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Applications of Model-driven Engineering in Cyber-physical Systems: A Systematic Mapping

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Abstract

Engineers face significant challenges in developing cyber-physical systems (CPS) due to their heterogeneous nature, i.e. the need for knowledge and skills from a wide range of academic and industrial disciplines, the integration of the artifacts of these disciplines and fields, and the difficulty of maintaining such heterogeneous artifacts should be taken into account. The development of CPS mostly needs a unified methodology that permits efficient raise of the abstraction level to overcome issues of heterogeneity induced by the multidisciplinary nature of the system. Model-driven engineering (MDE) is believed to be an alternative solution to overcome the challenges faced while developing CPS. This paper presents a systematic mapping study on using the MDE paradigm in CPS development and management. 140 research papers published during the period 2010 – 2018 are evaluated. The study mainly enables to find out the followed approaches when applying MDE for CPS, addressed CPS challenges, application domains and presented case studies. Results showed that the number of publications in this field is continuously increasing in recent years. Results also showed that metamodeling and model-based approaches are mostly adopted by the researchers affiliated to Europe, while DSL-based approach is adopted mostly by USA affiliated researchers. Only 45% of the studies consider a specific CPS application domain in which Smart Manufacturing is the most addressed domain followed by Critical Infrastructure, Health Care and Medicine. Moreover, the majority of the studies present case studies as the main evaluation method for the proposed MDE solutions. Conducting empirical evaluations is mostly missing. The results also revealed that various CPS challenges are addressed, and the most addressed ones are the complexity and interoperability aspects of CPS. Reporting on what previous researches have accomplished, as well as current research efforts and open challenges related to this field can guide researchers and developers in their further work on CPS design and

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implementation.

Keywords: Cyber-Physical Systems (CPS), Model-Driven Engineering (MDE), Systematic mapping (SM)

1 Introduction

The first emerge of the term "Cyber-physical system" (CPS) was in 2006 at the National Science Foundation [1]. CPS is a system whose computational and communication components measure, control and monitor physical phenomena such as pressure, temperature, light and touch [2, 3]. The measured data are transferred to the controllers/software through communication elements (i.e. wired/wireless network). The controllers/software make decisions/actions based on the received data from the sensors and send them through communication elements to actuators which in return make changes to the physical phenomena [4]. The overall architecture of a CPS is depicted in Figure 1.

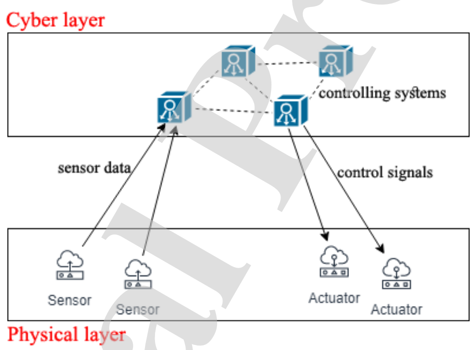

Figure 1: General CPS architecture

Applications of CPS include, but are not limited to, monitoring complex real-world environments, smart manufacturing (i.e. industry 4.0), smart building, critical infrastructures, like chemical and power plants, smart grids, natural gas distribution systems, transportation systems, etc. [2, 5].

Despite its wide range use, a unified development methodology for CPS has not been standardized yet. The abundance of different hardware platforms available makes the development of such systems very complex [6, 7, 8]. There is a need for a unified methodology that permits efficient raise of the abstraction level to overcome issues of heterogeneity induced by the multidisciplinary nature of these systems. Towards this goal, many researchers believe that Model-driven Engineering (MDE), which is frequently used in many business domains for software development [9], can also be a better alternative solution to overcome challenges such as development complexity, heterogeneity, adaptability, and they propose various applications of MDE for CPS development (e.g. [10, 11, 12, 13]).

MDE paradigm raises the abstraction level of software/system development from low-level artifacts to a higher-level of models and bridges the gap between problem identification and software implementation phases [9]. In general, models have two features. Reduction feature where the models focus on the main properties of a system and neglect the details to keep the representation of the system relatively easier, and Mapping feature whereby models are generalized from a prototype of the original system. Models can be used for different purposes such as sketches, blueprints, or programs. There is an increasing need for the use of such models in software development [14, 15]. In a similar manner, MDE-based techniques and approaches are being applied on the design and implementation of CPS. However, no secondary study, highlighting 1) previous researches, 2) current research efforts and 3) open challenges related to use MDE for CPS development, has been provided yet. Such an overview would be helpful to both researchers and practitioners for discovering the pros and cons for applying MDE in CPS and for identifying interesting research directions. Without such a secondary study, it may be cumbersome to determine what was proposed, what has been successfully completed and what rather has failed.

The aim of this study is to provide a Systematic Mapping (SM) study of the primary studies which benefited from MDE techniques and approaches during CPS development and management. Evaluation of research questions and analysis of the approaches proposed in 140 primary studies, published between 2010-2018, is performed. Furthermore, in this work, trends, bibliometrics and demographics are presented to help collecting important information such as the active authors/researchers in this domain, number of publications per year, preferred publication venues, most contributing countries to this field and other related information. Answering the research questions shows results like the most used modeling approach, the purpose for which the models were used, targeted CPS application domain, used evaluation approaches, addressed CPS challenges among many others.

Similar to other SM studies on software language engineering (e.g. [16], [17], [18], [19]), the results of our study may help the researchers to easily reach the desired class of studies and related publications considering the technologies, approaches, and best practices used in MDE of CPS. This study also enables researchers avoid unnecessary duplications of trial and error. Finally, it leads to identify research gaps and areas need more investigations and determine best practices and techniques which can be used.

The rest of the paper is organized as follows: Section 2 provides the related work. Section 3 describes the research methodology and protocol definition for the SM study. The results are shown in Section 4. The discussion of the results and the conclusions are presented in sections 5 and 6 respectively.

2 Related Work

A systematic literature review (SLR) on multi-paradigm modeling for CPS is presented in [20], where authors concentrate on studies that promote multi-modeling, multi-view, and multi-formalism approaches for CPS development. The study reported the most used approaches and tools in the primary studies for multi-paradigm modeling as well as indicating the type of formalism presented, and which tool and/or language is used for implementing it. Furthermore, they report the actors and stakeholders involved in the modeling process and their background knowledge.

In [21], authors performed an SLR of the model-based system engineering (MBSE) approaches proposed for the development of embedded systems. The study reviewed 61 research papers published during the years 2008-2014 in one of the four renowned scientific databases (IEEE, SPRINGER, ELSEVIER, and ACM). Subsequently, primary studies are grouped into six categories according to their relevance to the corresponding MBSE activity namely general category, modeling category, model transformation category, model verification category, simulation category, and property specification category. As the result, the study presents 28 tools which support modeling, model transformation, validation, and verification activities. The study examined the utilization of UML and SysML/MARTE profiles, and it also analyzed the application of both model-to-model and model-to-text transformations.

