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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), which is one of the most actively developing classes of complex software systems. This work discusses the results of a Systematic Mapping Study (SMS) aiming at identifying the relevant primary studies reporting on CPS modelling approaches addressing sustainability *over the last 10 years*. Our literature search yielded 2209 papers, of which 105 primary studies were deemed relevant for a detailed characterisation from the perspective of nine research questions, to extract information about sustainability attributes, methods, models/meta-models, metrics, processes and tools used to improve the sustainability of CPS. These questions also aimed at collecting data about domain-specific modelling approaches and application domains. The final results report on nine questions, highlight interesting correlations among them, and identify literature gaps worth investigating in the near future.

1. Introduction

Today's computing systems have increasing demands in terms of sustainability [1, 2]. One definition of sustainability is the “development that meets the needs of the present without compromising the ability of future generations

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to meet their own needs” [3]. Many researchers have been working to make computing systems more sustainable, which can be understood as supporting the “longevity of systems and infrastructure and their adequate evolution with changing surrounding conditions” [4]. As this research unfolds, it is vital to continually track its successes and discover potential directions to investigate in the future.

Another rapidly developing research area is that of *Cyber-Physical Systems* (CPS). CPS can be defined as systems that integrate computation, networking, and physical processes [5]. CPS monitor and control complex physical processes and are formed by large communicating networks with possibly heterogeneous sensors and actuators. One of the key concepts of CPS is to manage complex feedback loops between the physical and the cyber worlds [6]. Safety-critical CPS like aircraft and autonomous cars should be extensively analysed and tested to ensure that they do not fail in operation. One of the most important ways towards that end is the extensive use of modelling, analysis, and software engineering tools throughout the value chain and system’s life-cycle. Furthermore, CPS engineers need to manage the increasing complexity and multidisciplinary nature of CPS development [7]. Thus, it is paramount to understand the rapidly evolving state of the art in CPS modelling methodologies.

We focus our attention on the heart of the two aforementioned trends: CPS modelling approaches that address sustainability challenges. Indeed, sustainability is a major challenge for CPS [1], and modelling methodologies promise comprehensive solutions to multi-faceted engineering challenges (including sustainability) as well as insights into how we think about systems and their emergent qualities. Hence, we ask: *What modelling approaches exist for addressing sustainability of CPS?*

To answer this question we performed a *Systematic Mapping Study* (SMS) that methodically explored and analysed the last 10 years of literature on CPS modelling for sustainability. 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]. Therefore, we have particularly focused on the technical dimension of sustainability, which is most directly addressable by software engineering modelling. Although there are many systematic mapping studies and literature reviews on different topics of sustainability, CPS, and software engineering, so far none has been conducted to investigate the relation between sustainability and modelling of CPS.

Our search queries were built based on a *PICOC analysis* (Population, Intervention, Comparison, Outcome, Context) and updated based on findings from relevant related work. These queries were thoroughly tested in the chosen digital libraries and validated in a workshop with researchers from the NOVA LINCS research centre with significant experience in performing and evaluating systematic studies. The search queries were executed in four digital libraries (ACM, IEEE, SPRINGER and Science Direct). We assessed the results of the automatic searches in each database from January 2011 to January 2021, retrieving a total of 2209 candidate primary studies. After reading the abstracts we selected 599 papers to be fully read. The full-text analysis and applica-

tion of the inclusion, exclusion, and quality criteria resulted in removing 490 papers and selecting 105 for final data extraction. The extraction form was structured to offer a detailed characterisation of our research question from the perspective of *nine questions*. The first question presents the four sustainability attributes, at least one of which is addressed by each study: adaptability, resilience, reconfigurability, and efficiency. The other questions investigate sustainability methods, models/meta-models, sustainability metrics, processes and tools used to improve the sustainability of CPS, most active application domains and whether the approach was general-purpose or domain-specific. Each of these aspects was quantitatively correlated with the sustainability attributes and pertinent other aspects, leading to a comprehensive analysis of the literature, and the identification of 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. Finally, Section 5 concludes the paper.

2. Background and Related Work

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

2.1. Background

Cyber-Physical Systems (CPS). CPS are formed by computation, large communicating networks with possibly heterogeneous sensors and actuators, and physical processes [5]. Thus, these systems must manage complex feedback loops between the physical and the cyber worlds [6]. Examples of CPS can be found in domains such as smart manufacturing (e.g. [40]), building automation (e.g. [41]), or intelligent transportation (e.g. [42]).

Dealing with the increasing complexity and multidisciplinary nature of CPS development is challenging [8]. 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 [9]) propose different levels of abstraction and views to tackle the inherent complexity of large-scale and complex systems, offering rigorous models expressed in appropriate modelling formalism. In such cases, Model-Driven Development (or MDD) is used to build models that can be (formally) verified and used to simulate the system.

Sustainability in Software Engineering. Sustainability implies *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* [3]. This challenge calls for the integration of social equity, economic growth, and environmental preservation, considering also their effects on each other. These three dimensions have been integrated in a multidimensional line of thought that also encompasses an individual and a technical dimension [10]. Each dimension addresses different needs (e.g., improve employment indicators, reduce costs, reduce CO2 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 [11].

There is no common definition of sustainability in Software Engineering. Some existing works handle sustainability as a non-functional requirement (e.g., [12]), but we prefer to think of sustainability as “an emergent property of a software system” [13] 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 for each dimension, which, in turn, is composed of the quality attributes relevant for that dimension* [11].

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* [4].

Sustainability in CPS. When discussing sustainability in software, we typically distinguish between *sustainable software* which code satisfies good principles of sustainability (e.g., energy efficient, adaptable, etc.), and *software for sustainability* which supports sustainability goals, such as those of the five sustainability dimensions (environmental, social, economic, social, individual, and technical). Ideally, both interpretations should coexist in a software system to better contribute to a more sustainable living. 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 [14].

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]. To achieve this, Gunes et al. propose four fundamental qualities attributes to produce a sustainable system [1]: adaptability, resilience, reconfigurability, and efficiency. Adaptability refers to the capability of a system to change its state to survive by adjusting its own configuration in response to evolving needs and different circumstances in the environment. Thus, a highly adaptable system should be quickly adaptable to evolving needs or circumstances. Resilience refers to the ability of a system to quickly recover from faults, preserving its operation and delivering services with an acceptable quality in case the system is exposed to any inner or outer difficulties (e.g., sudden

defect, malfunctioning components, rising workload etc.). Hence, a resilient system should be self-healing and comprise early detection and fast recovery mechanisms against failures to continue to meet the demands for 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 able to fine-tune itself dynamically and coordinate the operation of its components at finer a granularity. Finally, efficiency refers to the amount of resources (such as energy, cost, time, etc.) the system requires to deliver specified functionalities. A highly efficient system should operate properly under optimum amount of system resources.

2.2. Related Work

During our SMS planning phase we found a few secondary studies addressing a combination of CPS, CPS Modelling and Sustainability, but none about sustainable CPS, reinforcing the need for our work on modelling sustainable CPS. Table 1 summarises our findings. Two of these works discuss particular kinds of CPS and their sustainability [15, 16]. Camarinha-Matos [16] discusses several aspects of smart grids, including sustainability as security, resilience and self-healing. Contrary to our work, his focus is on a particular kind of CPS, in this case, smart grids. Finally, Agostinho et al. [15] review the research effort in enterprise information systems (EIS) (not necessarily CPS) interoperability and MDD for the purpose of network interoperability sustainability. They conclude that the future of EIS needs to be properly monitored and controlled to enable a sustainable innovation and highlight models and model-driven as a means for improved support to reason about semantics. Again, this work is limited to a particular domain whilst our work discusses all kinds of CPS.

