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

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Abstract

Supporting sustainability through modelling and analysis has become an active area of research in Software Engineering. Therefore, it is important and timely to survey the current state of the art in sustainability in Cyber-Physical Systems (CPS), one of the most rapidly evolving classes of complex software systems. This work presents the findings of a Systematic Mapping Study (SMS) that aims to identify key primary studies reporting on CPS modelling approaches that address sustainability *over the last 10 years*. Our literature search retrieved 2209 papers, of which 104 primary studies were deemed relevant for a detailed characterisation. These studies were analysed based on nine research questions designed to extract information on sustainability attributes, methods, models/meta-models, metrics, processes, and tools used to improve the sustainability of CPS. These questions also aimed to gather data on domain-specific modelling approaches and relevant application domains. The final results report findings for each of our questions, highlight interesting correlations among them, and identify literature gaps worth investigating in the near future.

1. Introduction

The sustainability demands on modern computing systems are steadily increasing [1, 2]. Consequently, there is growing interest among software engineer-

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ing researchers in developing more sustainable systems. Much of this research focuses on evolving established requirements, modelling, and analysis methods to better support sustainability goals. Broadly, sustainability refers to the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3]. In this context, sustainability refers to "the capacity of a system to endure for a certain amount of time" [4]. For software systems, this translates to ensuring the "longevity of systems and infrastructure and their adequate evolution with changing surrounding conditions" [5]. As this research unfolds, it is important to track its successes to transform how software systems are built, maintained, and evolved for a sustainable future.

Another rapidly developing research area is that of *Cyber-Physical Systems* (CPS). For simplicity, 'CPS' will hereafter refer to both single and multiple Cyber-Physical Systems. A CPS can be defined as a system that integrates computation, networking, and physical processes [6], creating systems that interact with the real world in critical ways. Safety-critical CPS, such as aircraft and autonomous cars, should be extensively analysed and tested to ensure their safe operation. Achieving this requires extensive use modelling, analysis, and software engineering tools throughout the value chain and system's life cycle.

CPS engineers must manage the increasing complexity and multidisciplinary nature of CPS development [7]. Therefore, keeping up-to-date with advancements in CPS modelling methodologies is essential. According to Gunes et al., a sustainable CPS is "capable of enduring without compromising its requirements, while renewing the system's resources and using them efficiently" [1]. Since Model-Driven Engineering (MDE) is widely used to build CPS, it is reasonable to expect that sustainability is also included in such modelling approaches.

In this work, we focus on the *technical dimension* of sustainability, as this is the aspect we can most reliably address for these systems when using MDE. While many systematic studies and literature reviews examine sustainability, CPS, and software engineering individually, no research has yet investigated the intersection of sustainability with CPS modelling. Our study aims to fill this gap by exploring CPS modelling approaches that tackle sustainability challenges.

Sustainability is a major challenge for CPS [1], and modelling methodologies promise comprehensive solutions to multi-faceted engineering challenges, including sustainability. Modelling can help us understand and shape systems systems and their emergent qualities. Hence, we ask: *What modelling approaches exist for addressing the sustainability of CPS?* To address this, we break down our main question into *nine sub-questions*, each one investigating specific contributions relevant to it.

The first question presents the three technical sustainability attributes—adaptability, resilience, and efficiency—each of which is covered by at least one study. The remaining questions investigate sustainability methods, models/metamodels, metrics, processes and tools used to improve the sustainability of a CPS, along with the most active application domains, and whether the approach was general-purpose or domain-specific.

To answer our research question, we performed a *Systematic Mapping Study*

(SMS) covering the literature on on CPS modelling for sustainability from 2011 to 2021. Each perspective from our sub-questions was quantitatively correlated with the attributes of the technical dimension of sustainability and other pertinent aspects, leading to a comprehensive analysis of the literature and identifying some literature gaps for future research. Alongside the data extraction, we have also performed quality and self-assessment surveys to ensure the reliability of our results.

The remainder of this paper is structured as follows. Section 2 introduces the key ideas in CPS and their sustainability, as well as related work. Section 3 describes our research method, and Section 4 presents and analyses the results, and identifies the limitations of this study by discussing its threats to validity. Section 5 concludes the paper. Finally, we report in detail our research method in Appendix A and the primary studies by analysed category in Appendix B.

2. Background and Related Work

This section gives a brief summary of the concepts and related work in CPS, software engineering, sustainability, and systematic literature/mapping reviews/studies.

2.1. Background

Cyber-Physical Systems. CPS are formed by computation, large communicating networks with heterogeneous sensors and actuators, and physical processes [6]. Thus, these systems must manage complex feedback loops between the physical and the cyber worlds [8]. Examples of CPS can be found in domains such as smart manufacturing (e.g., [50]), building automation (e.g., [40]), or intelligent transportation (e.g., [45]).

Dealing with the increasing complexity and multidisciplinary nature of CPS development is challenging [9]. Typically, these systems require heavy simulation before implementation for prediction, design, and run-time decision support. Different disciplines (e.g., Electrical Engineering, Mechanics, Physics and Software Engineering) use different approaches, tools, and modelling techniques to cope with this complexity.

Recent research efforts (e.g., the MPM4CPS project [10]) propose different levels of abstraction and views to tackle the inherent complexity of large-scale and complex systems. To represent those abstractions, those projects promote the use of rigorous models expressed in an appropriate modelling formalism. In such cases, the Model-Driven Development (MDD) approach, thanks to language metamodelling and model transformations, is used to build models that can be (formally) verified and used to simulate the system.

Sustainability in Software Engineering. Sustainability is concerned with the integration of social equity, economic growth, and environmental preservation, also considering their effects on each other. These three dimensions have been integrated into a multidimensional line of thought encompassing an individual and a technical dimension [11]. Each dimension addresses different needs (e.g., improve employment indicators, reduce costs, reduce CO_2 emissions, promote high agency and easy system evolution) and impacts on the others and respective stakeholders. Therefore, sustainability-aware systems differ from other types of systems in that their functionality must explicitly balance the trade-offs between these dimensions [12].

There is no common definition of sustainability in Software Engineering. Some existing works handle sustainability as a non-functional requirement (e.g., [13]), but we prefer to think of sustainability as "an emergent property of a software system" [14] that should not be added to the software system in later stages of the development nor looked into in isolation. In general, we agree with the vision of "sustainability as a complex composite quality attribute, formed of five complex aggregates of quality attributes, one per dimension, which, in turn, is composed of the quality attributes relevant for that dimension" [12].

In this paper, we will focus on the technical dimension of sustainability, perceiving it as the "longevity of systems and infrastructure and their adequate evolution with changing surrounding conditions"[5].

Sustainability in CPS. When discussing sustainability in software, we typically distinguish between *sustainable software*, which code satisfies good principles of sustainability (e.g., energy efficiency, adaptability, etc.) and *software for sustainability*, which supports sustainability goals, such as those of the five sustainability dimensions (environmental, social, economic, individual, and technical). Ideally, both interpretations should coexist in a software system to contribute to a more sustainable lifestyle. Thus, sustainable software is energy-efficient, minimises the environmental impact of the processes it supports, has a positive impact on society and the economy, is inclusive and harms no one, and is amenable to evolve to increase its longevity. These impacts can occur directly (energy), indirectly (mitigated by service), or as a rebound effect [15].

In our context, a sustainable CPS is "capable of enduring without compromising its requirements, while renewing the system's resources and using them efficiently" [1] as defined by Gunes et al. They propose four fundamental quality attributes to produce such a system: adaptability, resilience, reconfigurability, and efficiency.

Adaptability refers to the capability of a system to change its state in response to evolving needs and changing environments. Thus, a highly adaptable system should quickly adjust to novel needs or circumstances.

Resilience refers to the ability of a system to recover from faults quickly, preserving its operation and delivering services with acceptable quality in case the system is exposed to any inner or outer difficulties (e.g., sudden defect, malfunctioning components, security breaches, etc.). Hence, a resilient system should be self-healing and comprise early detection and fast recovery mechanisms against failures to continue meeting the demands for its services.

Reconfigurability, on the other hand, enables a system to change its configurations in case of failure or upon inner or outer requests. A highly reconfigurable system should be self-configurable, meaning it can fine-tune itself dynamically and coordinate the operation of its components at a finer granularity.

Finally, *Efficiency* refers to reducing and optimising the number of resources (such as energy, cost, time, etc.) the system requires to deliver the specified functionalities. A highly efficient system should operate properly under the minimal required amount of resources. Note that, unlike the other three qualities, efficiency is considered under nominal, unperturbed conditions.

2.2. Related Work

During our SMS planning phase, we identified several secondary studies addressing CPS, CPS modelling, and sustainability, but none specifically focused on the modelling of sustainable CPS, reinforcing the need for our work. We gathered relevant related studies in two stages: initially, during the planning phase, to explore existing work and assess the necessity for our systematic study; and later, during the classification phase, to analyse the secondary studies identified for more detailed insights.

These studies were distributed among three authors for review and categorisation based on their relevance to CPS, CPS modelling, and sustainable software. In total, 19 studies were found to be directly relevant. Of these, 2 focused on CPS (not necessarily on its modelling) [16, 17], 8 on CPS modelling [18–25], 6 on sustainable systems (not CPS) [15, 26–30], and only 3 discussed both CPS and sustainability [31–33]. Even if these last two studies focus on CPS and sustainability, they do not address the modelling of "sustainable CPS". This highlights the novelty of our research.

Table 1 summarises the focus of the selected studies. The first two studies *focus on CPS without delving into specific modelling approaches.* Zhong et al. [16] present a comprehensive review of CPS-related topics, including IoT-enabled manufacturing and cloud computing in the context of intelligent manufacturing, emphasizing key enabling technologies like big data analytics and ICT. Similarly, Roy et al. [17] explore CPS in industrial environments, discussing the challenges of maintenance in Industry 4.0, particularly in terms of IoT integration, emphasising security concerns as a challenge in industrial contexts.

