6 studies. Efficiency and well use of resources are also addressed by the works classified, with 5 papers each. A few works (4) propose more generic formulations which may be used

to calculate concrete metrics (e.g. energy). Reliability is only addressed by 3 studies and only 2 discuss metrics for the environmental impact of the system.

We distinguish three scenarios in which metrics are discussed: *(i)* introduction of new metrics, *(ii)* introduction of frameworks for measuring sustainability (e.g., a framework to measure the sustainability of a CPS where different parts of the system can be evaluated using metrics defined by the user), and *(iii)* use of metrics to evaluate case studies. From the 32 papers discussing metrics, 21 propose new metrics to measure or qualify different aspects of sustainability [288, 47, 289, 290, 195, 265, 274, 226, 272, 231, 199, 51, 211, 196, 276, 285, 287, 264, 160, 136, 291], 8 propose some kind of framework or mathematical formulation that accepts metrics defined externally to measure sustainability of a system [279, 267, 282, 286, 102, 162, 271, 197], and 3 use metrics to evaluate a case study [206, 275, 220].

From all the studies, 27 present quantitative metrics [206, 288, 47, 289, 290, 195, 265, 274, 282, 286, 226, 272, 231, 102, 199, 162, 51, 211, 196, 276, 220, 285, 287, 197, 160, 136, 291], 3 papers present qualitative metrics [267, 271, 264], and 2 present qualitative and quantitative metrics [275, 279].

In summary, most of the metrics are for measuring a system's energy consumption, several propose frameworks to measure the sustainability of the system/organisation, and most metrics are quantitative.

4.3.3. Models for Sustainability

We identified 18 studies reporting some type of sustainability model (or green model), as listed in Table 20. Over half (10) of the reported models are supported by a modelling approach, 3 address adaptability, 10 tackle efficiency, 4 resilience and one addresses reconfigurability.

Regarding the methods used, most of the approaches use life-cycle analysis (13), while entity relationship, neural networks and cost-calculation are used by one study each. Finally, two studies do not report any method nor technique. Regarding evaluation, 6 papers use a case study (CS), 5 use empirical foundations (EF), 2 refer to lessons learned (LL) and the remaining 5 do not mention

Table 20: Reported models for sustainability

Paper	Modelling approach	Sustainability category	Method	Evaluation	Domain-Specific	Model type
[279]	-	Efficiency	ER	-	-	Behavioural
[195]	X	Adaptability	NN	EF	X	Mathematical
[226]	X	Efficiency	CC	EF	X	Algorithmic
[225]	X	Adaptability	LCA	CS	X	Behavioural
[128]	X	Resilience	LCA	-	X	Architectural
[196]	X	Resilience	LCA	LL	X	Mathematical
[205]	X	Resilience	LCA	EF	-	Behavioural
[271]	X	Resilience	LCA	CS	-	Architectural
[129]	X	Reconfigurability	LCA	CS	-	Architectural
[101]	X	Efficiency	LCA	CS	X	Behavioural
[156]	X	Efficiency	LCA	LL	X	Behavioural
[280]	-	Efficiency	LCA	-	X	Architectural
[100]	X	Efficiency	LCA	-	-	Mathematical
[281]	-	Efficiency	LCA	CS	X	Behavioural
[220]	X	Efficiency	LCA	EF	-	Behavioural
[285]	-	Efficiency	LCA	EF	-	Mathematical
[261]	-	Adaptability	-	-	X	Architectural
[197]	-	Efficiency	-	CS	X	Mathematical

any sort of evaluation. Finally, 11 studies report domain-specific green models and 7 report general ones. Finally, and regarding model type, 7 studies use behavioural green models, 5 use architectural green models and another 5 use mathematical green models, and only 1 study uses an algorithmic green model.

4.4. Application Domains of Modelling Approaches (RQ3)

This section analysis the data related to application domains of the primary studies. This analysis is based on the data collected for “RQ3 – Which application domains have been considered?”, which includes two sub-questions: “Q3.1 – Is the approach domain specific?” and “Q3.2 – Which application domain is addressed?”. In the case of Q3.2, a list of pre-defined main categories are considered. However, if non of the main categories were suitable for the domain of a study, the reviewer could suggest another domain in the description section of this question.

As the analysis of the data for application domains (RQ3), the following investigations are fulfilled. First, a high level analysis of domain-specific and

general-purpose studies for CPS is realised, considering their application domains according to the pre-defined categories, including Smart Manufacturing, Emergency Response, Air Transportation, Critical Infrastructure, Health Care and Medicine, Intelligent Transportation, Robotic for Service, and Building automation. Then, the number of studies addressing each of the groups in the pre-defined categories are analysed. Later, the sub-domains and case studies for each category are listed and elaborated. This part of the analysis includes reporting the studies which do not fall in any of the pre-defined groups and represented as “other” group with several sub-domains. Finally, the cross domain analysis and correlations between the application domains (RQ3) and the other RQs are realised.

Among the total of 266 studies, a number of 111 studies (about 42%) addresses a domain-specific approach for CPS. The remaining studies propose approaches or techniques to address CPS in general. Obviously, all domain-specific studies target at least one domain, either amongst our pre-defined major domains (such as smart manufacturing) or another new domain (or sub-domain of the defined major domains). In fact, most of the 111 studies proposing a domain-specific approach for CPS (99 studies, about 89%) fall in one of our pre-defined categories of main application domains. However, this categorisation of the main application domains is not enough to pin-point the exact domain of all studies, hence, they may have a sub-domain or suggest a new one. Almost 68% (76 studies) of the 111 domain-specific studies have a sub-domain.

As shown in Figure 13, the first rank of applications is with “Smart Manufacturing” application domain with 45 studies, which is about 41% of the studies referring to at least one domain. In second and third places we have “Critical Infrastructure” and “Building Automation” application domains with 41 studies (about 37%) and 37 studies (about 33%) of the studies, respectively. Note that the each paper may address more than one domain.