3. Research Method

Evidence-based Software Engineering provides core tools for evidence-based empirical studies, including secondary studies of research literature such as systematic mapping studies. A *Systematic Mapping Study* (SMS) provides a reliable and rigorous methodological process to conduct a bibliographic survey [33, 34]. This paper reports on a SMS we performed to **identify and analyse CPS modelling approaches addressing sustainability**, published in the period between 2011 and 2021. The quest is 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 to categorise the extracted methods, models, processes, tools, metrics and application domains for assessing the sustainability of CPS.

3.1. Search Process

Our research design process, illustrated in Figure 1, extends Kitchenham's [34] with a pre-planing phase.

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

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

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, Com-

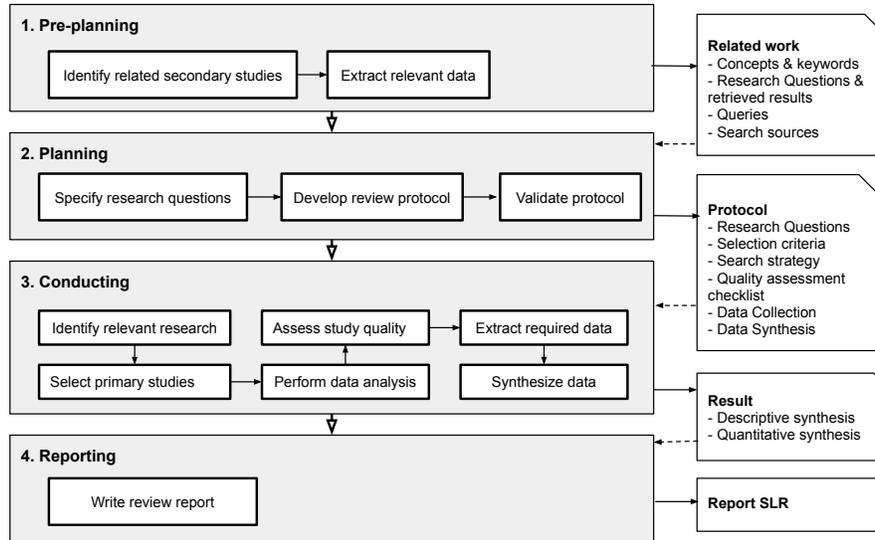


Figure 1: Review process overview based on [34]. (The blackhead arrow represents the flow between activities of the process; the dotted arrow indicates an input for the next phase; the whitehead arrow connects the main phases)

parison, Outcome, Context) analysis. Then, we developed the review protocol by defining the search strategy, selection criteria, quality assessment checklist and data extraction strategy. Finally, the protocol was validated in a closed workshop with seven experienced researchers in executing 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 automatically search for relevant primary studies. One reviewer read the titles and abstracts to decide on their inclusion or exclusion, according to a set of pre-established selection criteria. In case of doubt regarding a study’s admissibility, more of its content was read until a decision was made, always aiming at increased inclusiveness. The selected articles were distributed among seven reviewers to be fully read, classified based on a quality assessment checklist, and their content was recorded according to the data extraction strategy. Papers not conforming to the inclusion criteria would be excluded from the data extraction process. If a reviewer was unsure about a 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 from the reviewers during the data analysis were re-validated. The process ended with the analysis of the threats to validity of the study.

The technical report [35] extensively reports the details of the pre-planning and the planning phases.

3.2. 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 modelling of CPS existed. The second result was a list of seven systematic studies (in Table 2) that were used to extract relevant research questions, fundamental keywords and concepts, a set of queries that were used to strengthen and complement our own, and the digital libraries more relevant for our search. 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 2: Existing systematic studies on topics of interest

Paper	Year	Topic	Type
[32]	2011	Sustainability of software architectures	SLR
[36]	2012	Sustainability in software engineering	SLR
[14]	2014	Sustainability in software engineering	SMS
[37]	2013	Software sustainability measures	SLR
[38]	2015	Energy-efficient networking solutions	SMS
[39]	2016	CPSs security	SMS
[1]	2014	Applications and challenges in CPS	Survey

3.3. Planing: Protocol Construction

The planing phase started with the definition of the research questions and production of a well-defined review protocol. The produced protocol has been evaluated in different occasions and refined according to the obtained feedback.

3.3.1. Research Question

Our research questions were derived from the PICOC analysis in Table 3. 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?**

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 [36] used by the approach, as well any metrics and sustainability models. Finally, we retrieve the application domains and then analyse the coverage of specific case studies addressed in the primary

Table 3: 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 taking in consideration sustainability concerns (e.g. energy efficiency, resilience, accessibility, etc.).
Comparison	Not applicable
Outcomes	Models, processes, methods, metrics, 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.

studies. We distinguish approaches to be domain-specific – if they are developed just for a concrete application domain – and general purpose.

3.3.2. Search Strategy

We performed automatic searches from the beginning of 2011 till the beginning of 2021 in the ACM Digital Library (ACM), IEEE Xplore (IEEE), Science Direct (SD) and Springer Link (SL). These search sources are found to be the most popular, and were used by most of our the secondary studies [1, 14, 32, 36–39]. The search string reuses strings from the identified in the studies in Table 2, as follows:

(sustainab OR environment* OR ecolog* OR green OR ‘energy efficient*’ OR ‘energy-efficient*’) AND ((‘cyber physical’ OR ‘cyberphysical’ 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’)*

3.3.3. Inclusion and Exclusion Criteria

To select relevant publications answering our research question, we defined inclusion (I_i) and exclusion (E_j) criteria described in Table 4. We include peer-reviewed articles, 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, secondary studies, duplicated work or its extension, and works written in languages other than English. The inclusion and exclusion criteria are applied first during the screening phase of the titles, keywords and abstract of the primary studies, and then during the full-text reading of those selected papers.

Table 4: Inclusion and Exclusion 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 apply to research questions i.e. do not report the method for sustainability or modelling approach for CPS.
E4	Papers with the same content in different paper versions.
E5	Papers written in other than the English language.
E6	Purely hardware, or electrical engineering perspective papers.
E7	Purely application of sustainability in environmental domains (e.g. agricultural papers).
E8	Environmental used only in the context of technical (operational) environment of CPS, and not the impact on the environment.

3.3.4. Quality Assessment Criteria

The Quality Assessment Criteria in Table 5 was used to assess the quality of the studies after the data analysis. 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. Therefore, the list serves as a complement to the extracted data. QA1 to QA5 reflect the quality of the approach based on the content presented in the primary 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 6) 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 were discussed.

3.3.5. 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 serves to collect 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. The reviewers' 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 6 derived from the PICOC Outcomes.