The next eight studies explore *CPS with a focus on modelling.* Wortmann et al. [19] extend their previous mapping of modelling languages in Industry 4.0, offering a more recent and thorough review of modelling approaches. Chen et al. [21] address the challenges and advances of modelling for smart and sustainable enterprises, focusing on five distinct viewpoints—enterprise, information, computational, engineering, and technology—to present existing modelling approaches for CPS. Svendsen et al. [22] provide an overview of modelling approaches for critical infrastructures, highlighting techniques used to model both physical and information systems. Mosterman et al. [23] propose a model-based research agenda for the design and operation of CPS, addressing key challenges in modelling, technology implementation, and organisational aspects of CPS. Hehenberger et al. [24] discuss the transition from mechatronics to CPS, focusing on design challenges from the perspectives of physical processes, computation, and integration in cloud-based (IoT) systems. Zhuge et al. [25] introduce a methodology for modelling cyber-physical-socio-intelligence systems, which integrates physical, cyber, and social aspects into a unified model, highlighting the complexity of interactions in CPS. Additionally, Barisic et al. [18] review models and development processes for multi-paradigm modelling of CPS

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

Paper	**CPS**	**CPS Modelling**	**Sustain.**	**Focus of the study**
[16]	X			IoT, CPS, and cloud computing in intelligent manufacturing.
[17]	X			Maintenance in the industrial context, and the challenges of CPS maintenance.
[18]		X		Models, formalisms, and development processes used over the last decade for multi-paradigm modelling of CPS 4.0.
[19]		X		Application of modelling languages in Industry 4.0.
[20]		X		Model-driven engineering for CPS.
[21]		X		Challenges and current developments for sensing, smart and sustainable enterprises.
[22]		X		Modelling of critical physical and information systems.
[23]		X		Challenges and corresponding technologies for designing CPS.
[24]		X		Design and development methodology of CPSs.
[25]		X		Modelling Cyber-physical-socio-intelligence.
[26]			X	ICT of urban forms.
[27]			X	Digitisation of a food package's life cycle.
[28]			X	Sustainability in manufacturing operations scheduling, focusing on Energy Efficiency.
[15]			X	SE methods for sustainable software.
[29]			X	Resilience of IT and Computer Systems.
[30]			X	Sustainability in manufacturing scheduling.
[32]	X		X	Smart grids and aspects of sustainability.
[31]		X	X	Sustainable interoperability in networked enterprise information systems.
[33]		X	X	Understand, measure, and model the resilience approaches for CPS.

4.0, focusing on the evolving complexity of CPS and the formalisms required to address this challenge. Mohamed et al. [20] discuss model-driven engineering approaches to CPS, emphasizing the challenges of integrating multiple models to represent the interaction between physical and digital components in CPS.

The following six papers *focus on sustainability* address various aspects of sustainable systems, though none are directly related to CPS or its modelling. Bibri et al. [26] present a literature review on the role of ICT in developing sustainable urban forms, particularly focusing on smart cities, but their work does not involve CPS or embedded systems. Vanderroost et al. [27] explore the digitisation of the food packaging life-cycle, focusing on efficiency improvements in reducing food loss and operational costs, but only touch briefly on CPS-related technologies like sensing. Giret et al. [28] discuss sustainability in manufacturing, specifically regarding energy-efficient scheduling systems, but do not consider CPS or its dynamic modelling. Penzenstadler et al. [15] conduct a systematic mapping study on software engineering methods for sustainability, distinguishing between sustainable software as a product and software aimed at achieving sustainability goals, yet their work does not overlap with CPS. Bondavalli et al. [29] provide a research roadmap on assessing and improving resilience in IT and communication systems, touching on aspects of sustainability but without focusing on CPS. Finally, Koziolek et al. [30] review methods for evaluating software architecture sustainability, highlighting the need for empirical studies, but their focus remains on software architecture rather than CPS.

The *intersection of CPS and sustainability* is explored in three studies. Camarinha-Matos [32] surveys smart grids, examining various aspects of these systems, including sustainability factors such as security, resilience, and self-healing. However, this work focuses explicitly on smart grids as a distinct type of CPS rather than encompassing a broader range of CPS applications. Similarly, Agostinho et al. [31] review research in Enterprise Information Systems (EIS), addressing interoperability and model-driven development to promote network sustainability. They emphasise the importance of monitoring and controlling future EIS for sustainable innovation, yet their findings are limited to this specific domain, diverging from our broader investigation of CPS. Finally, the study by Colabianchi et al. [33] presents a comprehensive review of the literature on the resilience of CPS, framing these systems as socio-technical constructs that necessitate analysis from both technical and social perspectives. This contrasts with our work's focus on the technical dimensions of CPS modelling, highlighting the multifaceted nature of sustainability within CPS.

3. Research Method

Evidence-based Software Engineering provides core tools for evidence-based empirical studies, including secondary studies of research literature. An SMS provides a reliable and rigorous methodological process to conduct a bibliographic survey [34, 35] based on primary studies[1].

This paper reports on an SMS we performed to *identify and analyse CPS modelling approaches addressing sustainability*, published in the period between 2011 and 2021. We aim to identify model-driven methods and tools that lend themselves to a more systematic process of engineering the capabilities of self-healing, dynamic tuning, and good use of resources in CPS.

We summarise the state-of-the-art research trends and categorise the extracted methods, models, processes, tools, metrics, and application domains to assess the sustainability of CPS.

The details of the pre-planning and planning phases of our study are reported in Appendix A for the sake of reproducibility, and what follows is a brief summary. In Section 3.1, we introduce our research question; in Section 3.3, we report on the Conduction phase; and in Section 4, we report our results.

3.1. Research Question

The overall objective of our study is to offer an overview of the state-of-the-art modelling of sustainable CPS. Thus, our main research question (RQ) is: *What modelling approaches exist for addressing sustainability of CPS?* We divided this question into nine sub-questions addressing specific aspects which are relevant to answering our research question (see Table 2). We determine which sustainability attribute is addressed (Q1), as defined in Section 2.1, the sustainability approach to achieving this attribute (Q2–Q5), the modelling approach supporting sustainability (Q6–Q8), and the application domain(s) reported in the study (Q9).

Table 2: Research sub-questions

Id	**Question**	**Results**
Q1	Which sustainability attribute is addressed?	Sec. 4.1
Q2	Which method is used to address sustainability?	Sec. 4.2
Q3	What kind of sustainability metric is used?	Sec. 4.3
Q4	What type of model is used to specify sustainability?	Sec. 4.4
Q5	What instance of model/meta-model is used to specify sustainability?	Sec. 4.5
Q6	What modelling process is used?	Sec. 4.6
Q7	What modelling tool is used?	Sec. 4.7
Q8	Is the modelling approach domain-specific?	Sec. 4.8
Q9	Which application domain is addressed?	Sec. 4.8

Our search queries were built based on a *PICOC analysis* (Population, Intervention, Comparison, Outcome, Context) (see Table A.6) and updated based on findings from relevant related work. These queries were thoroughly tested in the four digital libraries: ACM, IEEE, Springer Library (SL) and Science Direct (SD). They were also validated in a workshop with researchers from the

[1]A primary study is an individual study that contributes to a systematic review [36].

NOVA LINCS research centre who have significant experience in performing and evaluating systematic studies.

3.2. Inclusion and Exclusion Criteria

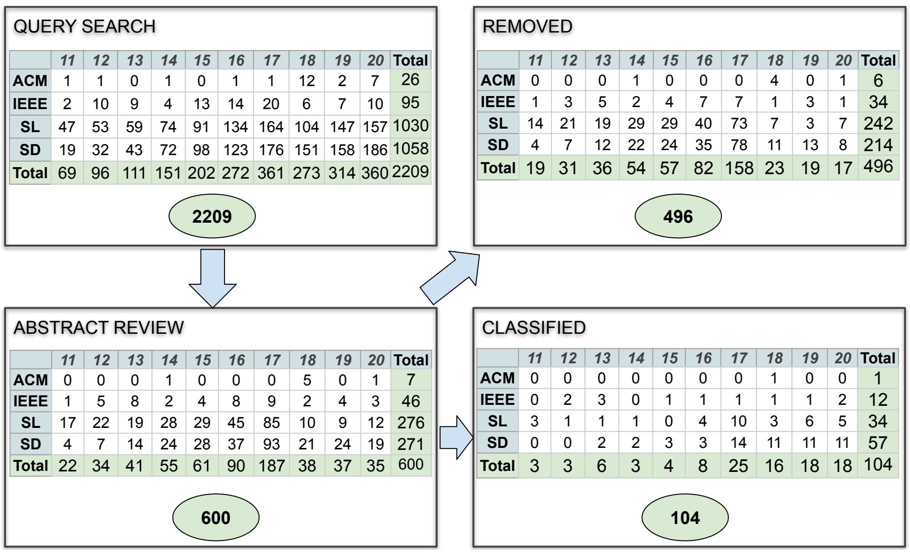
To select relevant publications that answer our research question, we define the inclusion (I_i) and exclusion (E_j) criteria described in Table 3. The goal of these criteria is to support a uniform, consistent, and efficient process of extracting the data from papers. Based on our intended scope, we include peer-reviewed articles (to ensure minimal quality), reporting on modelling of CPS or/and sustainability assessment reported in the period from January 1, 2011, to January 1, 2021. We exclude informal literature (to ensure a minimal amount of technical content), secondary studies (to ensure a clear focus on original technical contributions), duplicated work or its extension, and works written in languages other than English (to ensure that all the authors can understand the studies in a comparable fashion). The inclusion and exclusion criteria were were applied first during the selection phase of titles, keywords, and abstracts of the primary studies and then during the full-text reading of those selected articles.

Table 3: Inclusion (first part) and Exclusion (second part) criteria

Id	**Criteria**
I1	Publication date from 1/1/2011 to 1/1/2021.
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.
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 answer any of our research questions, that is, that 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	Papers addressing only hardware, or with an exclusive emphasis on electrical engineering.
E7	Papers only addressing the application of sustainability in environmental domains (e.g. agricultural papers).
E8	Papers mentioning Environmental in terms of system's operational context and not impact in the biophysical environment.

3.3. Conduction phase

The conduction phase consisted of three main activities: Query Search, Abstract Review, and Classification (see Figure 1). We executed the search string on each digital library during the Query Search activity. 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. We conducted an initial analysis for this set of studies and reported it in our technical report [37]. The final set of papers was retrieved in March 2021. After removing the duplicates, we obtained 2209 papers, most of which were from Science Direct (47.89%) and Springer Library (46.63%).