Table 21 classifies the primary studies based on their main application domains and considering the domain-specificity of the studies. The first column shows the name of the group (such as smart manufacturing), accompanied with

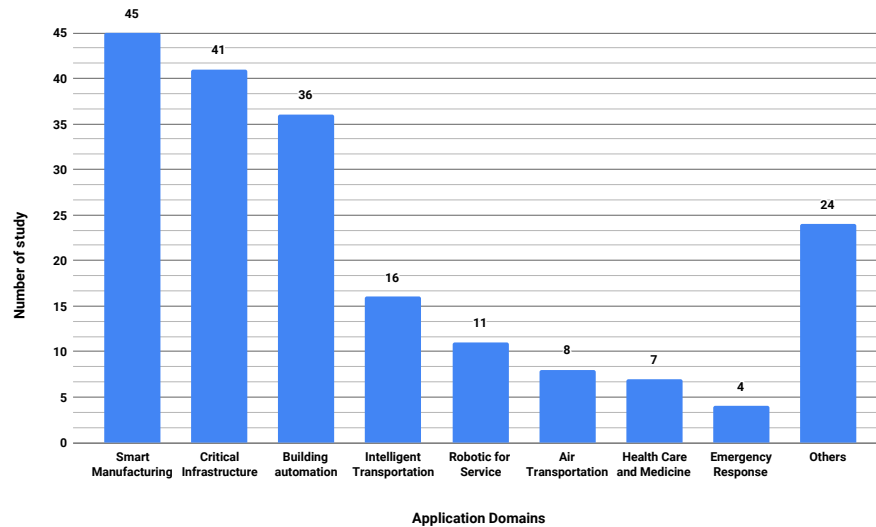


Figure 13: Number of studies in each major group of application domains

the list of studies targeting this application domain without any specific sub-domain. The second column lists all the studies falling in this group but focusing on a sub-domain or case study. The studies addressing the same sub-domain are grouped. Those studies not targeting any of the main domains but presenting another specific domain or case study constitute the “other” category.

Table 21: Classification of studies in application domains considering their domain-specificity

Domains	Sub-domains (or case studies)
Smart Manufacturing [114, 233, 132, 66, 141, 78, 281, 156, 193, 101, 130, 250, 134, 264, 124, 86, 89]	<p>Domain-specific: Production environments [162], Eco-friendly automation [35], Enterprise manufacturing [251, 259], Production systems [198], Garden and plant experimentation and impact on climate change [133], Power grid [228], Flexible Production [227], Hazard detection system over smart city and smart grid [72], Power consumption of machines [241], Smart Mining [236], Energy consumption on greenhouse lights [286], CPS in Industry [270], Data centre power management [288], Enterprise operating system [275], Smart grid [290], Wind turbine and Smart grids [284], Water management [112]</p> <p>General purpose: Drone Manufacturing [271], Industrial automation system (liqueur plant case) [247], IoT in cyber-physical manufacturing systems [246], Mine pump [164], Power management [74], Smart energy manufacturing for helicopter [73], Smart grid [34, 83], Transport objects station [166], Water filling production system [240]</p>
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Domains	Sub-domains (or case studies)
Emergency Response	Domain-specific: Military avionics (Firefighter) [219], Safety-critical systems [163], Urban emergencies [252] General purpose: Industry 4.0 [229]
Air Transportation [138, 266, 265, 197, 36, 257]	Domain-specific: UAV swarm design and mission application [176] General purpose: Road traffic management and Air traffic control [180]
Critical Infra-structure [225, 47, 195, 103, 207, 168, 221, 216, 200, 182, 214, 188, 172, 53]	Domain-specific: Distributed computing (data centers) [199], Safety-critical CPS [136], Water reservoirs [51], Safety-critical embedded systems [196], Maritime systems and Energy management [177], Autonomous power systems [113], Electronic warfare system [90], Energy management and Transportation management [212], Nuclear fuel [183], Electricity market system [274] General purpose: TT Ethernet [155], Anti-lock braking system [88], Cloud computing for e-Commerce [220], Critical Infrastructures in transportation system [218], Distributed computing (data centers) [102], Industrial park [254], Mission control with high-speed cameras in UAV systems [187], Nuclear reactor’s redundant coolant supply system [217], Power management [204], Resource management [94], Safety-critical RTES from the maritime and energy [68], Shop Analyser [255], Smart grid control [71], Smart home [189], Smart home [125], Solid waste management in EU [111], Supply chains [211]
Health Care and Medicine [161, 273, 57, 262]	Domain-specific: Medical devices [169], On-demand medical devices [170] General purpose: Pulse-Oximeter Thermal Effects, Drug Infusion, Physiological-Value-Based Key Agreement, and DC Environmentally Aware Scheduling [287]
Intelligent Transportation [222, 292, 173]	Domain-specific: Automotive [120], Autonomous vehicle operation [293], Car path tracking control [42], Hybrid transport systems [61], Railway transportation [50], Railway braking system [64], Train System [116] General purpose: Railway, Automotive, and Aerospace applications [215], Railway prototype [135], Train System [201], Advanced Vehicle Make [149], Cruise liners [65], Car engine with gearbox control [37]
Robotic for Service [119, 104, 184, 38, 152, 140]	Domain-specific: Control system of robots [160], Resilient mission robots [175], Robotic Application Development Process [139], UAV [106] General purpose: Telepresence Robots (RobAIR) for Life-Like environments [110]

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Table 21 – continued from previous page

Domains	Sub-domains (or case studies)
Building automation [137, 54, 69, 291, 258, 224, 67, 79, 93]	<p>Domain-specific: Automation system and Industry 4.0 [146, 40], Automotive [144], Data center energy plan and PHEV of employees [52], Exhibitions building [231], Hospital emergency room [192], Open data management for smart cities [186], Power grid [167, 272], Smart buildings [105, 283, 59], Smart grid [143], Smart home [41, 191]</p> <p>General purpose: Room modelling [108], Automotive [181], Controlling of Mechatronic products (Gearbox case) [63], Automation system and Industry 4.0 [92], Battery management system [153], Co-modelling for Mechatronic devices [123], Engine and Power-train simulation [203], Smart office [118], Water management [81], Smart home [190, 87, 121]</p>
Other	<p>Domain-specific: Smart phones for CPS [226], Component based servers [131], Nuclear power plant [107], Water consumption [24], Industrial facilitation [128], Gas distribution [44], Automotive [43], Image processing [194], Smart grid [151], Power grid cyber attack [77], Government systems processes [280], Marine Biology [261], Meteorological support for pollution [263]</p> <p>General purpose: Autonomous cars [158], Campus vehicle [95], Data center servers (cooling) [285], Smart phones [278], Smart power grid [129], Stream processing (gestures) of live models [159], Supply chains [46], System-of-systems analysis for Campus [289], Thermal plant [238], Traffic management in an urban intersection [58], Wind turbine system [48]</p>

It is worth noting that 155 studies (about 58%) out of all primary studies propose generic approaches for CPS. From these, 74 studies (almost half of the generic-purpose studies) do not present any application domain or case study.