We indicate which sustainability attribute (Q1), as defined in Section 2.1,

Table 5: Quality assessment and self-assessment criteria

Id	Assessment Criteria	Scale
QA1	How clearly is the problem of study described?	1 = Explicitly — 0.5 = Vaguely — 0 = No description
QA2	How clearly is the research context stated?	1 = With references — 0.5 = Generally — 0 = Vaguely
QA3	How rigorously is the method evaluated?	1 = Empirical foundation — 0.66 = Case study — 0.33 = Lessons Learned — 0 = No evaluation
QA4	How explicitly are the contributions presented?	1 = Explicitly — 0.5 = Generally — 0 = No presentation
QA5	How explicitly are the insights and issues for future work stated?	1 = With recommendations — 0.5 = Generally — 0 = No statement
SA1	Reviewers confidence about content of the study	1 = Very confident — 0.5 = Confident — 0 = Not very confident
SA2	Reviewers confidence about quality of the study	1 = Very confident — 0.5 = Confident — 0 = Not very confident

Table 6: Data Extraction Form for addressing the research question

Id	Question
Q1	Which sustainability attribute is addressed?
Q2	Which method is used to address sustainability?
Q3	What kind of sustainability metric is used?
Q4	What type of model is used to specify sustainability?
Q5	What instance of model/meta-model is used to specify sustainability?
Q6	What modelling process is used?
Q7	What modelling tool is used?
Q8	Is the modelling approach domain-specific?
Q9	Which application domain is addressed?

is addressed and which application domain was considered (Q9) in a study by using the categorisation provided Gunes et al. [1]. Further, we categorise which types of sustainability method (Q2) was addressed by using findings from Pezenstadler et al. [36] in Table 7.

The third part of the extraction form collects information about the quality of the primary study and the confidence of the reviewer as specified in Table 5.

3.3.6. Protocol Validation

Prior to the SMS conduction phase, we performed a protocol validation task with two goals in mind: (i) check that the protocol addresses the goals of the SMS, and (ii) solicit suggestions for improving the protocol. The protocol pre-validation was performed in a workshop meeting with the Automated Software Engineering (ASE) research group of the NOVA LINCS research centre from University NOVA of Lisbon. The protocol was presented to the group participants and the informal feedback received resulted in small changes in

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

	Q1 [1]	Q2 [36]	Q9 [1]
1	Adaptability	Entity-relationship	Smart Manufacturing
2	Resilience	Neural networks	Emergency Response
3	Reconfigurability	Cost calculations	Air Transportation
4	Efficiency	Life-cycle analysis	Critical Infrastructure
5			Health Care and Medicine
6			Intelligent Transportation
7			Robotic for Service
8			Building automation

the protocol. The validation was then performed online using a Google survey form, with questions that required single-choice and free-form responses. In total, seven reviewers were involved. All reviewers were from academia, and they were at least knowledgeable in SLRs and SMSs. Four of those reviewers authored published systematic reviews.

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

3.4. Conduction

In this section we detail how the primary studies were selected and how we validate the quality of the extracted data¹.

3.4.1. Obtaining the Data

During the conduction phase we had three main sub-activities: Query search, Abstract Review, and Classification (see Figure 2). During the Query search activity, we executed the search string on each digital library. The first set of papers was obtained in April 2017. A second search to retrieve the papers published after this date was executed one year later, in April 2018. A final set of papers was retrieved in March 2021. After removing the duplicates, we obtained 2209 papers, of which most of primary studies were obtained from ScienceDirect (SD) with 47.89% and Springer (SL) (46.63%) library.

¹Our complete archive of the retrieved data can be viewed at <https://docs.google.com/spreadsheets/d/1d6QnPVELsynsqe-4wLEQnqFxAvxq27GKnNxmARCYzDI>

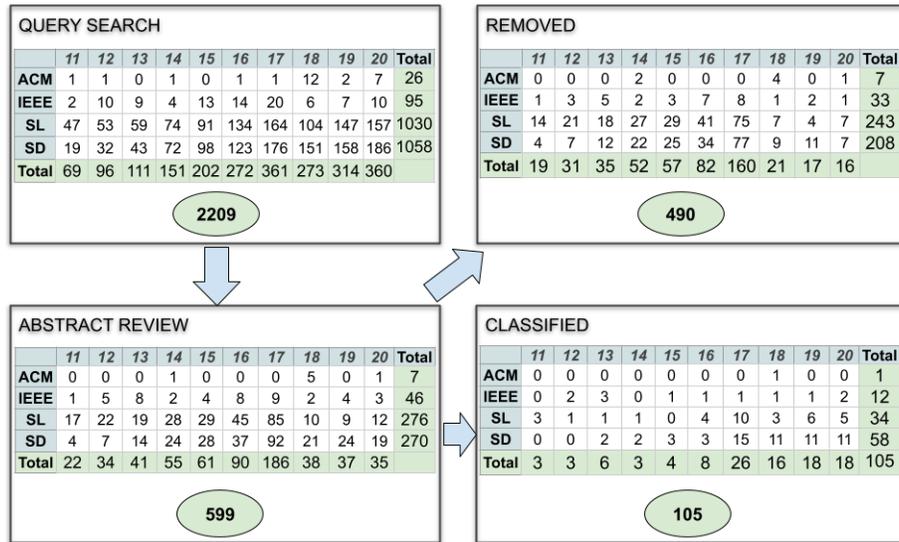


Figure 2: Conduction process and primary studies by year and library

The papers were added to an Excel workbook and their abstracts and conclusions copied there. By reading abstract and conclusions it was decided to include/exclude the study for the classification phase based on criteria presented in Table 4. The number of papers marked for exclusion were 276 for Springer, 270 for SD, 46 for IEEE, and 7 for ACM. The remaining 599 papers were imported to the Mendeley library and their full texts were downloaded for posterior classification. In the second iteration we prepared a separate individual data extraction sheet and assigned each paper randomly to one reviewer. The researchers read their papers and decided if the paper contributed to our research objective. If the paper did not present a modelling approach for sustainability of CPS it was excluded. In total, reviewers excluded 490 papers during this iteration and classified 105 papers (34 papers from Springer, 58 from ScienceDirect, 12 from IEEE, and, surprisingly, only one from ACM). We could observe a boost in the number of publications on modelling and sustainability for CPS from 2016.

4. Discussion of the Study Results

This section discusses the findings of our systematic mapping study. Besides presenting the results for each RQ, we also present 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” in a broad sense, referring to notable observations from two-way contingency tables between answers to a pair of research questions.

Q1. What sustainability attribute is addressed?

The sustainability attributes considered for this research question are those provided by Gunes et al. [1], as listed in the first column of Table 8. This table also shows the percentage of primary studies tackling each attribute (second column²) and the corresponding list of primary studies (third column)³.

Table 8: Studies addressing sustainability attributes

Attribute	% (#/total)	Primary study
Efficiency	50 (53/105)	[40, 43–94]
Resilience	31 (33/105)	[90, 92, 95–125]
Adaptability	17 (18/105)	[41, 42, 78, 89, 126–139]
Reconfigurability	12 (13/105)	[91, 93, 94, 121, 125, 135, 137, 139–144]

Half of the selected primary studies (50%, 53 out of 105) address **efficiency**, or the ‘good use of resources’. In this context, it is considered that a highly efficient system operates properly with an optimum use of system resources such as energy, money, time, etc. **Resilience** is the second highly discussed attribute (in 31%, 33 out of 105 studies), emphasising the value of ‘self-healing’ or the ability of a system to persist in its operation and deliver services with acceptable quality when the system is exposed to any inner or outer difficulties. These difficulties can be a sudden defect or some malfunctioning of components. About 17% (18 out of 105) 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, e.g. a rising workload. Finally, about 12% (13 out of 105) of the selected approaches address **reconfigurability**, or the ‘dynamic tuning’ ability of a system to change its configuration in case of failure or upon inner or outer requests.