QUERY SEARCH

	11	12	13	14	15	16	17	18	19	20	Total
ACM	1	1	0	1	0	1	1	12	2	7	26
IEEE	2	10	9	4	13	14	20	6	7	10	95
SL	47	53	59	74	91	134	164	104	147	157	1030
SD	19	32	43	72	98	123	176	151	158	186	1058
Total	69	96	111	151	202	272	361	273	314	360	2209

REMOVED

	11	12	13	14	15	16	17	18	19	20	Total
ACM	0	0	0	1	0	0	0	4	0	1	6
IEEE	1	3	5	2	4	7	7	1	3	1	34
SL	14	21	19	29	29	40	73	7	3	7	242
SD	4	7	12	22	24	35	78	11	13	8	214
Total	19	31	36	54	57	82	158	23	19	17	496

ABSTRACT REVIEW

	11	12	13	14	15	16	17	18	19	20	Total
ACM	0	0	0	1	0	0	0	5	0	1	7
IEEE	1	5	8	2	4	8	9	2	4	3	46
SL	17	22	19	28	29	45	85	10	9	12	276
SD	4	7	14	24	28	37	93	21	24	19	271
Total	22	34	41	55	61	90	187	38	37	35	600

CLASSIFIED

	11	12	13	14	15	16	17	18	19	20	Total
ACM	0	0	0	0	0	0	0	1	0	0	1
IEEE	0	2	3	0	1	1	1	1	1	2	12
SL	3	1	1	1	0	4	10	3	6	5	34
SD	0	0	2	2	3	3	14	11	11	11	57
Total	3	3	6	3	4	8	25	16	18	18	104

Figure 1: Conduction process and primary studies by year and library

The papers were added to an Excel workbook with their abstracts and conclusions. In the Abstract Review, we decided whether to include/exclude the study for the classification phase based on criteria presented in Table 3. We were more inclusive in this phase, keeping the papers mentioning sustainability OR modelling of CPS for the second phase. The papers marked for exclusion were 271 for SD, 276 for SL, 46 for IEEE, and 7 for ACM. The remaining 600 papers were imported to the Mendeley Library, and their full texts were downloaded for subsequent classification.

Finally, during the classification activity, we prepared a separate individual data extraction sheet and randomly assigned each paper to one reviewer. The researchers read their assigned papers and decided whether the paper contributed to our research objective. Papers that did not present an original modelling approach for the sustainability of CPS were excluded. Since one paper could fit under several inclusion/exclusion criteria, it was marked as included or excluded. Recognizing the potential for subjectivity in this process—given that only one reviewer made the decision for each paper —we address this limitation in more detail in Section 4.12. In total, reviewers excluded 496 papers during this iteration and classified 104 papers (57 papers from SD, 34 from SL, 12 from IEEE, and only 1 from ACM). We observed a boost in the number of publications on modelling and sustainability for CPS from 2016.

We make our complete archive of the retrieved data available at [38]. It contains the metadata of all analysed papers in two different spreadsheets, one with the included papers and the other with the excluded ones. The availability of all this data supports the reproducibility of our work.

4. Discussion of the Study Results

This section discusses the findings of our SMS. Besides presenting the results for each RQ, we also show the correlation of each question with the sustainability attributes, as sustainability is one of the most important aspects of our work. In this section, we use the word "correlation" broadly, referring to notable observations from two-way contingency tables between answers to a pair of research questions.

4.1. What sustainability attribute is addressed? (Q1)

The sustainability attributes considered for this research question were initially provided by Gunes et al. [1]. In the context of model-driven sustainability approaches for the CPS, we merge the sub-characteristics of adaptability and reconfigurability into one category: Adaptability. The main motivation for this merge is that most model-driven approaches focus on building self-adaptive CPS, which can change the internal configuration concerning the outside (environmental) or internal (operational) properties. The self-adaptive system aims to adjust various artefacts or attributes in response to changes in the device and the context of a complete system. Researchers in this area have proposed several solutions to incorporate adaptation mechanisms into CPS. The adaptation infrastructure implements self-adaptive capabilities to monitor, detect, decide, and act based on adaptation knowledge. When the adaptation is implemented in the runtime, it is called dynamic adaptation. A summary of the results discussed further are described in Table B.8.

4.1.1. Efficiency

More than half of the selected primary studies (55%, 57 out of 104) address *efficiency*, or the *good use of resources*. In this context, highly efficient systems operate properly while using their resources optimally and without waste. A typical theme in efficiency papers is reducing the used resources or predicting it with a longer-term goal of reducing it. The most commonly considered resource is, unsurprisingly, the energy, primarily in its electrical form (e.g., in smart cities [55], medical devices [56], and electric vehicles [57]). Other kinds of resources considered include water [58], computational power [59], and time [60]. Occasionally, studies target abstract notions of resource efficiency that can be specialised to a variety of resources [61, 62]. A sub-category of efficiency studies focuses on accurate quantification and prediction of energy consumption [63–65], expected to translate into long-term energy savings. The high proportion of efficiency papers and the wide range of considered resources highlight the *importance and variety of efficiencies* essential for sustainable CPS.

4.1.2. Resilience

Resilience is the second highly discussed attribute (in 33%, 34 out of 104 studies). Colabianchi et.all. [33] have studied the resilience of CPS and found three possible dimensions of resilience: *i) monitor and detect a fault or threat*; *ii) mitigation, fault tolerance, and vulnerability*; *iii) recovering.* Indeed, all these works present modelling, and in some cases measurement, the approach of resilience, thus fitting the first dimension [66–86]. They can range from modelling attacks [72], to monitor physical sensors' faults [87]. Moreover, several of these works address the verification of CPS at design time, e.g., [73, 75, 76]. The second dimension is also covered, but only by a single paper [87]. In this case, the CPS aims to mitigate faults in physical sensors by following different strategies. Finally, the third dimension is also covered, as in some cases, the authors present approaches that allow the CPS to recover from faults [88–97]. These include methodologies that discard new reading if considered faulty until regular ones are detected, resuming it regular operation at that time [90], or that send a different robot to complete a task if a failure is detected in multi-robot missions [91].

An increasingly important aspect is the need for these systems to incorporate human interaction (human-in-the-loop) when addressing resilience [33]. However, as also pointed out by others (e.g., [33]), significant progress is still needed in this area. Only two papers (of 34 addressing resilience) consider humans in their approaches [72, 83, 88]. In [72], the authors explicitly include human interactions with the system in the proposed model, but no particular attention is given to humans when addressing resilience. On the other hand, in [83], the authors propose a semantic framework with human-in-the-loop for facilitating automation in vulnerability assessment. Seiger et al. [88] propose *framework for self-adaptive workflows in CPS based on the MAPE-K feedback loop*, which includes human tasks as a possible solution for failures that occur during the process.

Since the papers of our study are focused on modelling CPS, it is no surprise that most of them are concerned with (formally) verifying or assessing resilience during the design phase. Moreover, although several works address recoverability, only one covers mitigation. This indicates that several works target a complete approach rather than *just" the mitigation of faults. From the data, we can also conclude that almost all the works seem to ignore the human-in-the-loop.*

4.1.3. Adaptability

About 29% (30 out of 104) of the approaches address *adaptability*, indicating the capability of a system to change its state to survive by adjusting its configuration in response to different circumstances in the environment or internally, e.g., a rising workload, uncertainties, or failure.

For adaptability based on the *internal properties* of systems, most approaches are architecture-based, focusing on self-adaptation in the presence of operational uncertainty caused by inaccuracies of sensed data and unreliable communication. To give a solution to these problems [39] introduces the Invariant Refinement Method for Self-Adaptation (IRM-SA) to capture high-level system goals and requirements in terms of invariants and, by their systematic refinement, to identify system components and their desired interaction. [40] introduces an approach for modelling multi-perspective process variability as a conceptual model capable of capturing people, data and things variability and targets stakeholders working in large-scale CPS. [41] introduces service-oriented model decomposition as a pragmatic approach to grasp the system functionality formally while simultaneously keeping independent of the concrete implementation of the functionality. [42] introduces an architecture for a cyber-eco system with cyberinfrastructure to control key ecosystem drivers at fine spatiotemporal scales that are expected to enable various concurrent long-term experimental studies. [43] proposes the design of self-adaptive software components based on logical discrete control approaches, in which the self-adaptive behavioural models enrich component controllers with knowledge not only of events, configurations and history but also of possible future configurations. [44] proposes the faults and the adaptation policy modelling method to develop a self-adaptive robot.

Regarding the **adaptation to environmental conditions**, we have goal-based approaches that optimise the input data. [45] presents an optimisation modelling method that monitors a CPS's environment and qualities to provide design-time and runtime solutions that satisfy the required goals of the system and its stakeholders by combining arithmetic functions generated automatically from goal and feature models as objective function input to an optimisation tool to compute, at design time, optimal solutions for common situations. [46] introduces the dependable information processing (DIP) method for handling multi-attribute environmental information in a smart city application. Information sensed from the environment is categorised in the initial stage regarding how it meets application requirements. It helps to identify the need and response of the application through different interacting spans and previous trials. [47] presents a system dynamics model incorporating fuzzy logic to simulate the adoption process. [48] uses downscaled global climate models (GCMs) to evaluate the effects of non-stationarity on air temperature forecasts. [49] introduces The Sustainable, Smart and Sensing Enterprise Reference Model (S3E-RM) - a methodology based on the action-research concept to pursue understanding and facilitating its implementation in Small and Medium Enterprises. [50] uses multi-agent systems as a suitable solution to address this challenge by analysing their benefits when applying them to the field of Smart Grids and surveying existing works and initiatives. Thus, we discovered a wide variety of adaptation techniques.

4.1.4. Combination of Attributes

The majority of the papers are concerned with one sustainability attribute. However, 17 papers target at least 2 attributes. The most common combination is *efficiency and adaptability*, addressed in 11 papers [40–42, 50, 98–104]. 4 studies address efficiency and resilience [74, 80, 85, 87], and only 2 address resilience and adaptability [84, 95]. Finally, 4 papers are addressing the combination of resilience and efficiency [74, 80, 85, 87].

4.2. What method is used to address sustainability? (Q2)

To characterise the methods to address sustainability, we followed the categorisation by Pezenstadler et al. [51] and summarised in Appendix A.3.3.

Among the studies reporting sustainability methods, 79% (82 out of 104) of the papers report a method used to address some sustainability concern, while 21% do not report any method. A little less than half of the papers (50 out of 104 studies, corresponding to 48%) use *life cycle analysis*, an iterative method widely employed to evaluate the life cycle environmental impact of a system. The results are used to help select products or processes that will positively impact the environment.