A further SLR is provided in [22], in which the authors investigate studies combining product line engineering (PLE) and MDE for the development of safety-critical embedded systems. This study examined whether there are empirical studies applied the aforementioned techniques in the development process of safety-critical embedded systems. The study expose that in recent years, use of MDE combined with PLE techniques to build safety-critical embedded systems is gradually growing. The study also states that the proposed approaches in the primary studies are not compared with any other related studies, besides, these approaches do not explicitly differentiate between the software and hardware variabilities.

An SM study is presented in [23] where the implementations of MDE in the field of mobile robot systems (MRS) are investigated. In this study, 69 research papers were selected, and as a result, the authors found out that many domain-specific modeling languages (DSMLs) are supported with tools which are mostly built ad-hoc. Also, they reported that the solutions based on UML and using Eclipse-based tools were less preferred in this field.

In contrast to the work presented in [21] and [22], our work focuses on conducting an SM study on the publications concerning the development of CPS using the MDE paradigm. The work herein and the SLR given in [20] both consider the development of CPS. However, the current study differs from the results of [20] in that our work identifies most of the MDE approaches used to develop the CPS, the purpose for which the models were used, and also presents CPS application domains and reports CPS challenges in the primary studies.

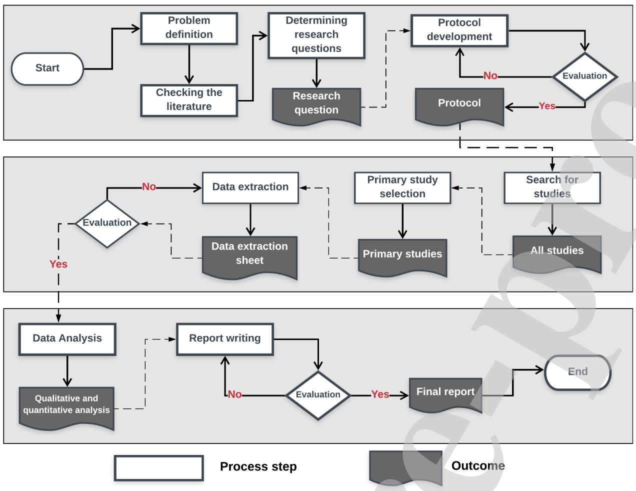

Figure 2: Overview of the systematic mapping study process

Table 1: Keywords definition based on PICOC criteria

Population	"cyber-physical system*" OR "cyber physical system*" OR "smart system*" OR "cyberphysical systems" OR "cps"
Intervention	MDE OR MDD OR MDA OR "model-driven *" OR "model driven *" OR "code generation" OR "generative approach*" OR "model-based approach*" OR "domain specific model*" OR metamodel* OR "meta-model*" OR "meta model*" OR "modeling approach*"
Comparison	Not applicable
Outcome	Report on the current state-of-the-art approaches, languages, tools and challenges of MDE for CPS.
Context	Peer-reviewed publications published between 2010 and 2018.

3 Methodology

This SM study was achieved by following the process proposed by [24] and [25] and using the guidelines defined by [26]. Figure 2 shows an overview of the followed process which will be discussed in the subsections below.

3.1 Research questions

In this study, the state-of-the-art MDE techniques in CPS development are taken into consideration. For this purpose, research questions were identified by following the PICOC criteria outlined in [26], see Table 1. The research questions of this study are defined as follow:

- **RQ1:** Are any of MDE approaches or techniques used in/for the development of CPS in the studies? **Objective:** With answering this question, the existing MDE approaches for CPS, modeling purpose, and the MDE phase addressed are reported.

  - **RQ1.1:** What is the modeling approach presented/used in the study?
  - **RQ1.2:** What is the purpose for which the models were used?

- **RQ2:** Does the study present any application domain? **Objective:** It is aimed to report the CPS domain like critical infrastructure, Smart Buildings, Industry 4.0 etc. which the primary studies are targeting.

  - **RQ2.1:** What is the application domain?
  - **RQ2.2:** What is the use case?

- **RQ3:** Is there any evaluation presented in the study? **Objective:** Reporting on the evaluation method followed by these primary studies such as case study, use case, example and empirical study.

  - **RQ3.1:** What is the evaluation approach?
  - **RQ3.2:** If the evaluation is based on a case study, what is the case study?

- **RQ4:** Does the study address any challenge(s)? **Objective:** Reporting on the CPS challenges which primary studies are addressing, also, challenges addressed during tool development/usage by the primary studies.

  - **RQ4.1:** Which CPS challenge(s) does the paper address?
  - **RQ4.2:** Does the study report challenges addressed during developing the MDE approach/tool?

3.2 Search and selection strategy

Our search strategy comprises four stages. 1- defining the selection criteria 2- conducting an automatic search across the most relevant scientific digital libraries, 3- removing duplicate studies, 4- including only the relevant studies to the topic by following predefined inclusion and exclusion criteria, 5- performing forward snowballing.

3.2.1 Inclusion & Exclusion Criteria (Selection Criteria)

Inclusion and exclusion criteria are used during the selection of the primary studies and also when conducting forward snowballing; this is to identify those papers directly related to the research questions as suggested in [26]. A paper is included in the pool of primary studies only if it satisfies all the inclusion criteria and none of the exclusion criteria. Inclusion and exclusion criteria we defined for this study are listed in Table 2.

Table 2: Inclusion and exclusion criteria.

Inclusion criteria		
	IC 1:	The study must propose at least one of the model-driven engineering (MDE) approaches or techniques for cyber-physical systems (CPS)
	IC 2:	The study must target cyber-physical systems and its domains
	IC 3:	The study must be a peer-reviewed study (journal papers, workshop papers, conference papers.)
	IC 4:	Models presented by the study must not be used for documentation and design purposes only.
	IC 5:	The study must be published in the period 2010-2018.
	IC 6:	The study must be available in full-text and published in a renowned digital library.
Exclusion criteria		
	EC 1:	The study is a secondary study (Survey, systematic mapping, systematic review, etc.)
	EC 2:	The study is irrelevant to the domain (i.e. cyber-physical systems) and the field of Software engineering
	EC 3:	The study is a summarized version of a complete work already in our SM study pool.
	EC 4:	The study is a kind of educational, editorial, tutorial, or other content (i.e., not a scientific paper).
	EC 5:	The study was written in other languages than English.

3.2.2 Performing automatic search

Initially, a manual search over digital libraries was implemented, which resulted in a large number of papers (on average, over 5000 results). Consequently, an automatic search was decided to be performed as it is recommended in [26] to conduct SM studies.

In order to perform an automatic search, search strings are to be developed. These search strings must fit the syntax of the targeted search engine. They should be “good-enough” to include as many relevant studies as possible, and concurrently, exclude irrelevant ones. We followed PICOC criteria [26], shown in Table 1 to define the keywords. The overall search string is as follows:

- (”model-driven development” OR ”model-driven engineering” OR ”model-driven architecture” OR ”code generation” OR ”generative approach” OR ”model-based approach” OR ”model-driven approach” OR ”domain specific model*” OR metamodel OR ”meta-model” OR ”meta model” OR ”modeling approach”) AND (”cyber-physical system*” OR ”cyber physical system*” OR ”smart system*” OR ”cyberphysical systems” OR ”cps”)

Due to the different syntax of each digital library, a specific search string for each of these libraries was created, Table 3 shows searched digital libraries and the corresponding search string(s) used. This is to ensure including as much relevant primary studies as possible. After concluding the automatic search, **646** studies were obtained.