The majority of the papers are concerned with one sustainability attribute, however 12 papers are targeting at least two attributes. Three of these address reconfigurability and adaptability [135, 137, 139], and another three address reconfigurability and efficiency [91, 93, 94]. For the remaining, two of each address adaptability and efficiency [78, 89], resilience and reconfigurability [121, 125], and resilience and efficiency [90, 92].

Q2. What method is used to address sustainability?

To characterise the methods used to address sustainability, we followed the categorisation proposed by Pezenstadler et al. [36] and summarised in Section 3.3.5. Table 9 presents the method categories, the percentage of primary studies using the method, and the list of the corresponding papers.

²This 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% of studies, being this 53 out of 105 studies.

³This is the general structure of the tables used to report our finding for each RQ.

Table 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 (15/105)	[40, 43, 64, 83, 91, 94, 100, 106, 107, 113, 114, 117, 130, 135, 136]
NN	4 (4/105)	[73, 78, 132, 142]
CC	21 (22/105)	[45, 49, 63, 69, 72, 74, 75, 81–84, 87–89, 93, 104, 121, 123, 125, 136, 141, 143]
LCA	49 (51/105)	[41, 44, 47, 48, 50–53, 55, 57–61, 79, 80, 82, 84–87, 91, 92, 95–97, 99, 101–103, 105, 108, 109, 112, 116, 120–122, 122–124, 126, 128, 129, 131, 133, 137–140, 143, 144]
<i>None</i>	21 (22/105)	[42, 46, 54, 56, 62, 65–68, 70, 71, 76, 77, 90, 98, 110, 111, 115, 118, 119, 127, 134]

Among the studies reporting sustainability methods, 79% (83 out of 105) of the papers report a method used to address some sustainability concern, while 21% (22) do not report any method. A little less than half of the papers (51 out of 105 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 in selecting products or processes that will have a positive impact on 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. Over 14% of studies use *entity-relationship modelling* to describe interrelated aspects relevant for the sustainability needs of a CPS. Finally, only four papers (3% 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.

Nine studies use two techniques, of which six combine life-cycle analysis with cost calculations [82, 84, 87, 121, 123, 143], two combine entity-relationship modelling with cost calculations [83, 136], and one combines entity-relationship modelling with life-cycle analysis [91].

Finally, Figure 3 depicts a summary of the correlation between methods and sustainability attributes, showing that LCA contains the larger proportion of efficiency and resilience, while reconfigurability and adaptability are the least addressed attributes by our labelled methods.

Q3. What kind of sustainability metric is used?

From the total 105 studies, 56 (53%) report some kind of sustainability metric, while 49 (46%) discuss no metrics at all. Table 10 summarises our findings for the extracted elements. Note that a paper may appear in more than one category as it may discuss more than one kind of metrics.

From the 56 studies discussing metrics, we distinguish three scenarios: (i) introduction of new metrics, (ii) introduction of frameworks for measuring sus-

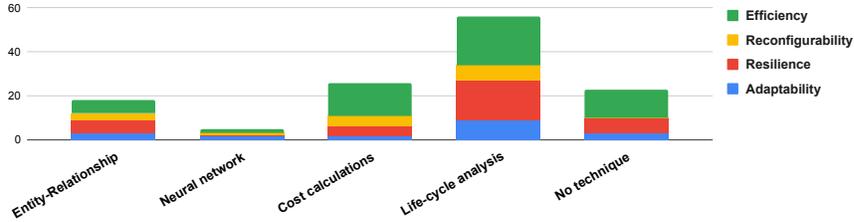


Figure 3: Correlation between methods (Q2) and sustainability attributes (Q1).

Table 10: Studies addressing sustainability metrics

Metric	% (#/total)	Primary study
New metrics	2 (2/105)	[86, 93]
Measuring frameworks	3 (3/105)	[54, 57, 59]
Metrics for case studies	18 (19/105)	[64, 74–76, 78, 84, 91, 92, 94, 113, 115, 119–121, 125, 134, 135, 137, 144]
Qualitative metric	7 (7/105)	[81, 83, 92, 94, 112, 137, 139]
Quantitative metric	38 (40/105)	[44, 45, 48, 54, 57–59, 64, 68, 69, 71–73, 79, 80, 82–85, 87–89, 91–93, 97, 100–102, 110, 111, 121–123, 125, 132, 135, 136, 142, 143]
<i>No metric</i>	47 (49/105)	[40–43, 46, 47, 49–53, 55, 56, 60–63, 65–67, 70, 77, 90, 95, 96, 98, 99, 103–109, 114, 116–118, 124, 126–131, 133, 138, 140, 141]

tainability (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, 2 propose new metrics to measure or qualify different aspects of sustainability, 3 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, 40 present quantitative metrics, 7 present qualitative metrics, and 2 present qualitative and quantitative metrics.

We analyse the various metrics categories against the sustainability attributes under study (Figure 4). 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 cases studies are quite well distributed amongst the four sustainability attributes.

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

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

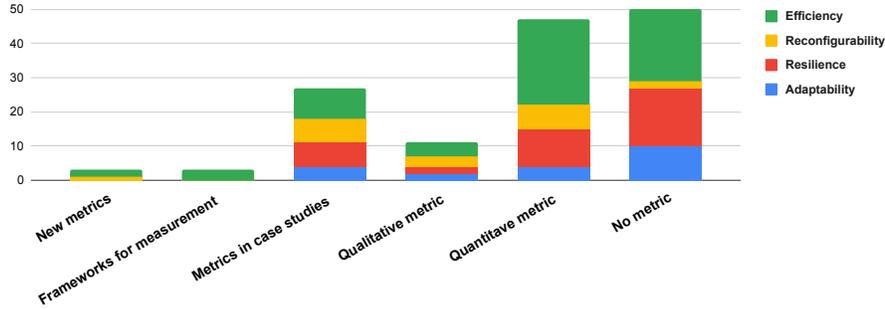


Figure 4: Correlation between metrics (Q3) and sustainability attributes (Q1).

of the 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 physical properties of a component). Table 11 summarises our findings.

Table 11: Types of models used for CPS sustainability

Model	% (#/total)	Primary study
Behavioural	18 (19/105)	[52, 53, 79, 80, 83, 86, 93, 94, 103, 113, 115, 116, 119, 120, 122, 131, 137, 139, 143]
Algorithmic	10 (10/105)	[54, 60, 71–73, 78, 87, 93, 97, 132]
Architectural	13 (14/105)	[45, 68–70, 76, 84, 91, 92, 94, 114, 117, 118, 123, 144]
Mathematical	16 (17/105)	[42, 74, 75, 81, 82, 84, 85, 88, 89, 95, 112, 124, 134, 138, 140–142]
<i>No sust. model</i>	46 (48/105)	[40, 41, 43, 44, 46–51, 55–59, 61–67, 77, 90, 96, 98–102, 104–111, 121, 125–130, 133, 135, 136]

A little over half of the studies (57 out of 105) use some type of model to represent sustainability related issues. Of these, most studies (19, corresponding to 33%) use some kind of behavioural model, 17 (30%) use mathematical models, 14 (25%) use architectural models. The remaining 48 studies (46%) use no models at all.

When analysing the the types of models considering the sustainability attributes, see Figure 5, we can see that efficiency is highly represented in all types of models. Moreover, architectural models never address adaptability,

whilst algorithmic definitions address primarily reconfigurability.