The *cost calculation* method is used by 21% of the primary studies to calculate and optimise the possible cost of each item that affects the standard cost of the system in terms of energy and time, for example. Approximately 14% of studies use *entity-relationship modelling* to describe interrelated aspects relevant for the sustainability needs of a CPS. Finally, only 4 papers (4% of the total) use *neural networks* (which are at the heart of deep learning algorithms) and are expected to provide adequate engineering support for achieving sustainable systems. Thus, we see that the *life cycle of the system* is central to enhancing its sustainability in general.

From the works we analysed, 9 studies use 2 techniques, of which 6 combine life cycle analysis with cost calculations [95, 96, 105–108], 2 combine entity-relationship modelling with cost calculations [61, 109], and 1 combines entity-relationship modelling with life cycle analysis [99]. Table B.9 summarises these findings.

Finally, Figure 2 depicts a summary of the relationship between methods and sustainability attributes, showing that neural network approaches do not address resilience. Moreover, all three attributes are addressed by the remaining methods, although for cost calculations, it is possible to see more prominence of works addressing efficiency.

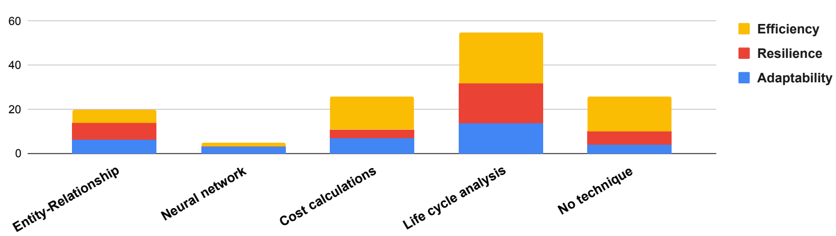


Figure 2: Relation between methods (Q2) and sustainability attributes (Q1).

4.3. What kind of sustainability metric is used? (Q3)

From the total 104 studies, 55 (53%) report some kind of sustainability metric, while 49 (47%) discuss no metrics at all, as summarised in Table B.10.

From the 55 studies discussing metrics, we distinguish three scenarios: *(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 (qualitative or quantitative) metrics to evaluate case studies. Within these studies, two propose new metrics to measure or qualify different aspects of sustainability, and another two propose some kind of framework or mathematical formulation that accepts metrics defined externally to measure a system's sustainability, and 19 use metrics to evaluate a case study.

From all the studies reporting metrics, 39 (71%) present quantitative metrics, 7 (13%)) present qualitative metrics, and 2 (4%) present both qualitative and quantitative metrics [61, 85]. Thus, we observe that primarily *quantitative sustainability metrics* are used often — although not universally.

We analyse the various categories of metrics against the sustainability attributes under study (Figure 3). We can see that most of the quantitative metrics are for the efficiency attribute. We can also see that the only frameworks proposed are for efficiency. The papers that use metrics for evaluating the case studies are quite well distributed amongst the three sustainability attributes. Finally, no papers proposing new metrics or frameworks address resilience.

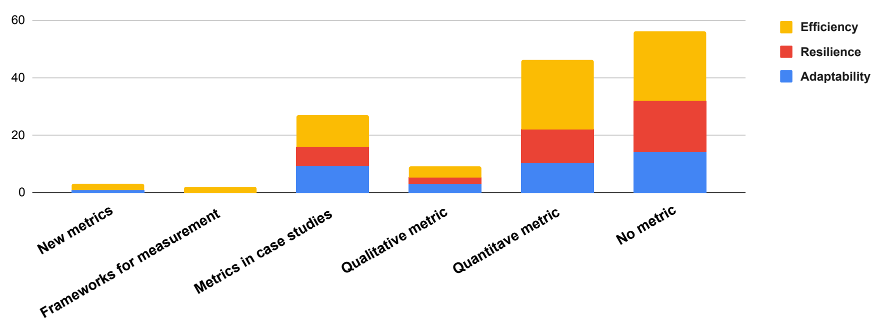


Figure 3: Relation between metrics (Q3) and sustainability attributes (Q1).

4.4. What type of model is used to specify sustainability? (Q4)

We classified models into behavioural, algorithmic, architectural and mathematical and organised the extraction form accordingly to facilitate data collection. These model types naturally arose from the process of iterative refinement of model types. While a behavioural model (e.g., UML activity, sequence, interaction diagram) describes the dynamic (runtime) behaviour of a system, showing what happens, or what is supposed to happen, when a system responds to a stimulus from its environment, an algorithmic model takes the form of an algorithm. On the other hand, an architectural model is a rigorous diagram created using available standards to illustrate a specific set of views inherent in the structure and design of a system and is organised in a way that supports reasoning about the structures and static behaviours of the system (e.g., UML component diagram). Finally, a mathematical model uses mathematical language to describe the behaviour of a system (e.g., differential equations to specify the physical properties of a component).

A little over half of the studies (55%, 57 out of 104) use some type of model to represent sustainability-related issues, as summarised in Table B.11. Of these, most studies (19, corresponding to 33%) use some kind of *behavioural model*, 17 (30%) use mathematical models, 14 (25%) use architectural models. Thus, we observed a diverse and balanced spread of model types, motivating a more detailed look at the models in the next question, Q5. The remaining 47 studies (45%) use no models at all.

When analysing the types of models considering the sustainability attributes, displayed in Figure 4, we can see that efficiency is highly amenable to analysis across all types of models.

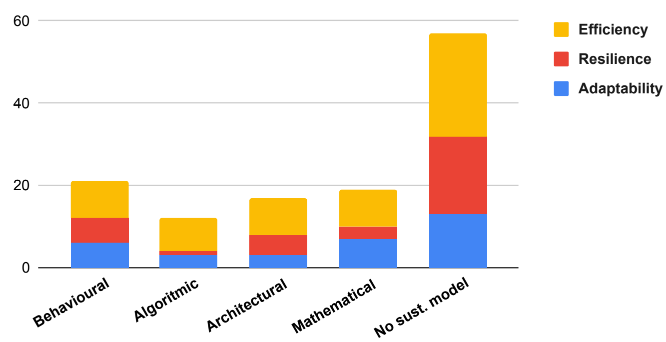


Figure 4: Relation between types of models (Q4) and sustainability attributes (Q1).

4.5. What instance of model/meta-model is used to specify sustainability? (Q5)

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 to 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*. To refine our results, the categories were iteratively merged with each other without losing the level of specificity. This process resulted in 12 mutually exclusive[2] high-level categories of models:

[2]Although the categories are mutually exclusive, each paper may use more than one model, therefore, the sum of all percentages is greater than 100%.

- *Equational* models included explicit equation-based modelling with differential equations, optimisation problem constraints, and structural equations in bond graphs. This category accounts for 17% of all models.
- *Component* models include any architectural or component-based models, excluding UML-like models (which form a separate category). These models account for 15% of all models.
- *Automata* include finite state machines, hybrid automata, probabilistic state machines, and other types of automata. This category accounts for 14% of all models.
- *Dataflows* include models focused on data exchange, such as block diagrams, synchronous dataflow models, and Simulink models. This category accounts for approximately 13% of all models.
- *Custom graphs* include specialised graph-based models that do not fall into the UML-like, component, and process categories. This category accounts for 9% of all models.
- *Program*-like formalisms include imperative languages similar to high-level programming languages. This category accounts for 9% of all models.
- *Meta-models* include language syntax models, data schemas, meta-models for agent descriptions, and other models of models. This category accounts for 8% of all models.
- *UML*-like models are based on UML, its profiles (most prominently, MARTE) and similar languages (most prominently, SysML). This category accounts for 8% of all models.
- *Process* models include formalisms that focus on the process of the system's evolution, such as Petri nets and process algebras, but exclude the dataflow and UML-related models from other categories. This category accounts for 6% of all models.
- *Specifications* include declarative system descriptions such as Z and UTP that do not fall into any other groups. This category accounts for 5% of all models.
- *Variability* models include feature models and similar methodologies and languages. This is the smallest among the named categories, and it accounts for less than 3% of all models used.
- *Other* models include all other types of explicitly reported models that did not fit into the above categories and did not merit the creation of another high-level category. This category accounts for about 8% of all models.
- Approximately 12% of the primary studies did not report any instance of a model/meta-model.

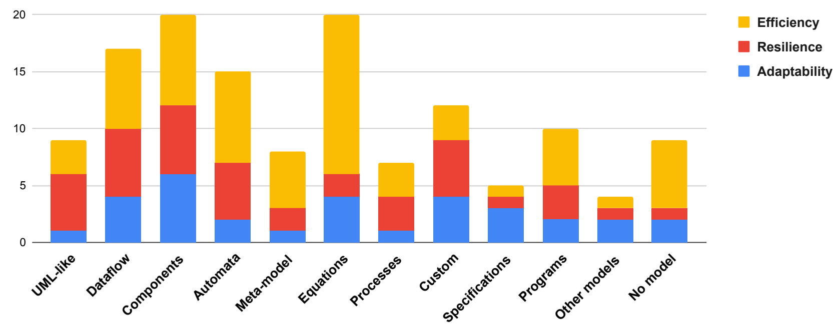


Figure 5: Relation between model instances (Q5) and sustainability attributes (Q1).

This information is further summarised in Table B.12.

Figure 5 presents the relationship between the model type and the sustainability attributes. From this figure, we can see that *equations* are the most used model type for efficiency (14 papers), followed by *automata* and *components* (8 papers). Resilience tends to be implemented with a *wide variety* of models: dataflow/components (6 papers each) and UML-like/automata/graphs (5 papers each). Adaptability is most commonly implemented with *component models* (6 papers), followed by dataflows/equations/graphs (4 papers for each type). We can also see that each model type has been used to address the three sustainability attributes.

4.6. What modelling process is used? (Q6)

Only 46 studies (44% of all studies) propose or report a process (see Table B.13 for more details). 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 diagrams, and other notations with precisely 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.

The most prominent way to represent a process is via an *informal graph.* The number of processes reported as informal text and formalised diagrams are similar. Together, the informal processes account for 80% of papers with processes and 36% of all studies.

Therefore, process descriptions in CPS sustainability research are mostly informal.