Table 3: Search strings used for each digital library

Digital Library	Results	Search query
IEEE	164	(”model-driven development” OR ”model-driven engineering” OR ”model-driven architecture” OR ”code generation” OR ”generative approach” OR ”model-based approach” OR ”model-driven approach” OR ”domain specific model*” OR metamodel OR ”meta-model” OR ”meta model” OR ”modeling approach”) AND (”cyber-physical system*” OR ”cyber physical system*” OR ”smart system*” OR ”cyberphysical systems” OR ”cps”)
ACM	55	recordAbstract:((”model-driven development” OR ”model-driven engineering” OR ”model-driven architecture” OR ”code generation” OR ”generative approach” OR ”model-based approach” OR ”model-driven approach” OR ”domain specific model*” OR metamodel OR ”meta-model” OR ”meta model” OR ”modeling approach”) AND (”cyber-physical system*” OR ”cyber physical system*” OR ”smart system*” OR ”cyberphysical systems” OR ”cps”))
Web of Science	16	TI=((”model-driven development” OR ”model-driven engineering” OR ”model-driven architecture” OR ”code generation” OR ”generative approach” OR ”model-based approach” OR ”model-driven approach” OR ”domain specific model*” OR metamodel OR ”meta-model” OR ”meta model” OR ”modeling approach”) AND (”cyber-physical system*” OR ”cyber physical system*” OR ”smart system*” OR ”cyberphysical systems” OR ”cps”))) AND LANGUAGE: (English)
Scopus	363	The related search string is too long to fit in this paper. Please see the online repository [27]
Science Direct	23	(”code generation” OR ”generative approach” OR ”domain specific modelling” OR ”modelling approach”) AND (”cyber-physical systems” OR ”cyber physical systems” OR ”smart systems” OR CPS OR ”cyberphysical systems”)
	12	(”model-driven development” OR ”model-driven engineering” OR ”model-driven architecture” OR ”model-based approach” OR ”model-driven approach”) AND (”cyber-physical systems” OR ”cyber physical systems” OR ”smart systems” OR ”cyberphysical systems”)
	9	(metamodel OR ”meta-model” OR ”meta model”) AND (”cyber-physical systems” OR ”cyber physical systems” OR ”smart systems” OR ”cyberphysical systems”)
dblp	4	(metamodel — ”meta-model” — ”meta model”) (”cyber-physical systems” — ”cyber physical systems” — ”smart systems” — ”cyberphysical systems”)
	0	(”model-driven development” — ”model-driven engineering” — ”model-driven architecture” — ”model-based approach” — ”model-driven approach”) (”cyber-physical systems” — ”cyber physical systems” — ”smart systems” — ”cyberphysical systems”)
	0	(”code generation” — ”generative approach” — ”domain specific modelling” — ”modelling approach”) (”cyber-physical systems” — ”cyber physical systems” — ”smart systems” — cps — ”cyberphysical systems”)

3.2.3 Removing duplicate studies

The pool of primary studies was stored in Mendeley reference manager[1]. Mendeley was also used to expedite the process of discovering duplicate papers. The duplication-checking process continued until further stages (i.e., forward snowballing). The eliminated duplicate papers were **113** studies. Two papers are considered as duplicate if:

- their title, author(s), publication date and venue are the same. In case of different versions of the same paper, the most recent one is kept.
- the same paper is published in different venues, the most recent one is selected.
- the same study has both journal and conference publications, the journal publication is considered since it contains the extended study and provides more information.

3.2.4 Selecting primary studies

Selection of studies was based on the inclusion and exclusion criteria defined in Section 3.2.1. The process of selecting primary studies is shown in Figure 3. Hence, 533 studies were covered in this stage. The inclusion or exclusion of studies were performed in three stages:

In stage 1, the primary reviewer goes through each study by reading its title, abstract, and checking the general content (figure, models, tables, etc.). Studies that satisfy the inclusion & exclusion criteria pass to the next stage (**278** papers were eliminated in this iteration). In stage 2, studies that passed stage 1 are read in a detailed manner, this is by further reading the introduction and conclusion sections of the paper and if necessary other sections (e.g. methodology and case study). Consequently, **88** papers were included and **82** papers were excluded, while **85** papers were left undecided "to be reviewed". Ultimately, in stage 3, the 85 papers left undecided in stage 2 are freshly reviewed with a secondary reviewer. In this stage, both reviewers must come to an agreement on either including or excluding a paper. This resulted in the inclusion and exclusion of **34** and **51** papers, respectively.

Concisely, 88 and 34 papers from stages 2 and 3 were included, respectively, forming a pool of 122 primary studies.

3.2.5 Forward Snowballing

To assure no potential primary studies are left out, studies that might not have been reached on the basis of automatic searching were also searched. It is critical to obtain a good sample of primary studies [28, 29] and various approaches including snowballing [30], quasi-gold standard [31], random sampling and margin of error [32] exist to facilitate the identification of the related primary studies.

[1] `https://www.mendeley.com`

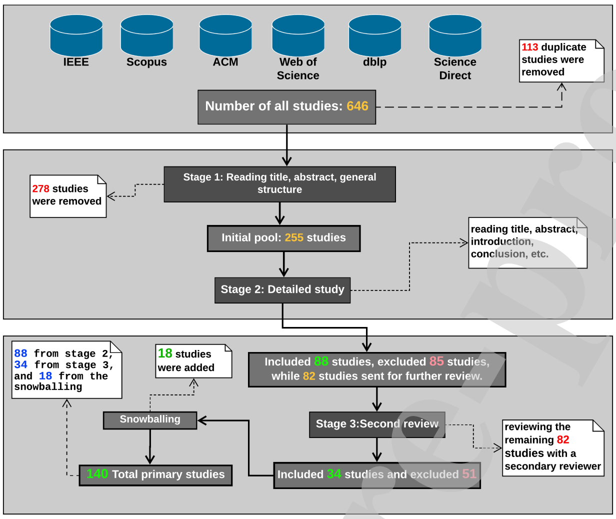

Figure 3: Search and selection process

It is also possible to combine these approaches. Conforming to the snowballing guidelines given in [30], the forward snowballing process was accomplished in this study by determining other papers citing any of the primary studies. We used Google Scholar to find those studies.

Forward snowballing was conducted during the study selection phase. Two iterations during forward snowballing were performed. In the first iteration, we obtained 15 studies after applying the criteria for inclusion and exclusion, and removing the duplicates. Then we made the second iteration on the studies obtained at the end of the first iteration. After applying the same process with the first iteration, the second iteration produced 3 new studies. This resulted in the inclusion of 18 papers to the pool of the primary studies, raising the total of primary studies to **140** papers. The list of all these primary studies are given in the appendix of this paper and are cited throughout the paper in **[P#]** format.