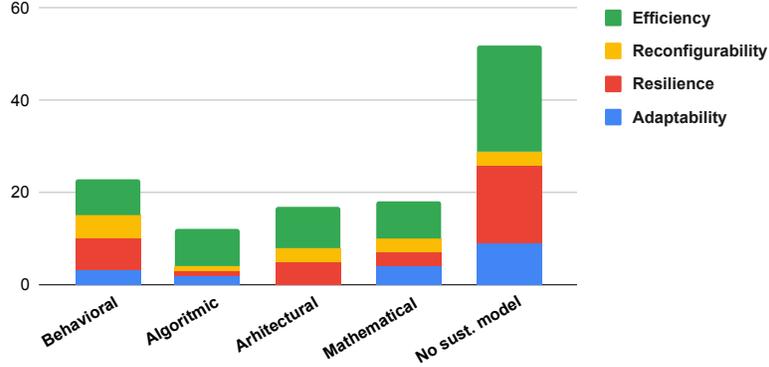


Figure 5: Correlation between types of models (Q4) sustainability attributes (Q1).

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

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

- Equational models included explicit equation-based modelling with differential equations, optimisation problem constraints, and structural equations in bond graphs. This category accounts for 18% 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 14% of all models.
- Automata include finite state machines, hybrid automata, probabilistic state machines, and other types of automata. This category accounts also 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 14% 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 excluding 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 is the smallest among the named categories and accounts for 5% of all models.
- Variability models include feature models and similar methodologies and languages. 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 creation of another high-level category. This category accounts for 8% of all models.
- Approximately 12% of the primary studies did not report any instance of model/meta-model.

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

Figure 6 presents the relationship between the model found and the sustainability attributes.

From the figure we can see that equations are the most used model type for efficiency (14 papers), followed by automata (8 papers). We can also observe that UML-like models, automata, and meta-models do not address reconfigurability.

Q6. What modelling process is used?

Only 48 studies (44% of all studies) propose or report a process. This finding shows that processes are less popular than models or tools, at least among the included studies. The reported processes are suggested for two main purposes: (i) organising the development and business processes, and (ii) suggesting a workflow of a system’s operation. Among the reported processes, we noted the following three forms of presentation:

Table 12: Model types in primary modelling studies.

Model type	% (#/total)	Primary studies
Equations	18 (19/105)	[50, 54, 55, 57, 58, 63, 74, 75, 81, 82, 84, 85, 88, 89, 97, 124, 132, 134, 142]
Component-based	14 (15/105)	[56, 65, 71, 76, 78, 92, 94, 95, 105, 109, 111, 123, 128, 130, 140, 144]
Automata	14 (15/105)	[46, 51, 53, 59, 60, 68, 83, 84, 106, 108–110, 116, 130, 133]
Dataflows	14 (15/105)	[43, 50, 52, 57, 60, 63, 84, 96, 105, 109, 120, 125, 127, 137, 141]
Custom graphs	9 (9/105)	[77, 92, 93, 100, 102, 116, 121, 136, 137]
Programs	9 (9/105)	[42, 50, 58, 72, 87, 90, 101, 119, 143]
Meta-models	8 (8/105)	[46, 59, 61, 66, 68, 96, 107, 130]
UML-like models	8 (8/105)	[41, 68, 80, 98, 113, 117, 118, 123]
Processes	6 (6/105)	[64, 71, 103, 114, 115, 139]
Specifications	5 (5/105)	[83, 109, 126, 137, 138]
Variability model	3 (3/105)	[91, 112, 135]
Other models	8 (8/105)	[69, 70, 73, 79, 86, 94, 122, 136]
<i>No model reported</i>	11 (12/105)	[40, 44, 45, 47–49, 62, 67, 99, 104, 129, 131]

- *Rigorous graphical processes*: formalised graphical notations including BPMN, activity diagrams, sequence diagram, and other notations with precise defined meanings of blocks and arrows.
- *Informal graphical processes*: general and abstract block-and-line diagrams indicating flows and orders of operations without precise or formalised meanings of the graphics primitives.
- *Informal textual processes*: textual descriptions of processes, including itemised lists and section-by-section breakdowns.

As Table 13 indicates, the most prominent way to represent a process is via an informal graph. The number of processes reported as informal text and

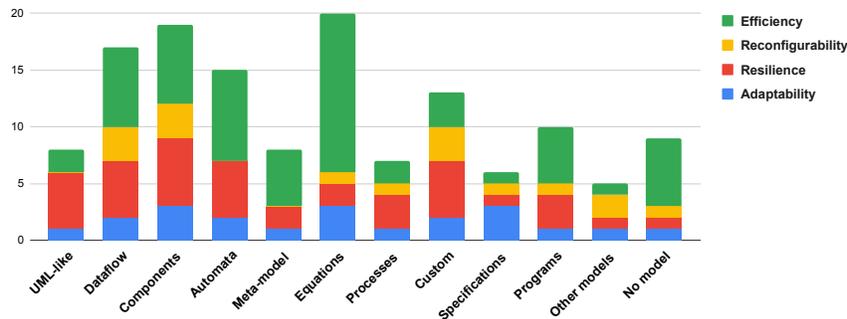


Figure 6: Correlation between model instances (Q5) sustainability attributes (Q1).

formalised diagrams is similar. Therefore, processes in CPS works are mostly informal.

Table 13: Primary studies by process presentation

Process presentation	% (#/total)	Primary studies
Rigorous graphical	9 (9/105)	[55, 70, 72, 80, 86, 98, 99, 122, 126]
Informal graphical	24 (25/105)	[42, 46, 49, 52, 62, 67, 71, 73–76, 90, 91, 96, 100, 105, 109, 112, 113, 115, 129, 131, 136, 137, 144]
Informal textual	11 (12/105)	[40, 45, 54, 64, 77, 78, 84, 107, 108, 123, 134, 141]
<i>No process</i>	56 (12/105)	[41, 43, 44, 47, 48, 50, 51, 53, 56–61, 63, 65, 66, 68, 69, 79, 81–83, 85, 87–89, 92–95, 97, 101–104, 106, 110, 111, 114, 116–121, 124, 125, 127, 128, 130, 132, 133, 135, 138–140, 142, 143]

In Figure 7 we illustrate the number of primary studies that address sustainability and follow some modelling process.

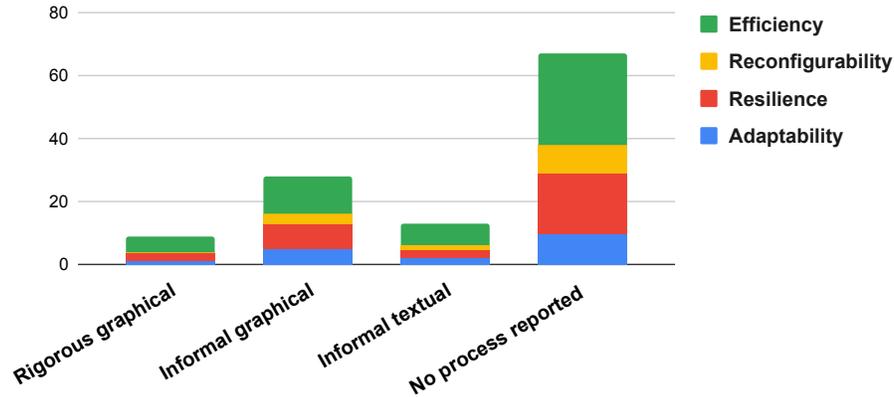


Figure 7: Correlation between modelling processes (Q6) sustainability attributes (Q1).