In Figure 6, we illustrate the number of primary studies that address sustainability and follow some modelling processes. It is possible to see that efficiency is mostly addressed using informal graphical processes. Like with the models, each sustainability attribute can be supported by any of the three types of processes.

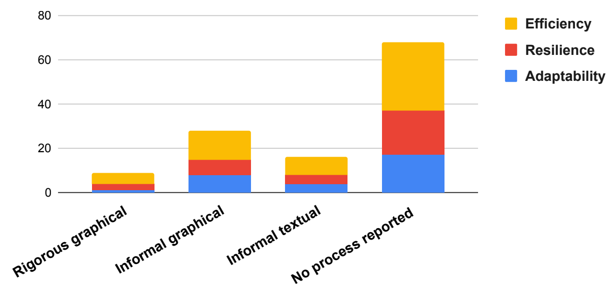


Figure 6: Relation between modelling processes (Q6) and sustainability attributes (Q1).

4.7. What modelling tool is used? (Q7)

As summarized in Table B.14, of the 104 total number of primary studies included in our analysis, only 37 (36%) were reported using some tool, while in 67 studies (64%) 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 parts of a CPS system and including some sustainability attributes.

These tools can be divided into 4 categories:

- *Eclipse-based/Papyrus-based.* This category contains the tools that are built based on the Eclipse platform. This category accounts for only 2 of 104 papers that reported using tools.

- *SysML/UML/MARTE-based.* This category contains profiles that are developed as extensions of the SysML/UML/MARTE model. Only one paper reported using this kind of tool.

- *Matlab/20-sim/Simulink/Modelica/UPPAAL-based.* This category contains tools that present some extensions or use general purpose modelling tools like Matlab, Simulink, Modelica and UPPAAL. This category accounts for 4 papers.

- *Custom tools.* This 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 30 papers.

According to the reported tools, we can conclude that using them to model CPS and their sustainability is *quite limited*. Contrary to our expectations, only 7% of the papers use well-known tools for modelling CPS, like Matlab or Simulink. Instead, we found some new proposed tools, such as COSEML [101], INTO-CPS [96], GreatSPN [110], Providentia [109], S.P.L.O.T. [99], DarwinSPL [111], MoSH [93], SAURON [81], ASPN [65], Cooja [80], FaMa and CyberSPL [77], or IBM CPLEX [45].

We noticed that papers that address adaptability do not use tools from the three specific categories we selected. Also, researchers developed new tools in almost an equal amount for each category. Indeed, for adaptability and efficiency, 11 news tools were proposed, while 12 were proposed for resilience.[3]

4.8. Is the modelling approach domain-specific? (Q8) and Which application domain is addressed? (Q9)

This section analyses whether the approaches reported by the primary studies are domain-specific (Q8) and also the application domains focused on by the studies (Q9). To facilitate data collection, we pre-defined the following list of application domains used in an existing study [1]: Smart Manufacturing, Emergency Response, Air Transportation, Critical Infrastructure, Health Care and Medicine, Intelligent Transportation, Robotic for Service, and Building Automation. If none of these were suitable, the reviewer was asked to add another domain to the description section.

Among the total of 104 studies, a total of 62 studies (60%) discuss a domain-specific approach (more details can be found in Table B.15). The remaining 42 (40%) studies discuss general-purpose approaches.

Most of the 104 studies propose domain-specific approaches (54 studies, about 87%) fall in one of our pre-defined domains.

14 (about 14%) of the studies address *Critical Infrastructure*, being this category the most tackled one.

In the second and third places, we have *Smart Manufacturing* and *Building Automation* application domains with 12 studies (about 11%) and 9 studies (about 9%) of the studies, respectively. Note that each paper reported at most one domain application. Some of the studies (8, about 8%) reported a domain outside of our categories. For instance, [77] addresses smart agriculture, and [46] addresses smart cities.

Figure 7 presents the relationship between sustainability attributes and application domains. Smart manufacturing and building automation are mostly related to the efficiency attribute. Although in most domains, efficiency is dominant, it is not present in any of the papers on robotics for service. Moreover,

[3]Some works address more than one sustainability attribute, and thus, the sum accounts for 34 and not 30.

critical infrastructures are also quite related to the resilience attribute, being of the three attributes the most represented one. However, *resilience is not addressed* in several domains (smart manufacturing, health care and medicine, and intelligent transportation) — an opportunity for future research.

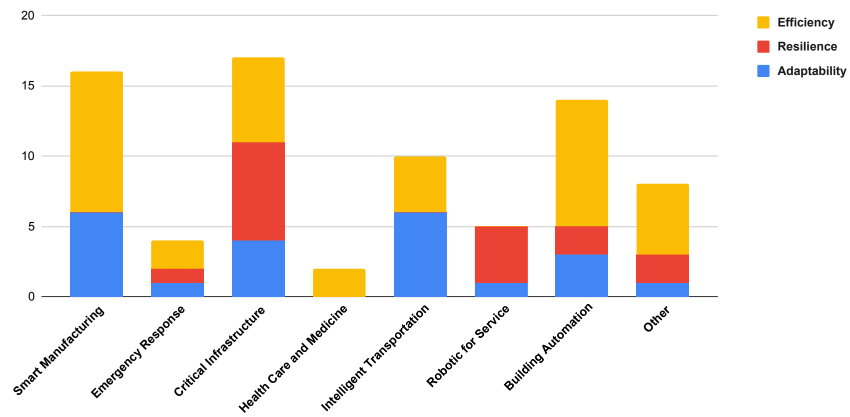


Figure 7: Relation between application domains (Q9) and sustainability attributes (Q1).

4.9. Noteworthy Relations between Research Questions

This section reports our findings when comparing the extracted data for pairs of research questions (other than Q1, reported above).

Most cost calculation studies use quantitative metrics. The majority (56%, 15 out of 27) of cost-calculation studies use quantitative metrics, perhaps unsurprisingly so, as shown in Figure 8. At the same time, among the papers with sustainability techniques, the life cycle analysis ones are least likely to report a metric (44%, 25 out of 57, do not report one).

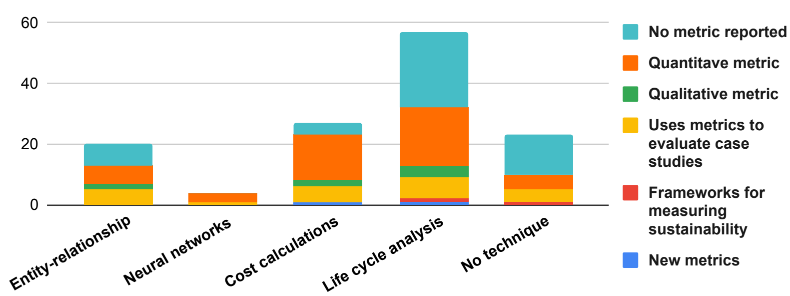


Figure 8: Relation between sustainability techniques (Q2) and metrics (Q3).

Behavioural sustainability is mostly addressed with life cycle analysis, with 62% (13 out of 21) of the studies. At the same time, algorithmic sustainability has the highest chance of being addressed with neural networks (27%, 3 out of 11) but not with entity-relationship modelling (we found no such studies). We also note that mathematical sustainability has the highest chance of being addressed with cost calculations or life cycle analysis (both with 42%, 8 out of 19). Figure 9 shows such relations between model types and sustainability models in papers that reported a sustainability model.

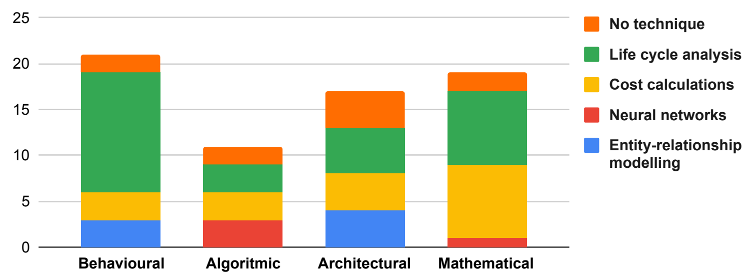


Figure 9: Relation between sustainability techniques (Q2) and model types (Q4).

Cost calculation and life cycle analysis techniques use mostly equational models, both counting 40% of them (8 out of 20), while cost calculation techniques do not use meta-models or processes, in our experience. Figure 10 shows the distribution of sustainability techniques in papers that reported model instances.

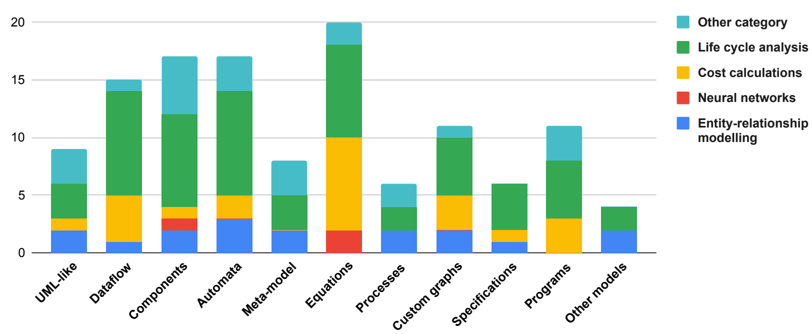


Figure 10: Relation between sustainability techniques (Q2) and model instances (Q5).

Life cycle analysis is compatible with various models. This observation can be witnessed in Figures 9 and 10: the life cycle analysis technique is substantially used with each model type and instance, thus suggesting its versatile, universal nature.

The use of metrics and cost calculations is mostly domain-specific. Quantitative metrics are used in domain-specific studies in 74% of cases (29 out of 39).

Interestingly, all of the 7 studies with qualitative metrics are domain-specific. Cost calculations are used in domain-specific studies in 77% of cases (17 out of 22). The rest of the sustainability techniques roughly balance domain dependence and independence.