In some of the studies, specific application domains are presented (in addition to the main application domains). This data is collected as the description of the application domains. To focus on the details of the application domains of the studies, the specific domains are presented in Table 22 for each main application domain.

Table 22: Specific application domains addressed in the primary studies

Domain	Primary studies
Smart Manufacturing	CPS in Industry [270], Data center power management [288], Drone Manufacturing [271], Eco-friendly automation [35], Energy consumption on greenhouse lights [286], Enterprise manufacturing [259, 251], Enterprise operating system [275], Flexible Production [227], Garden and plant experimentation and impact on climate change [133], Hazard detection system over smart city and smart grid[72], Industrial automation system (liqueur plant case) [247], IoT in cyber-physical manufacturing systems [246], Mine pump [164], Power consumption of machines [241], Power grid [228], Power management [74], Production environments [162], Production systems [198], Smart energy manufacturing for helicopter [73], Smart grid [34, 290, 83], Smart Mining [236], Transport objects station [166], Water filling production system [240], Water management [112], Wind turbine and Smart grids [284]
Emergency Response	Industry 4.0 [229], Military avionics (Firefighter) [219], Safety-critical systems [163], Urban emergencies [252]
Air Transportation	Road traffic management and air traffic control [180], UAV swarm design and mission application [176]
Critical Infrastructure	TT Ethernet [155], Antilock braking system [88], Autonomic power systems [113], Cloud computing for e-Commerce [220], Critical Infrastructures in transportation system [218], Distributed computing (data centers) [199, 102], Electricity market system [274], Electronic warfare system [90], Energy management and Transportation management [212], Industrial park [254], Maritime systems and Energy management [177], Mission control with high-speed cameras in UAV systems [187], Nuclear fuel [183], Nuclear reactor’s redundant coolant supply system [217], Power management [204], Resource management [94], Safety-critical CPS [136], Safety-critical embedded systems [196], Safety-critical RTES from the maritime and energy [68], Shop Analyser [255], Smart grid control [71], Smart home [189, 125], Solid waste management in EU [111], Supply chains [211], Water reservoirs [51]
Healthcare and Medicine	Medical devices [169], On-demand medical devices [170], Pulse-Oximeter Thermal Effects, Drug Infusion, Physiological-Vvalue-Based Key Agreement, DC Environmentally Aware Scheduling [287]
Intelligent Transportation	Advanced Vehicle Make [149], Automotive [120], Autonomous vehicle operation [293], Car engine with gearbox control [37], Car path tracking control [42], Cruise liners [65], Hybrid transport systems [61], Railway, Automotive, Aerospace [215], Railway braking system [64], Railway prototype [135], Railway transportation [50], Train System [116, 201]
Robotic for Service	Control system of robots [160], Relisient mission robots [175], Robotic Application development Process [139], Telepresence Robots (RobAIR) for Life-Like environments [110], UAV [106]

Continued on next page

Table 22 – continued from previous page

Domain	Primary studies
Building Automation	Automation system and Industry 4.0 [40, 146, 92], Automation [144, 181], Battery management system [153], Co-modelling for Mechatronic devices [123], Controlling of mechatronic products [63], Data center energy plan and PHEV of employees [52], Engine and Powertrain simulation [203], Exhibitions building [231], Hospital emergency room [192], Open data management for smart cities [186], Power grid [167, 272], Room modelling [108], Smart building [59, 105, 283], Smart grid [143], Smart home [191, 41, 190, 87, 121], Smart office [118], Water management [81]

To analyse the specific domains of all the studies, the number of repeating terms are presented in Table 23. These numbers were collected from the 133 studies providing specific domain(s). The top 20 domains are shown in this table. As it can be seen, smart grid, smart home, power grid, and Industry 4.0 have the highest number of repetitions among the primary studies.

Table 23: Number of repetition for the different terms in the application domains

Domains	Occurrences
smart grid	8
smart home	7
power grid	5
Industry 4.0	4
safety-critical; automation system; smart grid	3
distributed computing; braking system; medical devices; wind turbine; supply chains; water management; smart buildings; data centres; train system; power management; energy management; smart office; traffic management	2

The above mentioned analysis address the RQ3 per se. To find out the relation between RQ3 and the other RQs, their correlations are examined.

We analyse the correlation between RQ1, RQ2, and RQ3 in the sense that for each application domain group we check the studies addressing solely modelling, solely sustainability, or both of them for CPS. Also, for each of these items, we assess the studies which are domain-specific and general-purpose. To this end, we provided the general trend between these 3 aspects in Figure 14 and the details (such as summation) are shown in Table 24.

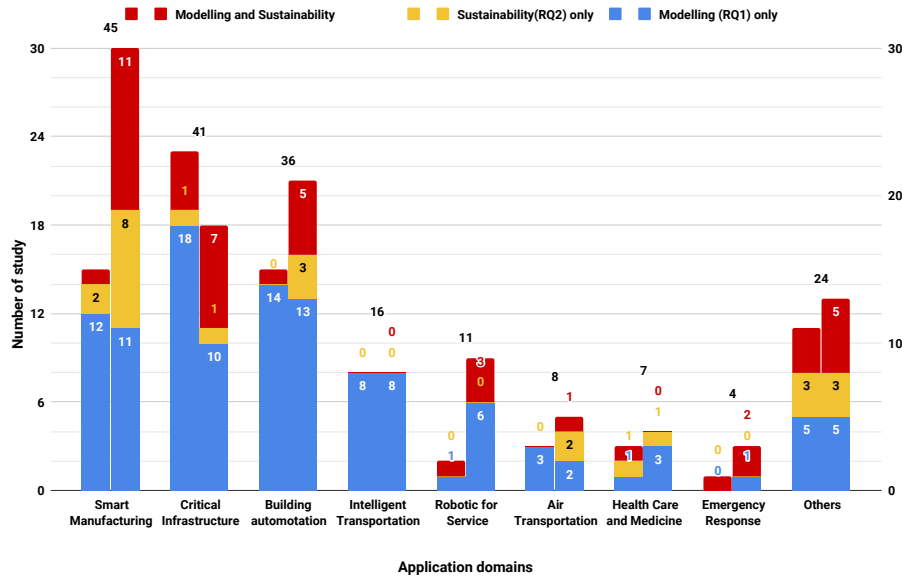


Figure 14: Correlation analysis for RQ1 (Modeling), RQ2 (Sustainability), and RQ3 (Application Domains). In each application domain, the left bar represents the general purpose studies and the right bar represents the domain-specific studies.