It is possible to see that efficiency is mostly addressed using informal graphical processes. Reconfigurability is the least addressed attribute and that it is not addressed by a single rigorous graphical process.

Q7. What modelling tool is used?

Of the 105 total number of primary studies included in our analysis, only 37 (35%) were reported using some tool, while in 68 studies (65%) authors did not report using a tool. Please note that we considered only papers in which authors explicitly emphasised using some tool (whether developed by the authors or an existing tool). Thus, if a paper simply mentioned that a tool could be used, it

was not included in our analysis and was marked as not reporting a tool. We were looking for papers that explicitly emphasised the use of tools in modelling some part of a CPS system and including some sustainability attribute.

These tools can be divided in 4 categories:

- Eclipse based/Papyrus based. This category contains the tools that are built based on the Eclipse platform. This category accounts for only 2 of 105 papers that reported using tools.
- SysML/UML/MARTE based. This category contains profiles that are developed as extension of SysML/UML/MARTE model. Only 1 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 tool. 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.

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

Table 14: Primary studies by tool type.

Tool type	% (#/total)	Primary studies
Eclipse based/Papyrus	2 (2/105)	[68, 105]
SysML/UML/MARTE	1 (1/105)	[113]
Matlab/20-sim/Simulink/Modelica/UPPAAL	4 (4/105)	[50, 59, 109, 120]
Custom tool (other)	29 (30/105)	[42, 46, 64, 66, 69, 71, 73, 86, 90, 91, 94, 98, 107, 108, 110–112, 115–117, 119, 123, 126, 129, 130, 135, 136, 138, 139, 144]
<i>No tool reported</i>	65 (68/105)	[40, 41, 43–45, 47–49, 51–58, 60–63, 65, 67, 70, 72, 74–85, 87–89, 92, 93, 95–97, 99–104, 106, 114, 118, 121, 122, 124, 125, 127, 128, 131–134, 137, 140–143]

According to the reported tools, we can conclude that use of tools to model CPS and their sustainability is quite reduced.

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 [94], INTO-CPS [123], GreatSPN [139], Providentia [136], S.P.L.O.T. [91], Darwin-SPL [135], MoSH [117], SAURON [116], ASPN [115], Cooja [90], FaMa and CyberSPL [112], or IBM CPLEX [42].

It is possible to see that both papers that address reconfigurability and adaptability do not use tools from the 3 categories we selected. Moreover, efficiency is the attribute for which custom tools have been developed, followed by resilience.

Q8. Is the modelling approach domain-specific? and Q9. What application domain for CPS is addressed?

This section analyses whether the approaches reported by the primary studies are domain-specific (Q8) and also the application domains focused by the studies (Q9). To facilitate data collection, we pre-defined the following list of application domain 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 in the description section.

Among the total of 105 studies, a total of 63 studies (60%) discuss a domain-specific approach. The remaining 42 studies discuss general-purpose approaches. Most of the 105 studies proposing domain-specific approaches (55 studies, about 87%) fall in one of our pre-defined categories.

As shown in Table 15, 15 studies (about 14%) of the studies address “Critical Infrastructure”, being this category the most tackled one. In 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 [112] addresses smart agriculture and [142] addressed smart cities.

Table 15: Primary studies by application domain.

Domain	% (#/total)	Primary studies
Critical Infrastructure	14 (15/105)	[57, 58, 66, 76, 77, 84, 94, 97, 99, 101, 102, 111, 121, 125, 137]
Smart Manufacturing	11 (12/105)	[40, 49, 55, 59, 62, 63, 70, 72, 93, 128, 129, 144]
Building automation	9 (9/105)	[41, 43, 46, 48, 73, 80, 89, 92, 127]
Intelligent Transportation	8 (8/105)	[42, 75, 81, 91, 134, 135, 139, 141]
Robotic for Service	5 (5/105)	[105, 107, 110, 123, 136]
Emergency Response	4 (4/105)	[47, 83, 106, 126]
Air Transportation	0	
Health Care and Medicine	2 (2/105)	[44, 74]
Other	8 (8/105)	[68, 82, 85–87, 112, 122, 142]
<i>No application domain</i>	40 (42/105)	[45, 50–54, 56, 60, 61, 64, 65, 67, 69, 71, 78, 79, 88, 90, 95, 96, 98, 100, 103, 104, 108, 109, 113–120, 124, 130–133, 138, 140, 143]

Figure 8 presents the relationship between sustainability attributes and application domains. Smart manufacturing, critical infrastructures and building automation are mostly related to the efficiency attribute. Moreover, critical infrastructures are also quite related to the resilience attribute.

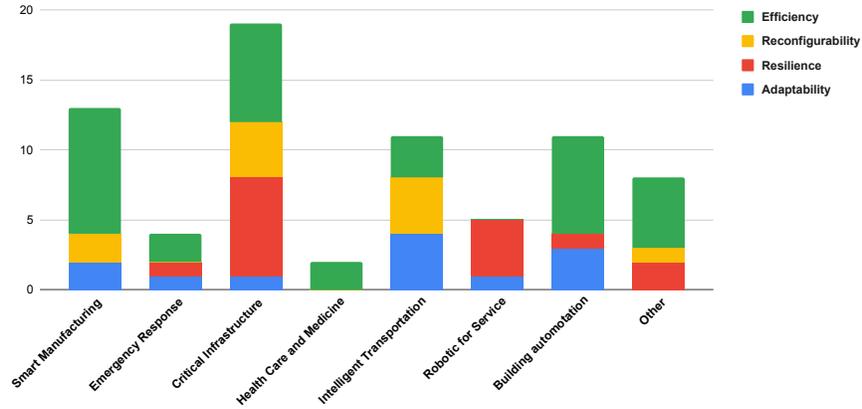


Figure 8: Correlation between sustainability attributes and application domains.

4.1. Noteworthy Correlations 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 (55%, 15 out of 27) of cost-calculation studies use quantitative metrics, perhaps unsurprisingly so, as shown in Figure 9. At the same time, among the papers with sustainability techniques, the life-cycle analysis ones are least likely to report a metric (42%, 25 out of 59, do not report one).

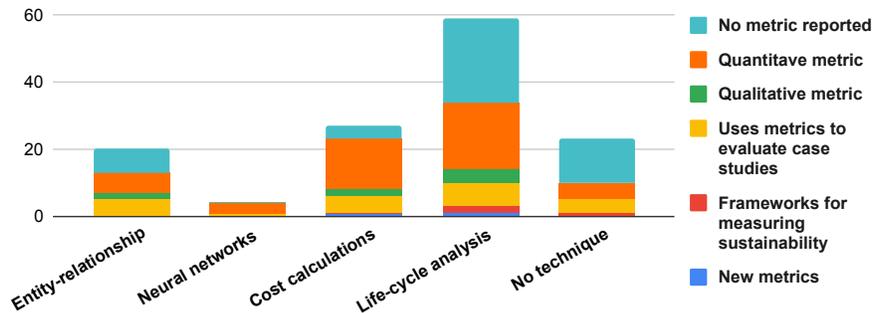


Figure 9: Correlation between techniques and metrics.