3.3 Data extraction

The data extraction sheet can be found in the online repository [27]. The data extraction form is shown in Table 4. Unlike in the selection stage, papers were read in a meticulous manner according to the protocol defined in this study. The data extraction process also went through 3 stages.

In the first stage, data from the primary studies (obtained by answering research questions) were extracted by the primary reviewer. Following the data extraction, the primary reviewer answered the quality and self-assessment ques-

Table 4: Data extraction form

#	Study data	Description	RQ
1	Study ID	unique identifier for the study	-
2	Bibliometric & demographics	Authors' name, Title of the study, Year of publication, Authors affiliated country, number of citations	-
3	Source	IEEE Xplore, ACM, Scopus, Science Direct etc.	-
4	Article type	Conference, Journal, Workshop etc.	-
5	Modeling approach	used modeling approach(s) by the study	RQ 1.1
6	Modeling purpose	The purpose for which the study used models	RQ 1.2
7	CPS application domain	The CPS application domain the study targeted	RQ 2
8	Type of evaluation	The type of evaluation (i.e. case study, use case, empirical study) the study presented	RQ 3
9	CPS challenges	The type of CPS challenge(s) the study addressed	RQ 4

tions for each paper. In stage 2, primary studies with a self-assessment score below 50% were reviewed by the secondary reviewer. After the study being evaluated, in case the secondary reviewer confirmed the data extracted by the primary reviewer, then, the paper was marked and it passed this stage, otherwise it went through stage 3. In the third stage, both reviewers discussed and argued over the conflicting papers towards reaching consensus.

More details on the followed methodology and the analysis of the results can be found in our technical report which is also available in the online repository [27]. It is worth indicating that the technical report investigates all the studies addressing MDE for CPS in a broader perspective. However, the present paper focuses specifically on applying MDE approaches to the different domains of CPS, the presented evaluations and the addressed CPS challenge(s) by the primary studies. To this end, the research questions introduced in this paper take into consideration to obtain findings on the MDE approaches used in the studies and the purpose for which the models were used (RQ1), targeted CPS application domains (RQ2), evaluation method(s) presented (RQ3), and the CPS challenge addressed (RQ4).

4 Results

In this section, the results and the findings of the conducted SM study are presented. The section starts with bibliometrics and demographics analysis, followed by the analysis of the research questions.

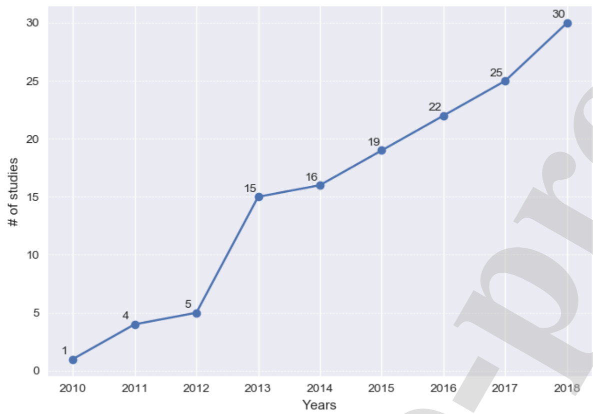

Figure 4: Publication trend per year

Table 5: Most cited papers

Study	Title	Year	Citations #
[P1]	Petri Net Modeling of Cyber-Physical Attacks on Smart Grid	2011	196
[P2]	Cyber-Physical Modeling and Cyber-Contingency Assessment of Hierarchical Control Systems	2015	84
[P3]	Modelling complex and flexible processes for smart cyber-physical environments	2015	67

4.1 Bibliometrics & Demographics

4.1.1 Publication trend per year

Basically, Figure 4 depicts the increase in the number of research papers on this topic. Between the years 2010-2018, researchers' interest in the domain of applying MDE for CPS had grown continuously for the period under observation.

4.1.2 Citation analysis and top-cited studies

In this section, results related to the citation distribution over the year of publication is presented. The number of citations was obtained using Google Scholar. Figure 5(a) shows distribution of citations over publication years, where Figure 5(b) shows the median number of all papers' citations published in a given year. Only 15% of the primary studies are never cited. The 3 most cited papers are listed in Table 5.

4.1.3 Active researchers in the domain

To get an overview of the most active researchers in this domain, the number of papers published by each author are counted. To keep the brevity of the

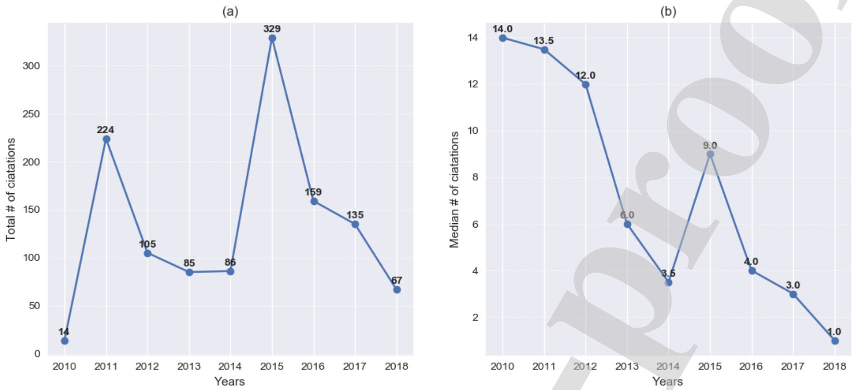

Figure 5: (a) Total number of citations per year, (b) Median number of citations per year

ranking results, Figure 6 shows only the researchers who published at least three papers in the pool of primary studies. The authors "Lichen Zhang" and "Janos Sztipanovits" have the greatest number of publications, each with 6 papers. Followed by "Dehui Du" and "Jonathan Sprinkle" with 4 papers each. The complete list of authors can be found in the accompanying online repository [27].

4.1.4 Countries contributing to the field (based on the author affiliations)

Conforming to the presentation guideline [33] for bibliometric studies in software engineering, most active countries are listed based on the affiliation of the authors who published papers in the field of applying MDE for CPS. If a researcher (author) moved between two or more countries, we assigned each of his/her papers to the exact affiliation information on top of each paper. If a paper was written by researchers from more than one country, the counters for each of those countries were incremented by one.