In Figure 14, for each application domain, the left bar represents the values for the domain-specific studies and the right bar represents the values for the general-purpose studies. Also, in each bar, the numbers for RQ1, RQ2, and RQ1&RQ2 are stacked bottom-up.

According to this correlation analysis, about two thirds (62%, 121 studies out of 192; see Table 24) of the studies addressing application domain(s) are considering the modelling aspect of the CPS while only 13% of the studies with application domains are addressing the sustainability aspect of the CPS. Moreover, about 24% of the studies are addressing both modelling and sustainability aspects of the CPS. We can conclude that there is a gap in conducting research on sustainability of CPS, specifically, in Intelligent Transportation, Robotic for Service, and Emergency Response application domains in which there is no reported research considering this aspect.

Finally, according to QA5 (How rigorously is the method evaluated?), about 61% of the primary studies have been evaluated with case studies, about 11%

Table 24: Statistics of correlation between RQ1, RQ2, and RQ3. DS: Domain-specific, GP: General-purpose

Domains \ RQ Criteria	Modeling(RQ1)			Sustain.(RQ2)			RQ1&RQ2			Total
	DS	GP	Total	DS	GP	Total	DS	GP	Total	
Smart Manufacturing	11	12	23	8	2	10	11	1	12	45
Critical Infrastructure	10	18	28	1	1	2	7	4	11	41
Building automation	13	14	27	3	0	3	5	1	6	36
Intelligent Transportation	8	8	16	0	0	0	0	0	0	16
Robotic for Service	6	1	7	0	0	0	3	1	4	11
Air Transportation	2	3	5	2	0	2	1	0	1	8
Health Care and Medicine	3	1	4	1	1	2	0	1	1	7
Emergency Response	1	0	1	0	0	0	2	1	3	4
Other	5	5	10	3	3	6	5	3	8	24
Total	59	62	121	18	7	25	34	12	46	192

with empirical studies, and about 9% simply presenting lessons learnt (altogether 81% of the studies are evaluated). Moreover, 76% of the evaluated studies address/present an application domain and only 43% of the evaluated studies present a domain-specific approach.

4.5. Modelling Approaches for Addressing Sustainability of CPS (RQ4)

Only 51 (19.2%) out of 266 primary studies proposed a modelling method for sustainability. We thus observe that the communities working on modelling and sustainability approaches are disconnected, and the intersection of these two topics is relatively unexplored.

4.5.1. Relation with RQ1 – Modelling Approaches for CPS

While investigating the relation between formal modelling (RQ1) and modelling-for-sustainability approaches (RQ4), we discovered that automata are the most

popular model type (Q1.1) for modelling sustainability issues. To arrive at this conclusion, we used the distribution of model types in RQ1 as the baseline, and investigated the deviations from it in the model types in RQ4, as shown in Figure 15).

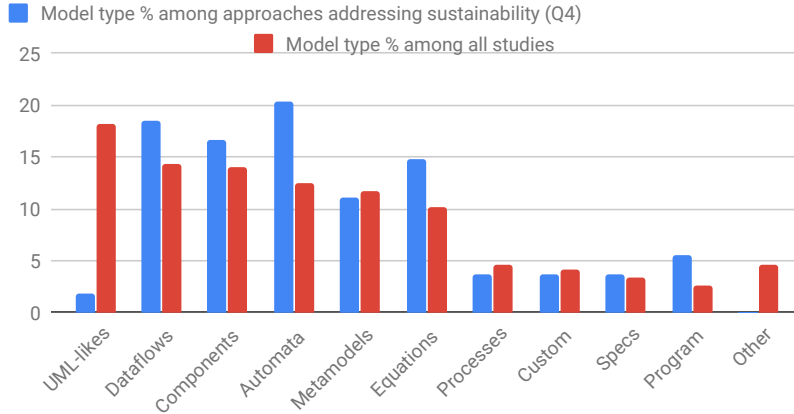


Figure 15: Comparing the prevalence of model types (Q1.1) in all studies with their prevalence in studies modelling for sustainability (RQ4). Each model in a study is counted separately.

Other relatively popular model types are dataflows, components, and equations. Interestingly, the most unpopular (by a large margin) model type for sustainability is UML-like models, which is surprising given how popular the UML-like models are for CPS in general. These findings are consistent with the findings in relation to sustainability approaches (RQ3), shown in Figure 12. We thus conclude that a literature gap exists in using UML-like models to represent and support sustainability. For process presentations (Q1.3), we observed roughly the same prevalence among modelling for sustainability as among all of the primary studies; comparing with Table 16 in Section 4.2.3: of all the cases, sustainability-addressing studies use rigorous graphical, informal graphical, and informal textual process representations in 19%, 52.4%, and 28.6%, respectively.

4.5.2. Relation with RQ2 – Sustainability Approaches

The 51 studies reporting modelling approaches for addressing sustainability of CPS based on sustainability categories are presented in Table 25. 40 of these

studies (78.4%) report sustainability technique (7 ER, 1 NN, 4 CC, 28 LCA). 17 (33.3%) report on metric, of which 16 propose some new metric and 1 uses an existing metric. All 17 studies propose/use quantitative metrics. 11 studies (21.6%) report a sustainable/green model (1 Algorithmic, 2 Architectural, 4 Behavioural, 4 Mathematical). We can note that the percentages are consistent with what was observed for sustainability approaches discussed in Section 4.3.