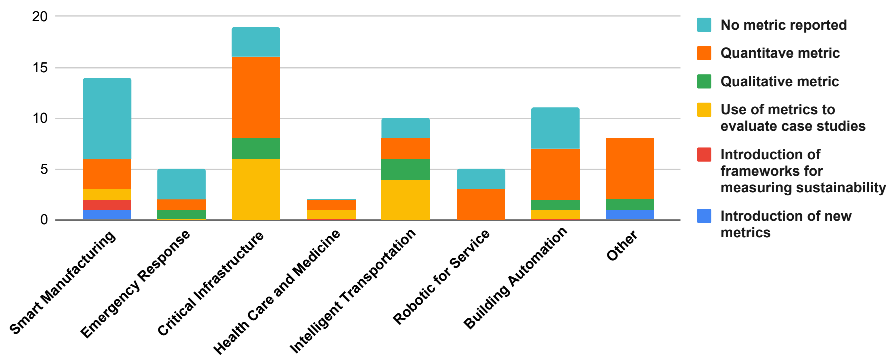


Figure 11: Relation between sustainability metrics (Q3) and application domains (Q9).

Smart manufacturing is the least likely to use a metric among all the domains, only using it in 57% of cases (8 out of 14). At the same time, *critical infrastructure and intelligent transportation* are most likely to use a metric: 84% (16 out of 19) and 80% (8 out of 10) of papers in those respective domains use a metric. To be more certain, we limited the above observations to the domains with at least 10 studies. Quantitative metrics appear to be general: they are used in every surveyed domain. Figure 11 shows the distribution of metric use in papers with specific domains.

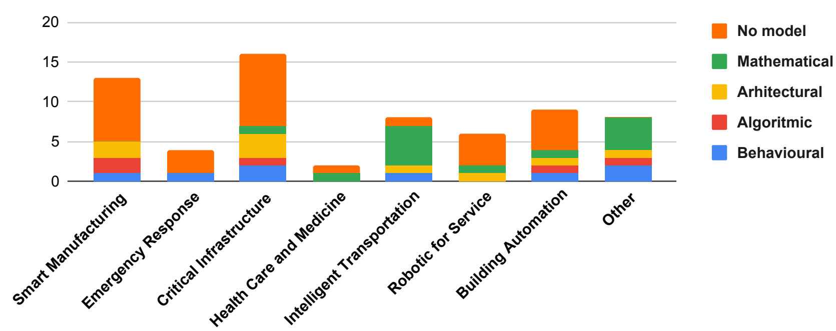


Figure 12: Relation of model types (Q4) and application domains (Q9).

Most intelligent transportation approaches use mathematical models, with 63% (5 out of 8) of papers reporting a mathematical model. Figure 12 shows how models are used in papers that target a specific domain. We also observed that the studies in smart manufacturing and critical infrastructure are less likely to use a model than not, yielding respectively the chance of 62% (8 out of 13) and 56% (9 out of 16) not using a model. Behavioural models are the most general across domains: they occur in all but 2 surveyed domains, and 58% (11 out of 19) of papers with behavioural models do not have a specific domain.

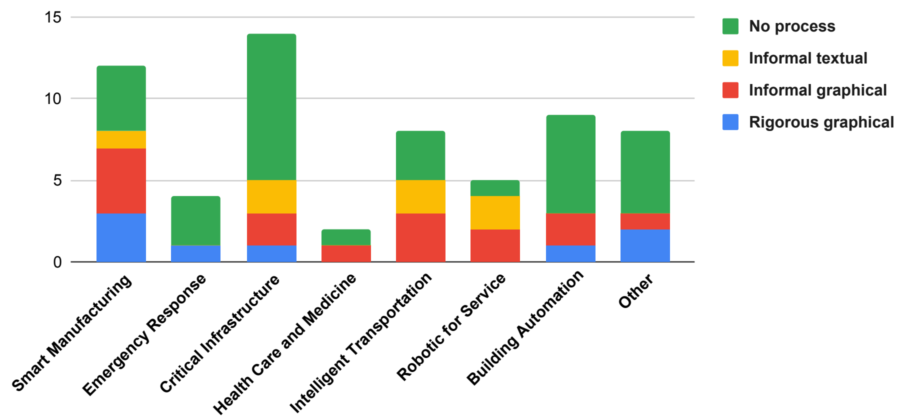


Figure 13: Relation between processes (Q6) and application domains (Q9).

In domains with at least 10 studies, *smart manufacturing is the most process-oriented domain*, relatively to other domains: 67% (8 out of 12) of smart manufacturing studies use at least some form of a process. At the same time, studies in critical infrastructure rarely report their processes: only 33% (5 out of 15) of papers in it had any form of a process. These observations are illustrated in Figure 13, illustrating how processes are used in papers targeting specific domains.

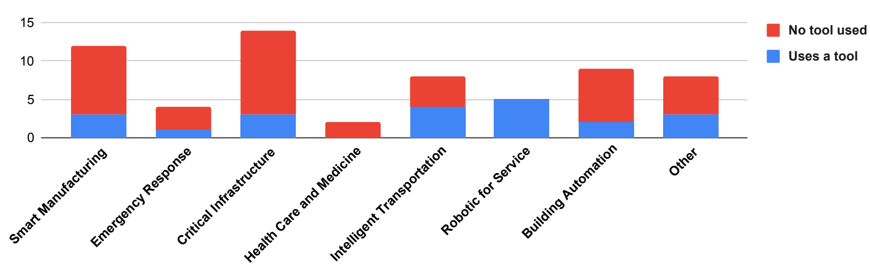


Figure 14: Relation between tool use (Q7) and application domains (Q9).

All five robotics-for-service papers reported using a modelling tool, whereas papers in healthcare and medicine generally did not report tool usage. For the remaining domains, while some papers mention tool usage, most still do not specify the tools used. This distribution of tool reporting across domains is illustrated in Figure 14, which shows the distribution of tool use in papers with specific domains.

4.10. Quality Assessment of Classified Studies

The results of the quality assessment of the classified studies are shown in Table 4. The first column presents the questions that the reviewers answered when extracting data from the primary studies. The second column presents an average score by weighting the numeric values of each answer. For instance, for *QA1* we calculate $(1\times83+0.5\times21+0\times0)/104 = 0.90$. The third column presents the possible answers, and the last column contains the number of primary studies for each answer.

Table 4: Quality assessment results

Assessment Question	Avg. Score	Answer options / Paper counts	
QA1: How clearly is the problem of study described?	0.9	1 = Explicitly	83
		0.5 = Vaguely	21
		0 = None	0
QA2: How clearly is the research context stated?	0.87	1 = With references	74
		0.5 = Generally	30
		0 = Vaguely	0
QA3: How rigorously is the method evaluated?	0.59	1 = Controlled experiment	16
		0.66 = Case study	69
		0.33 = Lessons Learned	8
		0 = No evaluation	11
QA4: How explicitly are the contributions presented?	0.81	1 = Explicitly	64
		0.5 = Generally	40
		0 = No presentation	0
QA5: How explicitly are the insights and issues for future work stated?	0.61	1 = With recommendations	44
		0.5 = Generally	39
		0 = No statement	21

To characterise the quality assessment criteria *(QA1)*, the quality of the content of the studies, namely the clarity of the motivation for the approach presented, we note that 80% of the studies clearly describe the problem (83 papers), and the remaining 20% (21 papers) describe the problem vaguely.

Regarding the clarity of the research context *(QA2)*, the reviewers found that none of the studies has vaguely focused on the research context. At the same time, a majority of papers described the research context with references reporting the advantages and limitations of the related work (74 out of 104 studies). Finally, 30 studies were classified as generally describing the research context.

We judge the rigour of the evaluation method *(QA3)* used in the primary studies based on their evaluation type. Almost two-thirds of the studies evaluate their solutions using case studies (69 studies) to illustrate the feasibility of the approach in certain cases, usually industrial/practical cases. 11 studies do not report any evaluation. Only 16 of the total number of studies use controlled experiment or the highest property where hypothesis regarding approach is statistically proved and can be reproduced based on an experimental design using different samples. Finally, 8 papers narrative report on the lessons learned, relying on their subjective perspective. To increase trust in the approaches presented, more controlled experimental studies need to be carried out.

When analysing the contributions *(QA4)*, we paid special attention to the results summary together with the evaluation methods, as well as how explicitly they address the problem solution. More than 60% of the studies (64 of them) explicitly present their contribution, meaning they contribute with a concrete solution and explain the scope of their contribution clearly in the conclusions. At the same time, the remaining 40 papers describe their contributions in general terms.

Finally, regarding future work *(QA5)*, 21 of the primary studies do not include directions for future work. From the remaining studies, 39 only offer general ideas for future work and 44 present future work with concrete recommendations.

From these results, we can conclude that most of the primary studies provide a *clear problem statement and a research context*. Most of the approaches are evaluated using a *case study* or with *controlled experiments*. Although in most of the cases, the contributions are *explicit and well-stated*, we note that the future work is often either very general or *lacks concrete recommendations* and is rarely reported with a concrete roadmap.

In the self-assessment part of the survey, the reviewers marked how confident they were about their understanding of the content and quality of the study. Confident responses were dominant for both of the questions (i.e. content and quality), with approximately half marked as very confident. These responses give the basis for *our confidence* in the study results reported above.

4.11. Summary of Results

The research papers that we surveyed from the last 10 years focus primarily on challenges in efficiency and resilience. The most common techniques to address these challenges are various forms of life cycle analysis. When it comes to evaluating the impact of these techniques, the use of metrics is not universal. When metrics are used, the quantitative ones are the primary choice, especially for efficiency. We observed the *highest research activity in the critical infrastructure and smart manufacturing domains.*

The choices of *models were surprisingly diverse*, with a wide variety of formalisms used to address sustainability in CPS, which is a general feature of CPS modelling research [18]. However, *, only half of those models focus on sustainability itself*, and the other half have an indirect impact on it by modelling the conventional aspects of the CPS. It is curious to note that *informal modelling processes are most commonly reported for efficiency and resilience*, in contrast to the more precise models and metrics used to address these sustainability attributes.

We have also *observed several* literature gaps, suggesting potential directions for future research. Regarding addressing sustainability challenges, we observed that *very few papers introduce novel metrics or frameworks for measuring sustainability* — or explore higher-level, qualitative metrics. Also, almost half of the models were neither specific to nor focused on sustainability itself. Another surprising observation is that *neural networks, despite their rapidly growing prevalence in the computing and engineering literature, have seen little to no applications in CPS sustainability modelling.* These observations highlight the limited focus on sustainability in the CPS modelling literature so far.