Behavioural sustainability is mostly addressed with lifecycle analysis, with 61% (13 out of 21) of the studies. At the same time, algorithmic sustainability has the highest chance of being addressed with neural networks (27%, 4 out of 11), but not with entity-relationship modeling (we found no such studies). We also note that mathematical sustainability has the highest chance of being addressed with cost calculations (42%, 8 out of 19). Figure 10 shows such correlations between model types and sustainability models in papers that reported a sustainability model.

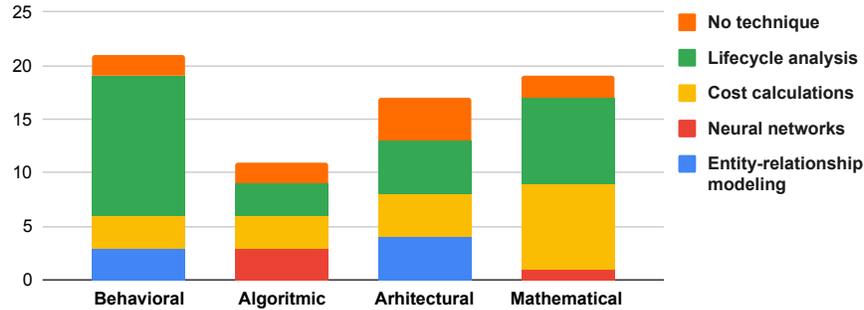


Figure 10: Correlation between sustainability techniques (Q2) and model types (Q4).

Cost calculation techniques use equational models the most, accounting for 42% of them (9 out of 21), while not using meta-models or processes, in our experience. Figure 11 shows the distribution of sustainability techniques in papers that reported model instances.

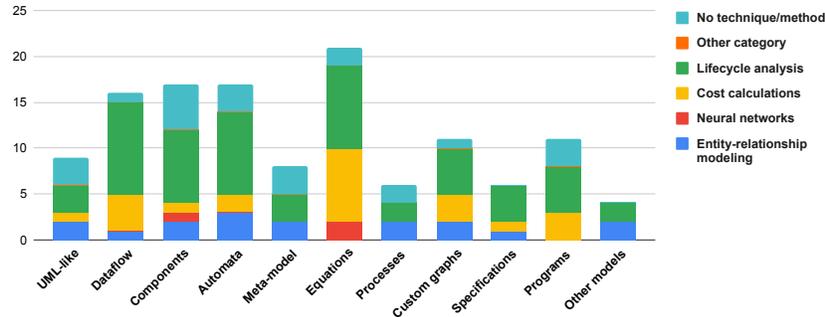


Figure 11: Correlation between sustainability techniques (Q2) and model instances (Q5).

Lifecycle analysis is compatible with a wide variety of models. This observation can be witnessed in Figures 10 and 11: the lifecycle 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. Metrics are used in domain-specific studies in 78% of cases (31 out of 40). Interestingly, all of the 7 studies with qualitative metrics are domain-specific. Cost calculations are used in domain-specific studies in 81% of cases (18 out of 22). The rest of the sustainability techniques are roughly balanced between domain dependence and independence.

Smart manufacturing is the least likely to use a metric among all the domains, only using it in 43% of cases (8 out of 14). At the same time, critical infrastructure and intelligent transportation are most likely to use a metric: 85% (18 out of 21) 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 12 shows the distribution of metric use in papers with specific domains.

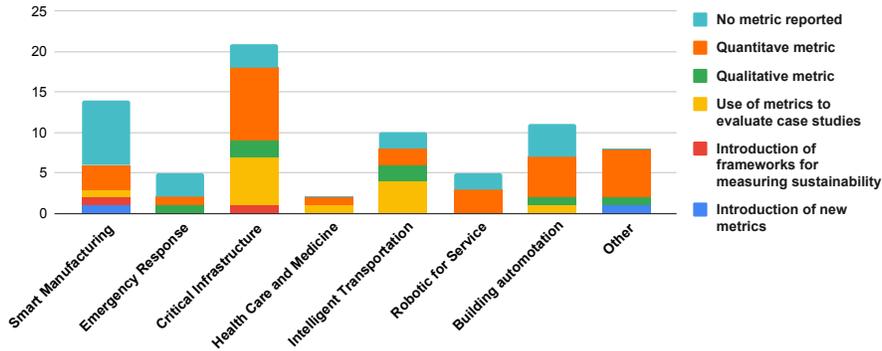


Figure 12: Correlation between metrics (Q3) and domains (Q9).

Most intelligent transportation uses mathematical models, with 63% (5 out of 8) of papers reporting a mathematical model. Figure 13 shows how models are used in papers that target a specific domains. 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 59% (10 out of 17) to not use a model. Behavioural models are the most general across domains: they occur in all but 2 surveyed domains, and 57% (11 out of 19) of papers with behavioural models do not have a specific domain.

In domains with at least 10 studies, smart manufacturing is the most process-oriented domain, relatively to other domains: 66% (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 the their processes: only 33% (5 out of 15) of papers in it had any form of a process. These observations are illustrated in Figure 14, which illustrates how processes are used in papers targeting specific domains.

All 5 robotics-for-service papers had reported a modelling tool, whereas most

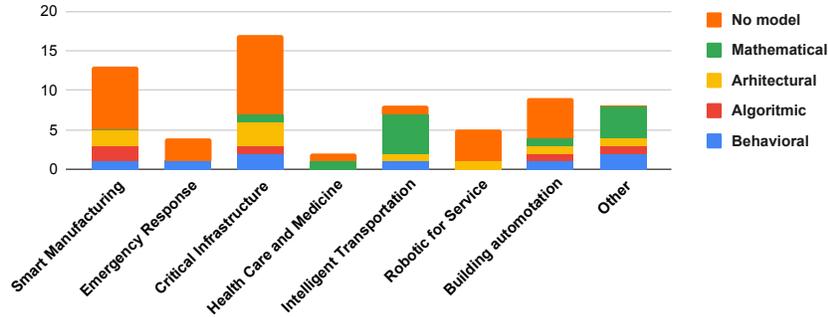


Figure 13: Correlation of model types (Q4) and domains (Q9).

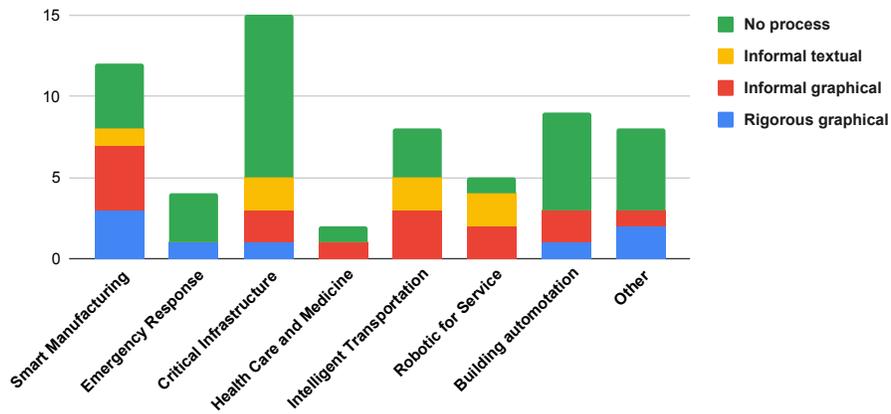


Figure 14: Correlation between processes (Q6) and domains (Q9).

domains are less likely to report a tool than not. This observation can be seen in Figure 15, which shows the distribution of tool use in papers with specific domains.