Table 25: Modelling approaches addressing sustainability (RQ4)

Category	% of total (51)	Primary study
Adaptability	17.6	[195, 225, 131, 251, 158, 105, 133, 219, 59]
Resilience	33.3	[47, 136, 160, 51, 211, 196, 48, 128, 205, 175, 107, 110, 255, 230, 38, 60, 163]
Reconfigurability	2	[129]
Efficiency	47.1	[102, 199, 162, 231, 206, 287, 100, 226, 197, 156, 101, 130, 157, 132, 227, 198, 108, 109, 40, 228, 229, 258, 35, 259]

4.5.3. Relation with RQ3 – Application Domains

The correlation analysis between Q3 and Q4 shows that 33 studies (about 30% out of 111 domain-specific studies) report modelling approaches for sustainability of CPS. On the other hand, only 11% (17 studies) of the general-purpose studies (155 studies in total) report modelling approaches for sustainable CPS.

Table 26 shows the list of studies reporting a modelling approach for sustainability of CPS. They are classified considering different application domains. Out of all 51 studies which report modelling approach for sustainability of CPS, Smart Manufacturing and Critical Infrastructure application domains with 12 and 11 primary studies respectively have the highest number of studies among all application domains. Intelligent Transportation application domain has no study report modelling approach for sustainability of CPS. Finally, in general the distribution of the studies addressing RQ4 (reporting a modelling approach for sustainability of CPS) between application domains is similar to the distribution the studies addressing Q3.2 (application domains). Also, in both of these research questions, the highest number of the studies belong to Smart Manufacturing, Critical Infrastructure, Building Automation, respectively.

Table 26: The correlation analysis between RQ3 (application domains) and RQ4 (modelling approaches for sustainability of CPS).

Domain	#	Primary studies
Smart Manufacturing	12	[35, 259, 251, 227, 133, 228, 162, 198, 132, 101, 156, 130]
Emergency Response	3	[219, 163, 229]
Air Transportation	1	[197]
Critical Infrastructure	11	[199, 177, 136, 196, 51, 47, 195, 225, 102, 255, 211]
Health Care and Medicine	1	[287]
Intelligent Transportation	0	
Robotic for Service	4	[160, 175, 38, 110]
Building automation	5	[40, 231, 105, 258, 108]
Without application domain	14	[131, 128, 107, 226, 158, 129, 48, 205, 206, 157, 109, 60, 100, 230]

4.6. Summary of Results

Our findings regarding modelling approaches for CPS (RQ1) can be summarised as follows:

- UML-like models, dataflow models, and other component models are the most common CPS formalisms.
- Primary studies that did not report models explicitly were associated with lower citation relevance and evaluation rigour. The more textually argumentative papers do not seem to have the same impact as those contributing with actual modelling artefacts.
- Most studies develop customised tools. Aside from those, the most common tools are based on Simulink, Modelica, and UPPAAL.
- Most studies that report processes use informal graphical presentation.

The summary of our findings regarding approaches for addressing sustainability (RQ2) as presented next:

- Sustainability approaches are getting some attention as about 32% of the papers report some approach for addressing sustainability concerns.

- Efficiency is the sustainability sub-characteristic most addressed (by around 51% of the works), followed by resilience (29%), and adaptability (17%). Reconfigurability is rarely addressed (only by 2% of the works).
- Life-cycle analysis is the most adopted method used to address sustainability (59% of the studies).
- Metrics for sustainability are rarely reported and most studies prefer to propose new (usually quantitative) metrics for measuring a system's energy consumption.
- For modelling sustainability, automata are the most used model type; UML-like models are used the least despite being common in modelling studies. Thus, a literature gap exists in using UML for sustainability modelling.
- In just a few studies (18 works – about 7%) do the authors propose some type of sustainability (or green) model, more often domain-specific (11 studies) rather than general purpose (7 studies).

The summary that follows relates the findings from RQ1 (modelling for CPS) and RQ2 (approaches for addressing sustainability).

- Across all studies, using models negatively correlates with addressing sustainability, meaning that there is a general disconnection between the communities that research CPS modelling and those who investigate sustainability of systems.
- For each sustainability approach, formal models are used with consistent frequency (between 40% and 60%). Resilience is the sustainability metric for which models are used the most.
- There is a literature gap for modelling methods and adaptability, reconfigurability, and efficiency of sustainable systems.

The summary regarding the relation between RQ1 (modelling for CPS) and RQ4 (modelling for CPS sustainability) is discussed next:

- Automata, dataflows, component-based, and equation-based models are particularly popular for modelling sustainability.
- There is a literature gap in using UML-like models for sustainability modelling.

We present now the summary of the results for analysing RQ3 (application domains for modelling approaches):

- Almost 89% of the domain-specific studies have at least one of the main application domains suggested in these studies. However, about 68% of the domain-specific studies have also a sub-domain.
- About 42% of the primary studies address a domain-specific approach for CPS. The rest proposes general-purpose approaches.
- Smart Manufacturing, Critical Infrastructure, and Building Automation application domains have the highest number of studies with respect to the 111 studies addressing at least one application domain (41%, 37%, and 33%, respectively). Note that the total number of references to domains is 192.
- Smart Grid, Smart Home, Power Grid, and Industry 4.0 (with 8, 7, 5, and 4 occurrences) are the terms with the highest number of repetition in the sub-domains of all the studies.

Finally we present the summary of the results for analysing the correlation between RQ3 (application domains for modelling approaches) and the other RQs:

- Almost two thirds of the studies addressing application domain(s) are considering the modelling aspect of the CPS while only 13% of the studies with application domains are addressing the sustainability aspect of the

CPS. Also, about 24% of the studies are addressing both modelling and sustainability aspects of the CPS.

- There is a gap in conducting research on sustainability of CPS, specifically, in Intelligent Transportation, Robotic for Service, and Emergency Response application domains in which there is no reported research considering this aspect.
- Finally, 76% of the evaluated studies (according to QA5, altogether 81% of the primary studies are evaluated with case studies, empirical studies, or with presenting lessons learnt) address an application domain but only 43% of the evaluated studies present a domain-specific approach.

5. Threats to Validity

Next we discuss the threats to validity of this work with respect to construct validity, internal validity, external and conclusion validity.

Construct validity. A potential threat respects the two sustainability characterisations (reconfigurability and adaptability), which are closely related. This may have been confusing to some reviewers. A similar issue respects the method characterisation for sustainability, where sometimes the difference between life-cycle analysis and other categories was not distinguishable as the method could apply to both. Additionally, the interpretation of the concepts “model” and “process” may vary among the reviewers: some may include a wide range of phenomena in them (e.g., an algorithm can be considered a model, and a process is any multi-step description), whereas others may require a formalised version of a model or process presented. To mitigate these three threats, several meetings were held to discuss and validate the classification. The participants of these meetings were the seven reviewers and an eighth person not involved directly in the reviewing process. After these meetings, one reviewer was responsible for checking and possibly reclassifying the results.