Figure 7 shows the ranking of countries with at least two publications. The top 5 countries are; USA with 39 publications (25.16%), China with 23 publications (14.84%), Germany with 16 publications (10.32%), Italy with 13 publications (8.39%), and France with 12 publications (7.74%). According to the analysis, 112 (80%) of the papers were written by the author(s) affiliated to one country, while 28 papers (20%) were jointly written by authors from more than one country. In terms of internationally authored papers and the collaborating nations, the collaboration between China and the USA is the highest [P4, P5, P2], followed by Sweden and Italy [P6, P7], and Tunisia and France

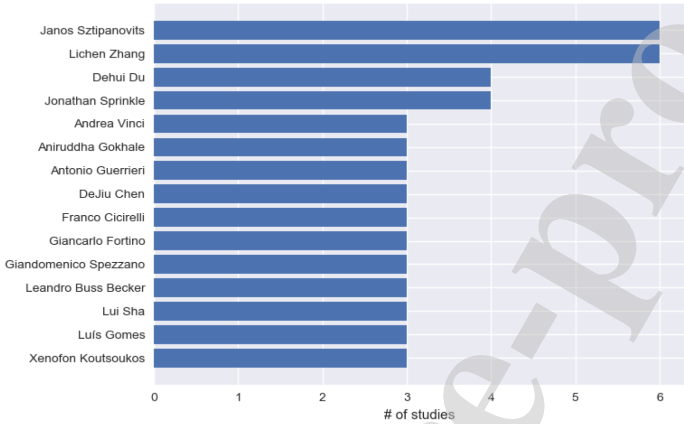

Figure 6: Authors with at least three papers

[P8, P9].

4.1.5 Publication venues

90 of the studies (64.75%) were conference papers, while 33 (23.74%) and 14 (10.07%) studies were journals and workshop papers respectively. Table 6 shows the ranking of the top venues with at least two studies. The complete list of the publication venues can be found in our technical report [27]. There are 16 venues in Table 6: 10 conferences/symposia, 4 journals, and 2 workshops. Interestingly, one can see that journals are at the bottom of the list with 2 publications each. That is, researchers in this field seem most likely preferring conferences than journals.

4.2 Research questions Analysis

In this section, the research questions are analysed, so the findings obtained according to these questions are reported.

4.2.1 Modeling approaches employed for applying MDE in CPS

The results and findings for **RQ1: Are any of MDE approaches or techniques used in/for the development of the studied cyber-physical system?** and its sub-questions are presented in here.

It is worth mentioning that some of the studies fit more than one group, that is, some papers reported more than one modeling approach and/or varying

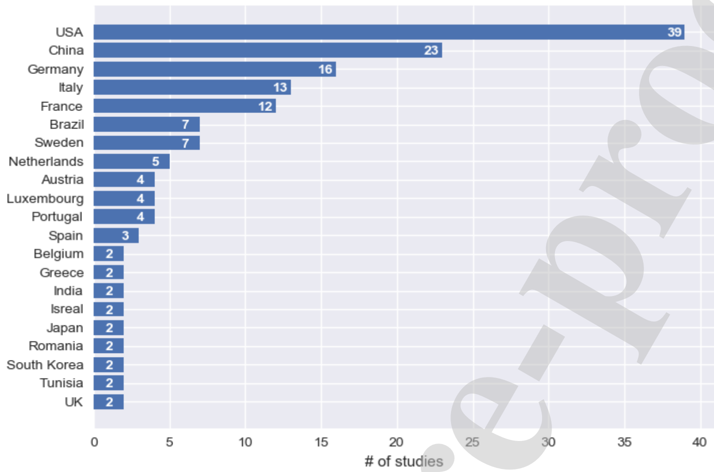

Figure 7: Countries contributing to the field (based on author affiliations)

Table 6: Venues with at least two papers

Venue type	**publication venue**	#
Conference	International Conference on Emerging Technologies and Factory Automation (ETFA)	6
Workshop	Workshop on Domain-specific modeling	6
Conference	ACM/IEEE International Conference on Cyber-Physical Systems (ACM/IEE ICCPS)	4
Conference	Industrial Cyber-Physical Systems (ICPS)	3
Conference	International Conference on Engineering of Complex Computer Systems (ICECCS)	3
Conference	International Conference on Industrial Informatics (INDIN)	3
Conference	Annual Computer Software and Applications Conference (IEEE COMPSAC)	2
Conference	Brazilian Symposium on Computing Systems Engineering (SBESC)	2
Conference	International Conference on Networking, Sensing and Control (IC-NSC)	2
Conference	International Systems Conference (SysCon)	2
Conference	ACM Symposium on Applied Computing (ACM SAC)	2
Journal	Advanced Engineering Informatics	2
Journal	IEEE Transactions on Smart Grid	2
Journal	IFAC Symposium on Information Control Problems in Manufacturing (INCOM)	2
Journal	International Journal of Critical Infrastructure Protection	2
Workshop	IFAC Workshop on Intelligent Manufacturing Systems	2

purposes of modeling (activity). Therefore, in this work, each study is assured not to be limited to only one group, and instead it is assigned to every possible group reported.

RQ1.1: What is the modeling approach presented/used in the study?

Various modeling approaches well-known in MDE domain are also being used in CPS development and management. For instance, metamodeling [34] is preferred in the definition of the constructs and their relations for CPS such as smart buildings or industrial control systems [P10, P11, P12]. Domain-specific languages (DSLs) [35, 36] are used in CPS research e.g. for the virtual CPS prototyping [P13], capturing the CPS control and communication [P14] or even co-simulation [P15, P16]. Moreover, model-based approach [37, 38] is followed in human-machine interaction modeling [P17], design of CPS control algorithms [P18, P19], CPS performance analysis [P20], etc. while component-based modeling [39, 40] is applied for the design and implementation of the connection between the main CPS components, including controllers, sensors, actuators and network [P21, P22, P23]. In addition to these approaches, CPS modeling based on e.g. UML, ontologies, Petri Nets, and patterns is also applied in the primary studies.

Figure 8 shows all these modeling approaches used by at least two studies. As can be seen, the most used approach is metamodeling. 15.86% of the primary studies (23 papers) reported metamodeling as the modeling approach used in their studies. This is followed by the model-based approach with 20 papers (13.79%), DSL with 18 papers (12.41%) and component-based approach with 15 papers (10.34%).

The remaining approaches, given in the following, are used only by single study each, so they are not shown in Figure 8: State Machine-based modeling, Model-Driven Development, Signal-based Modeling, Models@run time, Agent-oriented modeling, Dynamic Constraint Feedback (DCF), Properties Modeling, Stochastic Occurrence Hybrid Automata (SOHA)-based modeling, Model-Integrated-Computing (MIC), Microservice-based development and Theory-based modeling (e.g. modeling theory based on fuzzy logic).

Integrated approaches category comprises studies which promote either the integration of multiple approaches or multi-domain modeling approach. Studies employing integrated approaches are [P24, P25]. On the other hand, studies which used multi-modeling approaches are [P26, P27, P28, P29, P30, P31].

Figure 9 shows the distribution of modeling approaches over the years. For better comprehension of the chart, the most used approaches reported by more than 5 studies are given only. The most consistently used approach within the period of the study (2010-2018) was DSL except for 2010. This approach was at least reported by one paper between years 2011-2018. However, its growth fluctuates. Metamodeling and Model-based approach also showed a consistent presence between 2012-2018, while UML and Component-based approach were present continuously between 2013-2018. Although Metamodeling approach had minor reduction in its usage between the years 2012 and 2016, it always increased. For the years between 2015 and 2018, it is clearly observed that the Metamodeling approach was always amongst the top-most used 3 approaches.