From the modelling perspective, the research has not yet resulted in mature, general, and reusable tooling frameworks for CPS sustainability: the reported tools were custom and used a few times, which prevented us from generalising broader categories of the used tools. Similarly, we witnessed a negligible number of rigorous process descriptions. These observations suggest that *modelling has so far focused more on the theoretical aspects of CPS sustainability, and its tool-based and process-related aspects have not yet matured.*

Finally, the *least addressed domains were health care and air transportation*, which contrasts with general CPS modelling literature [18]. We hypothesise that, due to the comprehensive nature of sustainability, these domains are yet to be explored in CPS sustainability modelling.

4.12. Threats to Validity

Next, we discuss the threats to this work's validity in terms of constructing validity, internal validity, external validity, and conclusion validity.

Construct validity. A potential threat is related to the two sustainability attributes reconfigurability and adaptability that, for being closely related, may have been confusing to some reviewers. A similar issue is concerned with the method characterisation for sustainability, where sometimes the difference between life cycle analysis and other categories is not distinguishable. Additionally, the interpretation of the concepts "model" and "process" may vary among the reviewers: some may include a wide range of phenomena (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. Several meetings were held to discuss and validate the classification used to mitigate these three threats. The participants were the seven reviewers and an eighth person not involved directly in the reviewing process. After these meetings, one reviewer checked and possibly reclassified the results.

Internal validity. A first observation is that the researchers involved in this study have a background mostly in 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 SMSs 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. We performed several validity checks among the various authors to minimise this threat. In particular, the SMS process was performed following a "peer review" approach, where the authors discussed and resolved conflicts, 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, the 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 applies to other questions where different interpretations are possible, such as whether a study proposes a modelling process or addresses sustainability concerns. To further mitigate the threat, the reviews were once more checked by another reviewer with different expertise, and their inputs were taken for successive iterations of the results and interpretations.

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 of the topics under review. To address this possible limitation, the search was specified considering a set of trial searches and validated by the authors. The coverage and relevance of the retrieved studies were constantly checked among subgroups of the team. Another threat is related to the primary studies obtained from the used digital libraries. We performed three automatic searches: one at the beginning of 2017, another at the end of 2017, and another at the beginning of 2021. The second time aimed at capturing the publications from April to December 2017, but as the systems do not allow for selecting 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 most relevant works were considered for this study. Also, all the retrieved papers were available for download and *a posteriori* analysis.

Conclusion validity. The used methodology [35] 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 validated by the Software Engineering research group members of the NOVA LINCS research centre. This procedure helped minimise the risk of excluding relevant studies. Additionally, only one reviewer read the titles and abstracts of 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 unclear, the study was always included. Then, during the result analysis, different reviewers analysed a single question by using the information from the selected studies. However, this could result in a non-critical approach, for instance, accepting already given information as final. Nevertheless, for several papers, the author conducting the analysis contacted the author who extracted the information to clarify the information recorded, changing it whenever necessary. This procedure shows that the analysts were careful and critical when using the extracted data.

5. Conclusions

Sustainability in Software Engineering has been an active area of research over the past 10 years, and the interest in building sustainable products and systems is expected to grow further in the future. This work analyses how the topic has been addressed by the research community working on model-driven development of CPS and discusses the results of an SMS.

Our findings are a set of modelling approaches, techniques and tools, a list of the researched application domains, and several literature gaps. Among these findings, it is interesting to note that efficiency and resilience are the most common sustainability attributes addressed, and what is particularly different when compared to CPS development approaches, in general, is that reconfigurability is addressed as self-adaptability in this community and is merged with the notion of adaptability as there is no straightforward way to separate these sub characteristics. Most approaches address the sustainability concern at design time, which is very common in model-driven development. Further, that life cycle analysis methods and quantitative metrics are typically selected to model and evaluate those attributes and that critical infrastructure and smart manufacturing is the most active application domains where sustainability is considered while modelling CPS. The identified literature gaps indicate potential future research lines, particularly to devise new frameworks, methods, metrics, and tools to develop sustainable computing systems while measuring their impact on our living world. Ideally, the research and industrial communities at large will join efforts to address the five dimensions of sustainability and to create disruptive approaches to support the United Nations' sustainable development goals.

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Appendix A. Research Method

Appendix A.1. Search Process

Our research design process, illustrated in Figure A.15, extends Kitchenham's [35] with a pre-planning phase.

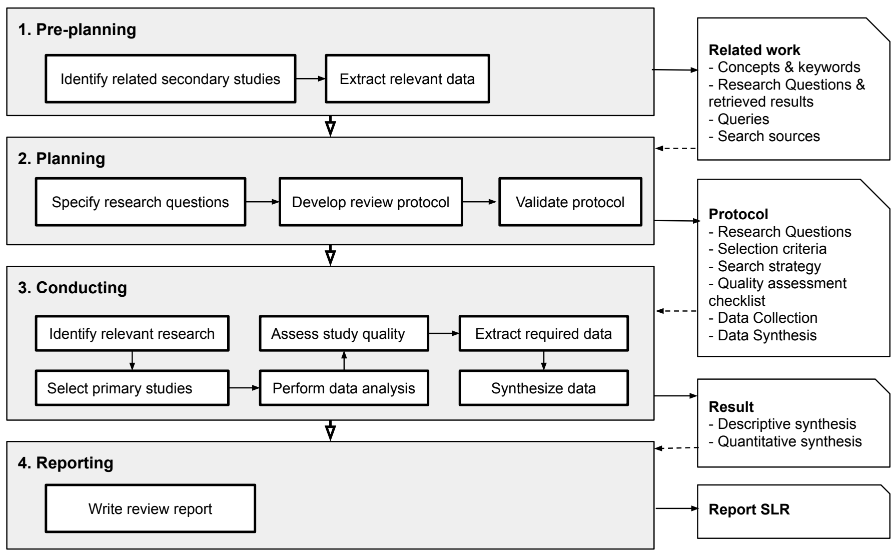

Figure A.15: Review process overview based on [35]. (The blackhead arrow represents the flow between activities of the process; the dotted arrow indicates an input for the next phase; the whitehead arrow connects the main phases)

In the *pre-planning* step, we searched for existing systematic secondary studies and surveys related to sustainability and 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. 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 who had executed SMS and SLRs. This workshop ended with a survey to collect additional information and suggestions from the workshop participants. During the *conducting phase*, the search queries were executed to search for relevant primary studies automatically. One reviewer read the titles and abstracts to decide whether to include or exclude them, using a set of pre-established selection criteria. If there was doubt regarding a study's admissibility, more of its content was read until a decision was made, always aiming for increased inclusiveness. The selected articles were distributed among seven reviewers to be fully read and 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 publication, it 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 to validate the fitness of the obtained results. The inputs provided by the reviewers during the data analysis were re-validated. The process ended with analysing the threats to the study's validity.

The technical report [37] extensively reports the details of the pre-planning and the planning phases.

Appendix A.2. Pre-Planning: Existing Work Shaping our Research Questions

The pre-planning phase identified existing secondary 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 the modelling of CPS existed. The second result was a list of seven systematic studies (in Table A.5) 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. The first five of the studies focus on describing sustainability in software engineering and systematically retrieve metrics and categorisations. The remaining two studies are systematic surveys on CPS, categorising the application domains for these systems and reporting sustainability as one of the important challenges to be addressed.

Table A.5: Existing systematic studies on topics of interest

Paper	**Year**	**Topic**	**Type**
[30]	2011	Sustainability of software architectures	SLR
[51]	2012	Sustainability in software engineering	SLR
[15]	2014	Sustainability in software engineering	SMS
[52]	2013	Software sustainability measures	SLR
[53]	2015	Energy-efficient networking solutions	SMS
[54]	2016	CPSs security	SMS
[1]	2014	Applications and challenges in CPS	Survey

Appendix A.3. Planing: Protocol Construction

The planning phase started with the definition of the research questions and the production of a well-defined review protocol. The protocol was evaluated on various occasions and refined according to the feedback obtained.

Appendix A.3.1. Research Question

Our research questions were derived from the PICOC analysis in Table A.6. The overall objective of our study is to offer an overview of the state of the art on modelling sustainable CPS. Thus, our main research question is: **What modelling approaches exist for addressing sustainability of CPS?**

Table A.6: PICOC analysis

PICOC	Definition
Population	The set of studies reporting on works for modelling CPS and approaches for sustainability, 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 techniques, tools, technologies, and procedures for CPS modelling while considering sustainability concerns (e.g. energy efficiency, resilience, accessibility, etc.).
Comparison	Not applicable
Outcomes	Models, processes, methods, metrics, and tools used to address the sustainability of CPS during their modelling/design phase, as well as a list of the application domains considered.
Context	All practitioners: Academy and Industry.

To answer this research question, we expect to retrieve the type of models used to describe the discussed approach or system, the list of modelling approaches and tools developed to support the approach or used by the reported approach, and the systematic process, if any, supporting the given approach. Also, we expect to retrieve the methods [51] used by the approach, as well as any metrics and sustainability models. Finally, we retrieve the application domains and then analyse the coverage of specific case studies addressed in the primary studies. We distinguish approaches to be domain-specific – if they are developed just for a concrete application domain – and general purpose.

Appendix A.3.2. Search Strategy

We performed automatic searches in the ACM Digital Library (ACM), IEEE Xplore (IEEE), Science Direct (SD), and Springer Link (SL) of papers from the beginning of 2011 until the beginning of 2021. These search sources are found to be the most popular and were used by most of our secondary studies [1, 15, 30, 51–54]. The search string reuses strings from the identified in the studies in Table A.5, as follows:

> *(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')*

Appendix A.3.3. Data Extraction Strategy

After selecting the relevant primary studies, the reviewers initiated the data extraction using a predefined and validated extraction form. This form is divided into three parts. The first part collects meta-data regarding the publication (Authors, Title, Year, Venue, CitationKey serving as a unique identifier and URL), hence storing general information about the selected study. For traceability, each reviewer's name was stored for each paper.

The second part collects the information to answer our research question, for which we defined the nine questions in Table 2 derived from the PICOC Outcomes. We populate the answer categories in the second part from the existing literature. For example, as shown in Table A.7, the answers for Q1 and Q9 were populated from Gunes et al. [1], Q2 answers were taken from Pezenstadler et al. [51], and the details about the other questions can be found in Section 4. To allow the possibility of discovering categories unknown before data extraction, we added the open-ended textual "other" answer to all research questions. All the answers with "other" were discussed among the authors to consider adjusting the answer categories. Thus, our extraction strategy balances the reuse of the existing literature surveys and the flexibility of adjusting the answer categories found in inductive coding based on the grounded theory methodology.