Internal validity. A first observation is that the background of the researchers involved in this study is mostly on Software Engineering. This can be seen as a possible cause for bias during the paper selection and data extraction phase. However, most of the authors are experienced in performing systematic review and mapping studies, and also have an extensive track record in a wide variety of research topics and domains. We believe this expertise limits the negative effects of this threat. Another possible threat is that some decisions of the SMS process may have been subjective, particularly those regarding the application of the inclusion and exclusion criteria, and the selection of the data to extract. To minimise this threat, we performed several validity checks among the various authors. In particular, the SMS process was performed following a “peer review” approach, where conflicts were discussed and resolved by the authors, hence mitigating threats due to personal interpretation. Finally, certain extraction choices may have been difficult to handle consistently, due to potential ambiguities in our assigned labels. For example, domain specificity of a contribution may be difficult to judge — at least without an attempt to apply an approach to a new domain. Some approaches may appear domain-specific, but in fact apply to many CPS domains. To mitigate this threat, our extraction relied on the reporting and claims by the authors, rather than the interpretations of the reviewers. That is, we only marked an approach as non-domain-specific if the study explicitly claims or demonstrates generality. The same applied to other questions where different interpretations are possible, such as whether a study proposes a modelling process or addresses sustainability concerns.

External validity. This refers to how well the results of our research study can be generalised to other settings, i.e., how the primary studies are representative for the topics under review. To address this possible limitation, the search was specified considering a set of trial searches and validated by the authors, and the coverage and relevance of the retrieved studies were constantly checked among subgroups of the team. Another threat respects the primary studies obtained from the used digital libraries. We performed two automatic searches within

one year difference. The second time aimed at capturing the publications from April-December 2017, but as the systems do not allow to select publications by month, we searched for the whole year. We were surprised to observe that the set of papers returned from the Springer library was not the same for the first part of the year, that is, some papers retrieved in the first search were not retrieved in the second search. In those cases, we merged the papers returned in the first and second string search executions. In fact, there is always the risk of missing some relevant works. To mitigate this, we used the digital libraries considered more relevant in Computer Science, and so we believe that the more impactful works were considered for this study. Also, all the retrieved papers were available for download and *a posteriori* analysis.

Conclusion validity. The used methodology [27] considers that not all the relevant primary studies can be identified, so there is the possibility that some studies excluded in this review could, instead, have been included. To mitigate this, the inclusion and exclusion criteria were cautiously designed and verified by the authors, and also validated by members of the Software Engineering research group of the NOVA LINCS research centre. This procedure helped minimising the risk of excluding relevant studies. Additionally, only one reviewer read the titles and abstracts off all the papers, making the decision to include a study for data extraction. For all the cases where the decision about inclusion or exclusion was not clear, the study was always included. Then, during the result analysis, different reviewers performed the analysis of a single question by using the information of the selected studies. However, this could result in non-critical approach, for instance, accepting already given information as final. Nevertheless, for several papers the author doing the analysis contacted the author who did the extraction to clarify the information recorded, changing it whenever necessary. This procedure shows the analysts where carefully and critically using the extracted data.

6. Research Agenda

An analysis of the results of this study highlights various limitations and gaps of the existing body of knowledge. The following research roadmap is built on those issues and aims at challenging the academic and industry communities for further advancements.

Modelling of CPS. Several types of models have been used, from automata to component diagrams. However, it remains unclear how these models map to the needs of stakeholders. We envision empirical evaluation to evaluate the usability of these kinds of models, for instance, in terms of learnability, user error protection, and appropriate recognizability [294]. Further, for models that fall short in these concerns, new domain-specific modelling languages should be developed to better express the concepts to communicate with the domain experts. It is particularly important to tailor these languages to the stakeholder needs, as well as rigorously define them with a meta-model and formal constraints on the abstract syntax.

Modelling tools. Concerning the tools developed and used in modelling approaches, it was observed that only less than half of the approaches used tools or had tool support. So development of modelling or model-driven frameworks are needed to empower CPS modelling. Also most of the tools are general purpose, so development and implementation of domain-specific modelling tools is an area that requires the attention of researchers and practitioners.

Modeling processes. Processes are also important in this roadmap. Less than half of the approaches provide a well-defined process. Therefore, research on efficient process models makes another topic of the research agenda.

The five dimensions of sustainability and their short and long term effects. Sustainability is a vast concern, so different aspects of the five sustainability dimensions (environmental, economic, social, individual, technical) and their complex inter- and intra-relationships need to be investigated to model and engineer

proper sustainable systems. Another important issue to explore is to study the immediate, enabling and structural effects [295] of a software system in the five dimensions of sustainability. Also, we believe that, with time, more system domains will be explored to contemplate sustainability in their development. Finally, existing CPS modelling approaches should be developed for adaptation, reconfigurability, and efficiency for approaches to sustainability.

Modelling for sustainable CPS. Concerning modelling approaches for addressing sustainability of the CPS itself, in addition to all of the above considerations, we see a potential to use UML/SysML-like models to represent and analyse the sustainability concerns. First, such models would support building a taxonomy/catalogue of relevant modelling patterns to sustainability. Second, such models would enable systematic trade-off analysis of sustainability dimensions, similarly to how they enable analysis of different software qualities. Finally, when developing sustainable systems, it is important to offer a reasoning framework to study the various short, and long term effects of the system in the various pillars of sustainability.

7. Conclusions

This work discusses our journey through a systematic mapping study to gather information regarding the state of the art of cyber-physical systems development and how such systems development addresses sustainability. It is divided into four research questions. The first elicits existing modelling approaches for CPS and corresponding tools, (meta-)models, and processes independently from sustainability issues. The second research question looks for sustainability approaches that are or can be applied to CPS, hence collecting methods, metrics and models used for different kinds of systems. The third question aims at distinguishing between domain-specific and general-purpose approaches, to identify which CPS are domain specific and may not generalise. Finally, the fourth research question searches for modelling approaches addressing sustainability of CPS.