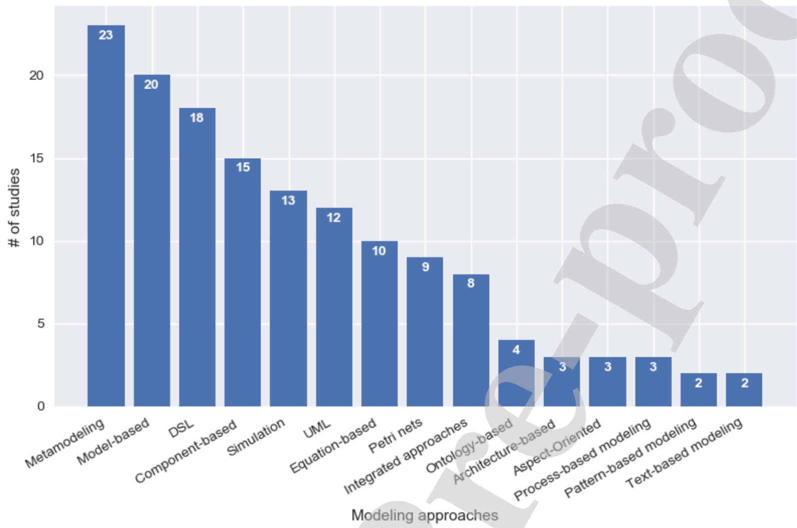

Figure 8: Reported modeling approaches

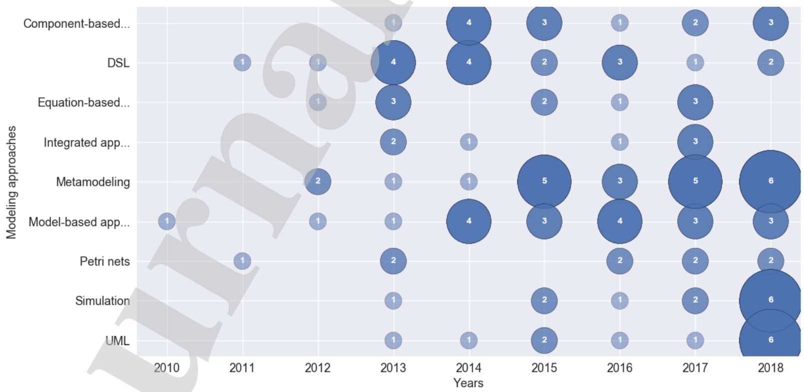

Figure 9: Distribution of the reported modeling approaches over the years

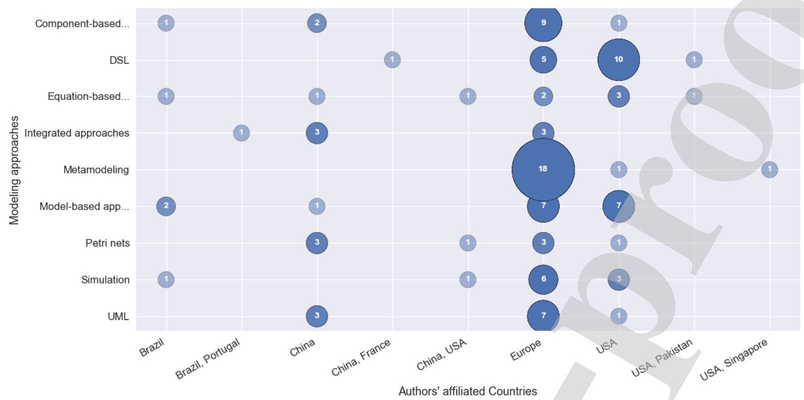

Figure 10: Reported modeling approaches vs. Authors' countries

For further understanding of the modeling approaches, the distribution of the most reported approaches over the countries is shown in Figure 10. Countries having more than 5 studies based on the authors' affiliations, are given only. Furthermore, we considered all the European countries as one for a better comprehension of the chart. Some of the studies were written jointly by the authors affiliated to two or more countries, which resulted in showing some pairs in the chart. It can be seen that the Metamodeling and Model-based approaches are mostly used in Europe. On the other hand, DSL approach is mostly used in the USA and its usage surpasses all the European countries combined.

Further, it is important to mention that although equation-based approach is reported by 10 studies, it was used jointly with other approaches in 5 out of the 10 studies. [P32] used equation-based modeling with DSL where they developed DSML for the performance analysis purpose. [P33] also used DSL with equation-based approach to develop a DSML for simulation. Along with equation-based modeling, [P34] used a simulation-based approach. Ptolemy II modeling tool and Simulink Design Verifier (SLDV) were utilized for Model-based Testing and formal verification. [P35] used both equation-based and Petri nets-based modeling approaches. The study used discrete/continuous Petri nets for scheduling the analysis. [P36] used Metamodeling-based approach with equation-based modeling for the development of meta-models using Visual Environment for Cyber-Physical Modelling (VE-CPM). The remaining studies, which used equation-based modeling as their only approach, did not present any tool/language except [P37] that presented a tool HA-SPIRAL for code generation. To this end, the equation-based modeling approach is somewhat useful as a supporting approach rather than as an independent approach in the field of applying MDE for CPS.

RQ1.2: What is the purpose for which the models were used?

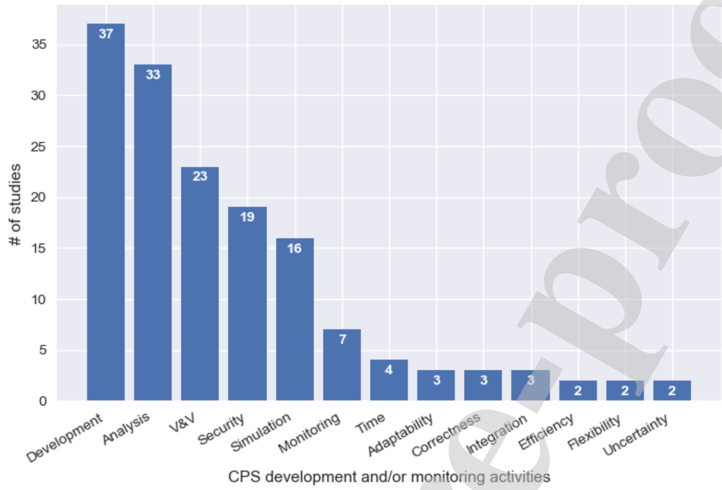

Figure 11: Reported CPS development and/or monitoring activities in which the modeling approaches are used

Out of the 140 studies, 136 of them reported their purpose for using the models, while the remaining 4 studies did not state their purpose. From these 136 studies, 111 of them reported only one CPS development and/or monitoring activity, while 22 reported two activities, 2 reported three activities, and the last paper reported four activities. Figure 11 shows only the activities reported by at least 2 studies for better comprehension of the chart. Moreover, Figure 12 represents the distribution of modeling approaches over these activities. All these activities are shown in the online repository [27] together with the approaches used and the studies reported them. Reported activities are as follows:

- **Development:** 37 papers (22.42%) are grouped under this category. These studies can be put into two categories: firstly, papers that developed DSL, Metamodel, tool, or language, secondly, studies that aim at automating the development process of a system, and perform tasks like transformation, code generation, building libraries, design process, and others. The most used approaches for this activity are Metamodeling and DSL. 8 studies used each of the two approaches. Model-based approach was used by 7 studies, while 3 studies reported Component-based approach. Further, Equation-based approach, Integrated approaches, and Architecture-based approach was reported by 2 studies each, while the rest of the approaches were reported by 1 study each.