Table A.7: Special categorisations and their mapping to some of our research questions

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 reviewer's confidence as specified in Table 4. We did not define any exclusion criteria regarding the quality of the study, but we found it meaningful to present statistics and observe the impact of the study. To reflect the confidence of the reviewer, we defined two self-assessment criteria: S1 (regarding answers provided in the data extraction form in Table 2) 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.

Appendix A.3.4. Protocol Validation

Prior to the SMS conduction phase, we performed a protocol validation task with two goals in mind: (i) checking that the protocol addresses the SMS goals and (ii) soliciting 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 the University NOVA of Lisbon. The protocol was presented to the group participants, and the informal feedback received resulted in small changes in it. The validation was then performed online using a Google survey form, which had questions requiring 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 and SMSs. Four of those reviewers authored published systematic reviews. Details of survey results can be found in technical report[37].

The reviewers agreed that the need for this SMS was 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's objective and suggested several clarifications that improved the 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.

Appendix B. Additional report to results

Appendix B.1. What sustainability attribute is addressed? (Q1)

Table B.8 shows the percentage of primary studies tackling each attribute (second column[4]) and the corresponding list of primary studies (third column)[5].

Table B.8: Studies addressing sustainability attributes

Attribute	**% (#/total)**	**Primary study**
Efficiency	54.8 (57/104)	[40–42, 50, 55–65, 74, 80, 85, 87, 98–107, 112–139]
Resilience	32.7 (34/104)	[66–97, 140, 141]
Adaptability	28.8 (30/104)	[39–50, 84, 95, 98–104, 108–111, 142–146]

Appendix B.2. What method is used to address sustainability? (Q2)

Table B.9 presents the method categories, the percentage of primary studies using the method, and the list of the corresponding papers.

Table B.9: Methods used to address sustainability (ER = Entity Relationship; NN = Neural Networks; CC = Cost Calculations; LCA = Life-Cycle Analysis)

Method	**% (#/total)**	**Primary study**
ER	14.4 (15/104)	[43, 50, 61, 68, 74, 78, 79, 87, 90, 91, 93, 99, 101, 109, 111]
NN	3.8 (4/104)	[46, 48, 55, 103]
CC	21.2 (22/104)	[47, 56–58, 61, 63, 84, 89, 95, 96, 100, 104–109, 113, 117, 129, 134, 139]
LCA	48.1 (50/104)	[39, 40, 42, 44, 49, 59, 60, 64, 66, 67, 69–73, 75, 77, 81, 83, 85, 86, 95–97, 99, 105–108, 110, 112, 115, 116, 118–121, 123, 125–128, 138, 140–146]
None	21.2 (22/104)	[41, 45, 62, 65, 76, 80, 82, 88, 92, 94, 98, 102, 114, 122, 124, 130–133, 135–137]

Appendix B.3. What kind of sustainability metric is used? (Q3)

Table B.10 summarises our findings for the extracted elements. Note that a paper may appear in more than one category as it may use more than one kind of metrics.

[4]This column presents the percentage of studies in each row of the total number of studies addressed by our work – first number – followed by the absolute number of studies – second number – and the total number studies – third number. For instance, for efficiency, there are 50.1% of studies, being this 53 out of 105 studies.

[5]This is the general structure of the tables used to report our finding for each RQ.

Table B.10: Studies addressing sustainability metrics

Metric	% (#/**total**)	**Primary study**
New metrics	1.9 (2/104)	[60, 100]
Measuring frameworks	1.9 (2/104)	[122, 126]
Metrics for case studies	18.3 (19/104)	[56, 63, 65, 74, 78, 83–85, 94, 95, 98, 99, 101, 103, 106, 111, 136, 144, 146]
Qualitative metric	6.7 (7/104)	[57, 61, 77, 85, 101, 110, 144]
Quantitave metric	37.5 (39/104)	[46, 48, 55, 58, 59, 61, 64, 67, 68, 70, 74, 76, 84–86, 92, 95, 96, 99, 100, 104–109, 111–113, 116, 122, 125, 126, 133–135, 138–140]
No metric	47.1 (49/104)	[39–45, 47, 49, 50, 62, 66, 69, 71–73, 75, 79–82, 87–91, 93, 97, 102, 114, 115, 117–121, 123, 124, 127–132, 137, 141–143, 145]

Appendix B.4. What type of model is used to specify sustainability? (Q4)

Table B.11 summarises our findings.

Table B.11: Types of models used for CPS sustainability

Model	% (#/**total**)	**Primary study**
Behavioural	18.3 (19/104)	[60, 61, 64, 65, 78, 81, 83, 86, 94, 100, 101, 108, 110, 120, 121, 138, 141, 142, 144]
Algorithmic	9.6 (10/104)	[48, 55, 58, 70, 100, 103, 107, 122, 127, 135]
Architectural	13.5 (14/104)	[62, 79, 82, 85, 93, 96, 99, 101, 106, 113, 133, 134, 136, 146]
Mathematical	16.3 (17/104)	[45–47, 56, 57, 59, 63, 72, 77, 97, 98, 104–106, 139, 143, 145]
No sust. model	45.2 (47/104)	[39–44, 49, 50, 66–69, 71, 73–76, 80, 84, 87–92, 95, 102, 109, 111, 112, 114–119, 123–126, 128–132, 137, 140]

Appendix B.5. What instance of model/meta-model is used to specify sustainability? (Q5)

The categories of models and their percentages among all models are shown in Table B.12. The references to the primary studies can be found in this table.

Table B.12: Model types in primary modelling studies.

Model type	% (#/**total**)	**Primary studies**
Equations	17.3 (18/104)	[46, 48, 56, 57, 59, 63, 70, 97, 98, 104–106, 118, 122, 123, 125, 129, 139]
Component-based	15.4 (16/104)	[42, 43, 66, 72, 75, 85, 92, 96, 101, 103, 124, 130, 135, 136, 143, 146]
Automata	14.4 (15/104)	[43, 44, 61, 73, 75, 76, 81, 90, 106, 114, 119, 121, 126, 127, 133]
Dataflows	13.5 (14/104)	[41, 47, 66, 71, 75, 83, 84, 87, 106, 118, 120, 127, 129, 144]
Custom graphs	8.7 (9/104)	[68, 81, 85, 95, 100, 109, 137, 140, 144]
Programs	8.7 (9/104)	[45, 58, 67, 80, 94, 107, 108, 118, 125]
Meta-models	7.7 (8/104)	[43, 71, 91, 114, 126, 128, 131, 133]
UML-like models	7.7 (8/104)	[40, 64, 78, 82, 88, 93, 96, 133]
Processes	5.8 (6/104)	[65, 74, 79, 110, 135, 141]
Specifications	4.8 (5/104)	[39, 61, 75, 144, 145]
Variability models	2.9 (3/104)	[77, 99, 111]
Other models	7.7 (8/104)	[55, 60, 62, 86, 101, 109, 134, 138]
No model reported	11.5 (12/104)	[49, 50, 69, 89, 102, 112, 113, 115–117, 132, 142]

Appendix B.6. What modelling process is used? (Q6)

Table B.13: Primary studies by process presentation

Process presentation	% (#/**total**)	**Primary studies**
Rigorous graphical	8.7 (9/104)	[39, 58, 60, 62, 64, 69, 86, 88, 123]
Informal graphical	24 (25/104)	[45, 49, 55, 56, 63, 65, 66, 68, 71, 75, 77, 78, 80, 99, 102, 109, 114, 117, 120, 132, 135, 136, 142, 144, 146]
Informal textual	11.5 (12/104)	[47, 50, 73, 74, 91, 96, 98, 103, 106, 113, 122, 137]
No process	55.8 (58/104)	[40–44, 46, 48, 57, 59, 61, 67, 70, 72, 76, 79, 81–85, 87, 89, 90, 92–95, 97, 100, 101, 104, 105, 107, 108, 110–112, 115, 116, 118, 119, 121, 124–131, 133, 134, 138–141, 143, 145]

Appendix B.7. What modelling tool is used? (Q7)

The references to the primary studies reporting both models and tools can be found in Table B.14.

Table B.14: Primary studies by tool type.

Tool type	% (#/**total**)	**Primary studies**
Eclipse based/Papyrus	1.9 (2/104)	[66, 133]
SysML/UML/MARTE	1 (1/104)	[78]
Matlab/20-sim/Simulink/ Modelica/UPPAAL	3.8 (4/104)	[75, 83, 118, 126]
Custom tool (other)	28.8 (30/104)	[39, 43, 45, 49, 55, 60, 65, 73, 74, 76, 77, 80, 81, 88, 91–94, 96, 99, 101, 109–111, 114, 131, 134, 135, 145, 146]
No tool reported	64.4 (67/104)	[40–42, 44, 46–48, 50, 56–59, 61–64, 67–72, 79, 82, 84–87, 89, 90, 95, 97, 98, 100, 102–108, 112, 113, 115–117, 119–125, 127–130, 132, 136–144]

Appendix B.8. Is the modelling approach domain-specific? (Q8) and What application domain for CPS is addressed? (Q9)

Table B.15: Primary studies by application domain.

Domain	% (#/**total**)	**Primary studies**
Critical Infrastructure	13.5 (14/104)	[67, 69, 70, 84, 92, 95, 101, 106, 125, 131, 136, 137, 140, 144]
Smart Manufacturing	11.5 (12/104)	[42, 49, 50, 58, 62, 100, 102, 117, 123, 126, 129, 146]
Building Automation	8.7 (9/104)	[40, 41, 55, 64, 85, 87, 104, 114, 116]
Intelligent Transportation	7.7 (8/104)	[45, 47, 57, 63, 98, 99, 110, 111]
Robotic for Service	4.8 (5/104)	[66, 76, 91, 96, 109]
Emergency Response	3.8 (4/104)	[39, 61, 90, 115]
Health Care and Medicine	1.9 (2/104)	[56, 112]
Air Transportation	0 (0/104)	
Other	7.7 (8/104)	[46, 59, 60, 77, 86, 105, 107, 133]
No application domain	40.4 (42/104)	[43, 44, 48, 65, 68, 71–75, 78–83, 88, 89, 93, 94, 97, 103, 108, 113, 118–122, 124, 127, 128, 130, 132, 134, 135, 138, 139, 141–143, 145]