The end result is a set of modelling approaches, methods, and tools, as well as a list of the considered application domains and usage limitations. Among the various findings, it is interesting to confirm that UML-like and dataflow models are the most common for modelling CPS, unlike for sustainability, where automata is the most common model and the modelling approach is life-cycle analysis. Regarding tools for CPS, the most used are Simulink, Modelica and UPPAAL. The sustainability sub-characteristics mostly addressed are efficiency and resilience. Regarding application domains, the most common are smart manufacturing, critical infrastructure and building automation, and about 89% of the domain-specific studies address at least one of the main application domains. The identified limitations were the base for a research agenda challenging academics and practitioners for further investment in five major topics: modelling of CPS, tool support, deeper understanding of the five sustainability dimensions, and the modelling of sustainable CPS.

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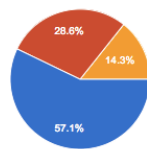
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Appendix A. Protocol Validation Survey

The protocol was first validated during a workshop in which participated researchers from Automated Software Engineering (ASE) NOVA LINCS research group. After receiving the first opinions, the protocol was revised and documented in excel file ⁷. A survey ⁸ was conducted as a part of the protocol evaluation process the excel file link served as the SMS protocol reference to guide participants review.

What is your overall expertise concerning the SLRs?



I am a lecturer and/or publisher of SLR.	4	57.1%
I am knowledgeable in SLRs, though not an expert.	2	28.6%
I am not an expert. My evaluation is that of an informed outsider.	1	14.3%
Other	0	0%

Figure A.16: Expertise of participants

The following researchers filled the form:

- Eric Rocha de Souza
- Jácome Cunha
- João Araujo
- Charlie Lopes
- Cristiano De Faveri
- Denise Lazzeri Gastaldo Bombonatti
- Enyo Gonçalves

We can see in Figure A.16 that most of participants were experts in regarding SMS, while other had relevant knowledge. Only one participant reported to not be a expert.

⁷<https://goo.gl/4CFjLw>

⁸[[Google Forms survey URL](#)]

Is the definition of SLR Objective sound?

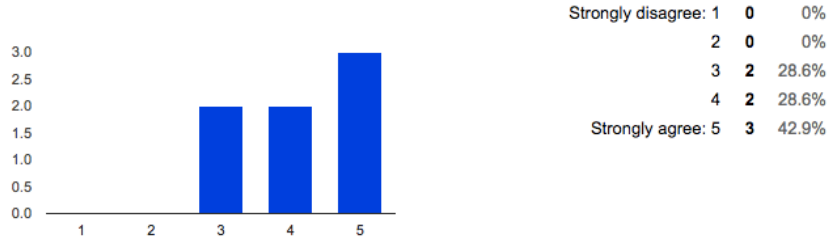


Figure A.17: SLR Objective

Is the need for SLR justified?

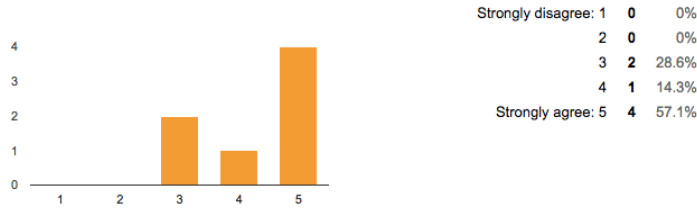


Figure A.18: Need for SMS

Regarding protocol itself, we first asked participants to report their opinion on SMS Basic Data (see Figure A.17 and Figure A.18). Most of participants agree that objective is sound and a need for performing SMS is justified.

We received a valuable feedback on how to improve our objectives and justification which were applied to revised protocol. The feedback suggested clarifying the benefits and beneficiaries of this SMS, as well as justifying the need for a sustainability-specific SMS.

Do the research questions cover the specific work objective?

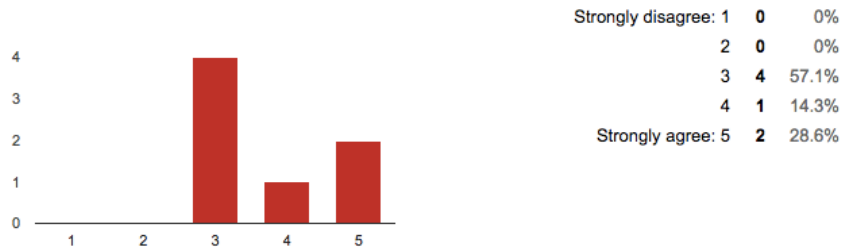


Figure A.19: Research Question conform to Objective

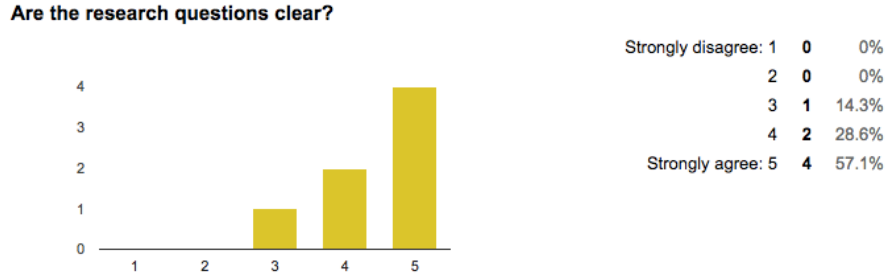


Figure A.20: Clarity of Research Questions

Further, we assessed opinion and recommendations regarding our Research Questions (see Figure A.19 and Figure A.20). Reviewers agree that research questions cover our work objectives and are expressed clearly. The comments about research our questions and PICOC strategy requested making RQ3 and RQ4 orthogonal to RQ1 and RQ2. Also, the feedback asked to clarify the criteria of applicability of modeling methods to CPS and specific domains. Finally, the feedback suggested asking about models, tools, and languages separately from each other.

Next, we assessed opinion and recommendations regarding our Search Sources (see Figure A.21). Reviewers agree that selected conferences, journals and workshops are representative to the area of study. Further, they suggested investigating the following venues and search engines:

- The International Conference on Cyber-Physical Systems (ICCPS).
- The International Conference on Model Driven Engineering Languages and Systems (MODELS).
- The International Conference on Conceptual Modeling (ER).
- The SCOPUS indexing service.
- The ISI Web of Science indexing service.