- **Analysis:** Reported by 33 studies (20%). Here, the aim of the studies is mainly focused on analyzing an existing system (DSL, metamodel, tool)

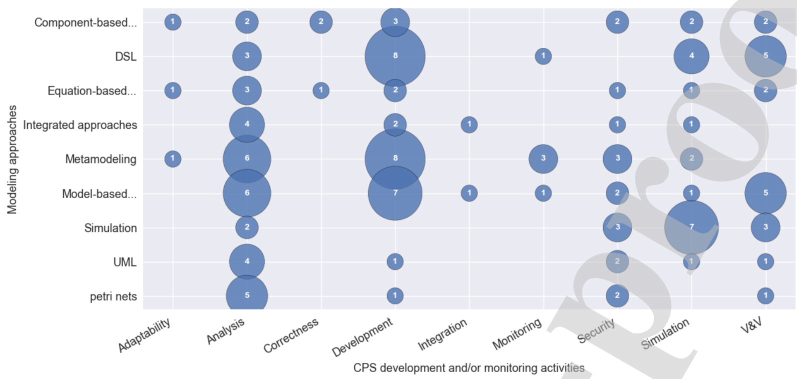

Figure 12: Modeling approaches distribution over CPS development and/or monitoring activities

for various activities. The most reported ones include: safety analysis, performance analysis, requirement analysis, security analysis, cost and energy consumption analysis, dependability analysis, and so on. Metamodeling and Model-based approaches are the most reported approaches for this activity with 6 studies for each, followed by Petri nets with 5 studies, Integrated approaches and UML each reported by 4 studies, 3 studies each for DSL and equation based approach, 2 studies reported Simulation and Component based approach for each, while the rest of the approaches were reported by 1 study for each.

- **Validation and Verification (V&V):** 23 studies (13.94%) in this group conducted V&V activities regarding DSML validation, metamodel verification, behavior verification, verification of correctness, safety properties verification, model-based testing, formal verification and so on. Approaches used for this activity are distributed as follows: 5 studies reported DSL and Model-based approach for each, followed by Simulation-based approach with 3 studies. Equation-based, Component-based and Ontology-based approaches were reported by 2 papers each. The rest of the approaches were reported by 1 study each.

- **Security:** 19 studies (11.52%) are concerned about the security of CPS from different aspects. Studies reported about safety are also grouped in this set. Activities conducted by this group includes threat modeling, attack modeling, analyzing cyber-attacks, security evaluation and experimentation, safety guarantees of the generated code, and safe reconfiguration. The most used approaches for this activity are Metamodeling and Simulation which are reported by 3 studies each. Model-based approach, Component-based approach, Pattern-based approach, UML and Petri nets were reported by 2 studies each, while the rest of the approaches were reported by 1 study each.

- **Simulation:** The aim of the studies in this group (16 studies (9.70%)) is the use of simulations for various purposes like using simulations for verification reasons or accompanying it with DSML, while other studies used it for the analysis purpose. Mostly, studies reported simulation along with other activities like V&V, Analysis and Development. Obviously, the most used approach for this activity is Simulation-based approach which is reported by 7 studies. It is followed by 4 studies reporting DSML, 2 studies for Metamodeling and 2 studies for Component-based approach.

- **Monitoring:** 7 studies (4.24%) reported about CPS monitoring or management activities, such as performance monitoring, runtime behavior monitoring, process monitoring, monitoring simulation activities and results. The most reported approach in this group is Metamodeling with 3 studies. Other existing approaches were reported by 1 study each.

- **Time:** 4 studies (2.42%) seek to improve CPS execution time.

- **Adaptability:** 3 studies (1.82%) support the implementation of self-adaption aspect of the system.

- **Correctness:** 3 studies (1.82%) support the correctness of the system (DSML, metamodel, tool), often in terms of the correctness of operations or the generated code.

- **Integration:** 3 studies (1.82%) seek to combine different aspects of CPS and support their integration.

The remaining activities which were reported by only one study can be seen in the technical report [27]. For a deeper understanding of how studies addressed modeling approaches and the activities for which they were used, studies can be grouped into three categories:

- Studies which presented one modeling approach and used it for one modeling purpose, e.g. [P10, P38, P39, P40, P14, P41, P42, P43, P44]

- Studies which presented one modeling approach and used it for more than one modeling purpose. Studies using the same approach for two different modeling purposes are [P11, P45, P6, P46] while studies using the same modeling approach for more than two modeling purposes are [P5, P47].

- Studies which presented more than one modeling approach and used it for one modeling purpose. For instance, [P36] used both metamodeling and equation-based modeling approaches for the development purposes while [P35] used petri nets and equation-based approach for CPS analysis. [P32] used DSL and equation-based approaches for analysis purposes, and finally [P48] followed UML and pattern-based modeling approaches for the security of CPS.

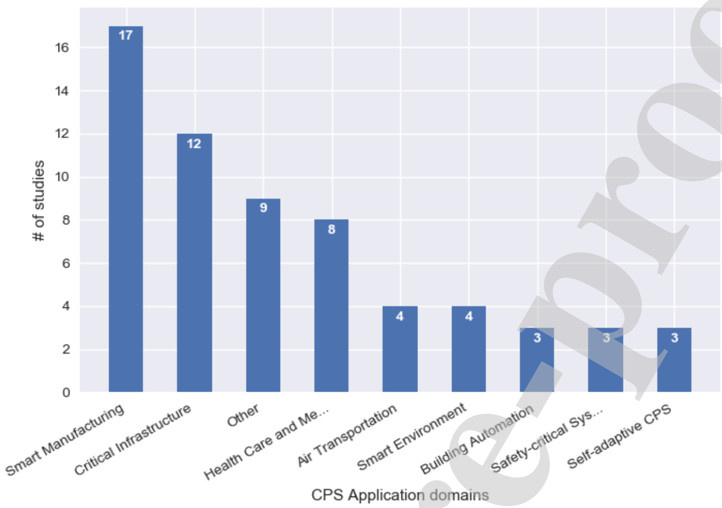

Figure 13: CPS application domains targeted by the studies.

4.2.2 Targeted CPS application domains

In this section, the results and findings for **"RQ2: Does the study present any application domain?"** and its sub-questions are presented. It is worth indicating that a study designed and exemplified for a specific CPS application domain can also be extended to be used for other CPS application domains. However, we prefer adhering only to the application domains explicitly indicated by the studies instead of any indirect estimation on the generalizability of these studies.

Figure 13 depicts the reported CPS application domains targeted by the primary studies. There are various CPS domains, such as Critical Infrastructure, Smart Manufacturing, Air Transportation, Emergency Response, Intelligent Transportation, Health Care and Medicine [41]. 63 studies out of total 140 studies (about 45%), addressed a specific CPS domain, while the rest of them addressed CPS in general. CPS application domains are correlated with the evaluation methods presented by the examined studies. Results of this correlation are presented in Table 7.