4.2. Quality Assessment of Classified Studies

The results regarding the quality assessment of the classified studies are shown in Table 16. The first column presents the questions that the reviewers answered when extracting data from the primary studies. The second column presents an aggregated score based on the numeric value of each answer. For instance, for *QA1* we calculate $(1 \times 84 + 0.5 \times 21 + 0 \times 0)/105 = 0.9$. The third column presents the possible answers, and the last column contains the number of primary studies for each answer.

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 (84

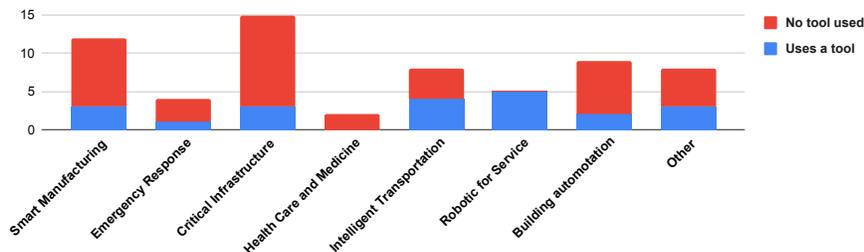


Figure 15: Correlation between tool use (Q7) and domains (Q9).

Table 16: Quality assessment results

Assessment Question	Avg. Score	Answer options / Paper counts	
QA1: How clearly is the problem of study described?	0.9	1 = Explicitly	84
		0.5 = Vaguely	21
		0 = None	0
QA2: How clearly is the research context stated?	0.86	1 = With references	75
		0.5 = Generally	30
		0 = Vaguely	0
QA3: How rigorously is the method evaluated?	0.63	1 = Empirical foundation	16
		0.66 = Case study	70
		0.33 = Lessons Learned	8
		0 = No evaluation	11
QA4: How explicitly are the contributions presented?	0.81	1 = Explicitly	65
		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	45
		0.5 = Generally	39
		0 = No statement	21

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 studies have vaguely focused on the research context, while a majority of papers described the research context with references reporting the problems and advantages of the related work (75 out of 105 studies). Finally, 30 of the studies were classified as describing the research context generally.

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 (70 studies), while 11 studies do not report any evaluation. Only 16 of the total number of studies use empirical evaluations, while the rest only discuss lessons learned. In order to increase trust in the approaches presented, more empirical 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 60% of the studies (65 of them) explicitly present their contribution, meaning they contribute with a concrete solution and explain the scope of their contribution clearly in the conclusions, while the remaining 40 papers describe their contributions in general terms.

Finally, regarding (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 45 present future work with concrete recommendations.

From these results, we can conclude that most of the primary studies provide motivation for their problem and provide a research context. Most of approaches are evaluated using a case study or empirically. Although in most of the cases the contributions are explicit, we note that the future work is either very general or lacking concrete recommendations and are 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), having around half marked as very confident. These responses support our confidence in the main results of the study, reported earlier.

4.3. Summary of Results

This section summarises the takeaway messages from our analysis of the papers published on CPS modelling for sustainability in the last 10 years.

The research papers that we surveyed 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 model instances were surprisingly diverse, with a wide variety of formalisms used to address sustainability in CPS, which is a general feature of CPS modelling research [19]. 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. In terms of 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 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 the healthcare and air transportation, which contrasts with general CPS modelling literature [19]. We hypothesise that, due to the comprehensive nature of sustainability, these domains are yet to be explored in CPS sustainability modelling.

4.4. Threats to Validity

Next we discuss the threats to validity of this work with respect to construct 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 was not distinguishable. Additionally, the interpretation of the concepts “model” and “process” may vary among the reviewers: some may include a wide range of phenomena in them (e.g., an algorithm can be considered a model, and a process is any multi-step description), whereas others may require a formalised version of a model or process presented. To mitigate these three threats, several meetings were held to discuss and validate the used classification. The participants of these meetings were the seven reviewers and an eighth person not involved directly in the reviewing process. After these meetings, one reviewer was responsible for checking and possibly reclassifying the results.

Internal validity. A first observation is that the background of the researchers involved in this study is mostly on Software Engineering. This can be seen as a possible cause for bias during the paper selection and data extraction phase. However, most of the authors are experienced in performing systematic review and mapping studies, and also have an extensive track record in a wide variety of research topics and domains. We believe this expertise limits the negative effects of this threat. Another possible threat is that some decisions of the SMS process may have been subjective, particularly those regarding the application of the inclusion and exclusion criteria, and the selection of the data to extract. To minimise this threat, we performed several validity checks among the various authors. In particular, the SMS process was performed following a “peer review” approach, where conflicts were discussed and resolved by the authors,

hence mitigating threats due to personal interpretation. Finally, certain extraction choices may have been difficult to handle consistently, due to potential ambiguities in our assigned labels. For example, domain specificity of a contribution may be difficult to judge — at least without an attempt to apply an approach to a new domain. Some approaches may appear domain-specific, but in fact apply to many CPS domains. To mitigate this threat, our extraction relied on the reporting and claims by the authors, rather than the interpretations of the reviewers. That is, we only marked an approach as non-domain-specific if the study explicitly claims or demonstrates generality. The same applied to other questions where different interpretations are possible, such as whether a study proposes a modelling process or addresses sustainability concerns.

External validity. This refers to how well the results of our research study can be generalised to other settings, i.e., how the primary studies are representative for the topics under review. To address this possible limitation, the search was specified considering a set of trial searches and validated by the authors, and the coverage and relevance of the retrieved studies were constantly checked among subgroups of the team. Another threat respects the primary studies obtained from the used digital libraries. We performed 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-December 2017, but as the systems do not allow to select publications by month, we searched for the whole year. We were surprised to observe that the set of papers returned from the Springer library was not the same for the first part of the year, that is, some papers retrieved in the first search were not retrieved in the second search. In those cases, we merged the papers returned in the first and second string search executions. In fact, there is always the risk of missing some relevant works. To mitigate this, we used the digital libraries considered more relevant in Computer Science, and so we believe that the 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 [34] considers that not all the relevant primary studies can be identified, so there is the possibility that some studies excluded in this review could, instead, have been included. To mitigate this, the inclusion and exclusion criteria were cautiously designed and verified by the authors, and also validated by members of the Software Engineering research group of the NOVA LINCS research centre. This procedure helped minimising the risk of excluding relevant studies. Additionally, only one reviewer read the titles and abstracts off all the papers, making the decision to include a study for data extraction. For all the cases where the decision about inclusion or exclusion was not clear, the study was always included. Then, during the result analysis, different reviewers performed the analysis of a single question by using the information of the selected studies. However, this could result in non-critical approach, for instance, accepting already given information as final. Nevertheless, for several papers the author doing the analysis contacted the author who

did the extraction to clarify the information recorded, changing it whenever necessary. This procedure shows the analysts were careful and critical when using the extracted data.

5. Conclusions

Sustainability in Software Engineering has been an active area of research in the past 10 years, and the expectation is that the interest in building sustainable products and systems will grow further in the years to come. This work analyses how the topic has been addressed by the Cyber-Physical Systems Modelling community and discusses the results of a systematic mapping study.

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, that life-cycle analysis methods and quantitative metrics are typically selected to model and evaluate those attributes, and that critical infrastructure and smart manufacturing are the most active application domains. The identified literature gaps indicate potential lines of research for the future, 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 should 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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