We did include ICCPS, whereas the other conferences were agreed to be not as relevant to CPS to warrant manual examination. However, research works

from these workshops are indexed by libraries we use as search sources. Also, we did test our string for library like Scopus, but it retrieved 1400 papers, leading to an impractically large collection of primary studies.

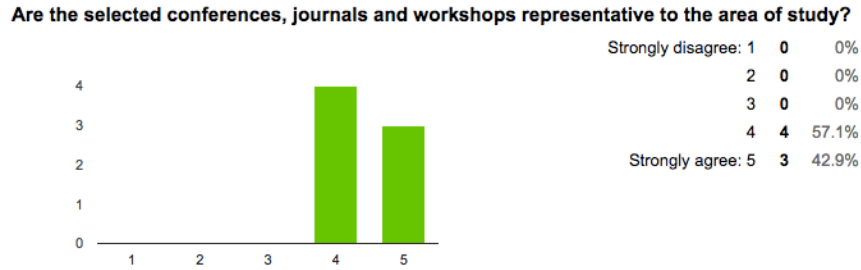


Figure A.21: Search Sources

Next, we assessed opinion and recommendations regarding our Search Query (see Figure A.22). Reviewers agree that selected keywords are sufficient for achieving the SMS objectives. The reviewers recommended refinement of the terms related to software and model-based engineering, as well as inclusion of a keyword for energy efficiency. As a result, we did include the term 'energy-efficient*' and 'model-driven' to our final query as suggested by reviewers. Reviewers left following comments:

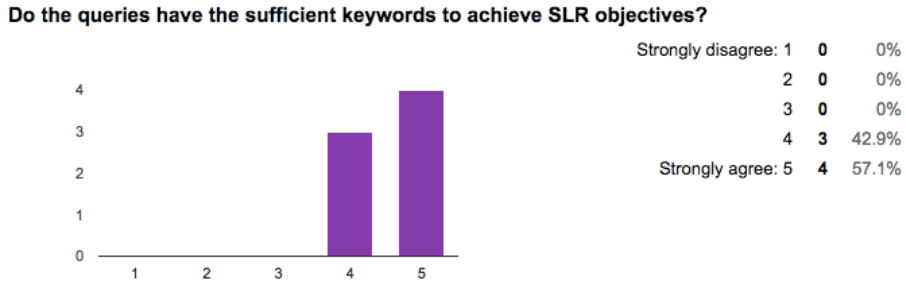


Figure A.22: Search keywords sufficiency

Next, we assessed opinion and recommendations regarding our Inclusion and Exclusion Criteria (see Figure A.23). Reviewers agree that defined criteria is complete enough to achieve the study objectives. Additionally, the reviewers recommended more specific formulations for relevance and explicit mentioning

of the primary studies, as well as indicating the specific dates of the search query.

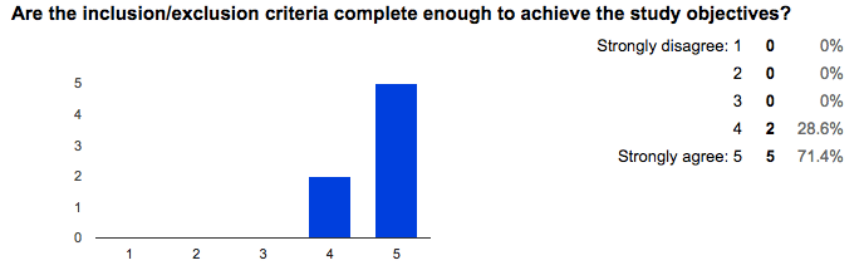


Figure A.23: Inclusion and Exclusion Criteria

Next, we assessed opinion and recommendations regarding our Data Extraction Strategy(see Figure A.24). Reviewers agree that defined extraction form is complete enough to achieve the study objectives. Reviewers recommended using an open-ended "other" field for the domains, separating academic and industrial applications, and also designing the data extraction form based on the planned analysis of the results.

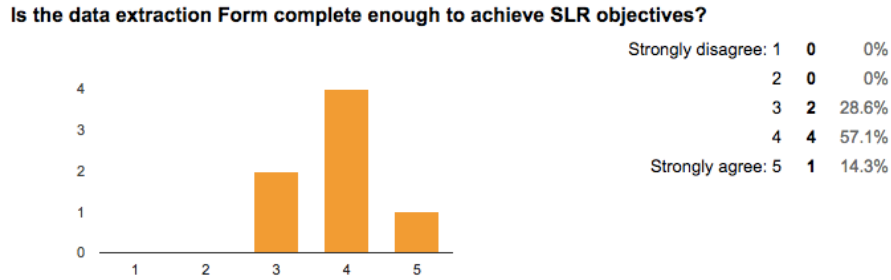


Figure A.24: Inclusion and Exclusion Criteria

Next, we assessed opinion and recommendations regarding our Data Quality Assessment Strategy (see Figure A.25). Reviewers strongly agree that defined quality assessment is complete enough to achieve the study objectives. The reviewers suggested adding a question about the motivation of the study, which we formulated as a problem description question.

Finally, we asked the reviewers to leave other comments related to this re-

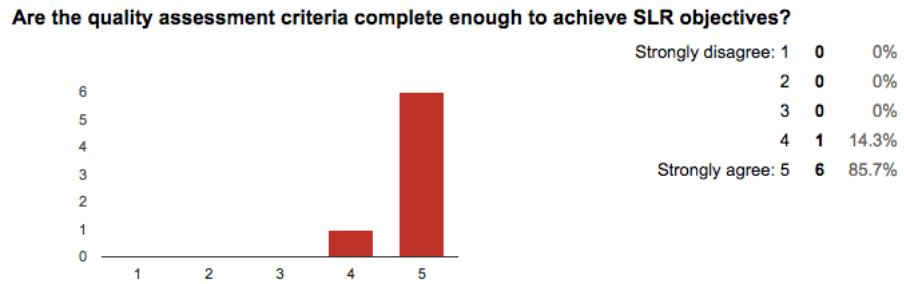


Figure A.25: Inclusion and Exclusion Criteria

view. The comments were generally enthusiastic, with some that cautioned about different interpretations of sustainability and others indicated willingness to help more with reviewing the study.

The reviewers took between 20min and 2h to complete this survey form. All in all they agree that a protocol is complete enough to address our research objectives. Except this recommendation we did obtain the relevant suggestions which we used to clarify better our protocol and improve it.