- Smart Manufacturing: Addressed by 17 out of total 63 studies (26.98%). Studies under this category aim at optimizing productivity in factories (smart factories). Applications included in these studies take into account Industry 4.0/Cyber-physical production systems (CPPS) [P49, P50, P51, P52, P22, P53, P54, P55], specific industrial applications [P24, P56, P57], automation systems [P58, P27], evolvable production systems [P45, P59], and assembly systems (ASs) [P60].

- Critical Infrastructure: 12 studies (19.05%) reported under this category. It refers to the public infrastructures and valuable properties. Applications grouped under this category cover smart grids [P61, P48, P62, P1, P2, P63, P64, P13], irrigation networks [P32], railway networks [P65, P29], water distribution systems [P66].

- Health Care and Medicine (HC&M): 8 studies (12.70%) reported under this category. Included sub-categories are Medical Cyber-Physical Systems (MCPS) [P34, P67, P68, P69], medical best practice guidelines [P70, P4] and smart medical devices [P71, P72].

- Air Transportation: 4 studies (6.35%) reported under this category. Applications are; Unmanned Aerial Vehicles [P25, P73], Air Traffic Control (ATC) [P19], Aerospace CPS [P26].

- Smart Environments: Addressed by 4 studies (6.35%). The smart environment is a physical environment in which sensing, actuating, networking, and computation capabilities are enriched. Its goal is to gather information/knowledge about the environment in order to adapt itself to the needs and behaviors of the inhabitants. The followings are the studies grouped under this category: [P74, P11, P3, P75].

- Building Automation: Reported by 3 studies (4.76%). Studies in this category aim at providing optimum automation and control to buildings' heating, air conditioning, lighting, etc. by deploying sensors, actuators, and control systems. Studies classified under this group are [P12, P15, P76].

- Safety-critical Systems: Reported by 3 studies (4.76%). Safety-critical systems are systems whose failure or malfunction can have a severe loss, in terms of human or economic consequences. Studies of this cluster include [P77, P78, P79].

- Self-adaptive Systems: 3 studies (4.76%) reported under this category. Self-adaptive systems are systems that modifies their own behavior during the runtime using feedback due to the constant changes in the system. The followings are the studies grouped under this cluster: [P6, P80, P81].

- Other: Studies which did not fit any of the aforementioned categories are grouped under this category. They are as follows: Distributed cyber-physical systems [P82], smart contracts [P83], networked control systems [P84], racing sailboats [P85], intelligent transportation [P86], smart systems [P87], material handling applications [P88], cloud-based CPS [P89], complex systems [P90].

Table 7: CPS application domain correlated with the evaluations presented by the studies.

Domain	Evaluation type	Description
Smart Manufacturing	Case study	IKEA Gregor office chair [P60], assembly production system [P45], assembly system [P59], Petroamazonas EP Oil Company [P53], liqueur plant [P54], industrial water process system [P56], enterprise production line [P55]
	Empirical study	OMiRob [P24]
	Example	robot packaging system [P16], Pick and Place Unit [P50], Vehicular Ad-hoc NETwork [P27], pneumatic stopper unit [P22], water treatment plant SWaT [P57].
	Use case	end-to-end communication use case for an Industry 4.0 application [P49], White-goods production [P52]
Critical Infrastructure	Case study	flood level prediction [P32], SCADA system [P48], secondary-voltage control system [P2]
	Empirical study	Smart Grid [P61], Water Distribution System [P66]
	Example	Railway network [P65], monitoring of smart grids [P62], smart meter [P1], process plant design [P13]
	Use case	Virtual Power Plant [P63]
Health Care and Medicine	Case study	Simplified stroke [P70], simplified cardiac arrest [P4], Holter Monitor [P71], Clinical scenario [P68], Generic Patient Controlled Analgesia Infusion Pump (GPCA) system [P69].
	Empirical study	clinical scenarios [P34]
	Use case	patient-controlled analgesia infusion pump [P72]
Smart Environment	Case study	smart environment scenario [P74], smart office [P11, P75]
	Example	newspaper fetching task [P3]
Air Transportation	Case study	lunar rover system [P26], Unmanned Aerial Vehicle [P25]
	Example	VTOL Unmanned Aerial Vehicle [P73]
	Use case	Malaysia Airlines Boeing 777 carrying flight MH-370 [P19]
Safety-critical Systems	Case study	battery management system [P77], railway signaling system [P79]
	Empirical study	rocket system and its payload [P78]
Building Automation	Case study	energy-aware building [P76]
	Example	Smart Building [P12], Room Thermostat [P15]
Self-adaptive CPS	Case Study	Smart Power Grid [P6], self-driving miniature vehicle [P80], Water Monitoring [P81]

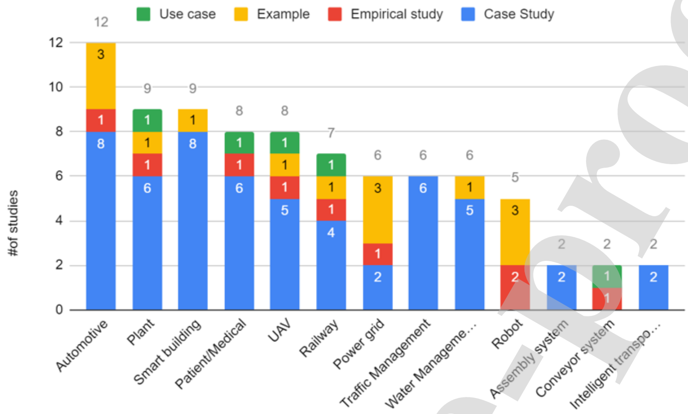

Figure 14: Distribution of the evaluations types over the CPS application domains.

4.2.3 Conducted evaluations for the proposed solutions

In this section, the results and findings for **"RQ3: Is there any evaluation presented in the study?"** and its sub-questions are given.

Out of the 140 studies, 129 studies (92.1%) evaluated their solution, methodology or tool proposed for MDE of CPS. Among these studies, 70 of them (54.3%) performed this evaluation by means of a case study, 31 of them (24%) presented an example, 17 studies (13.18%) conducted an empirical study, and 11 studies (8.53%) covered only one use case. It is worth indicating that almost all of the empirical studies were performed as controlled experiments except one which conducted a survey.

This SM study grouped these evaluations performed by the primary studies according to specific CPS application domain categories (e.g. Automotive, Smart building, Power grid, Water Management). Hence, one can easily see e.g. the distribution of evaluation alternatives over CPS development studies for Automotive domain or how many studies performed on MDE of CPS for traffic management domain considered use cases as the evaluation method. 82 studies out of the 129 studies fitted into the categories shown in (Figure 14), while the other 47 studies which do not fit in any of the clusters were grouped under "Other" cluster – not shown in the chart. The raw data related to this analysis and the related categorization can be found in the accompanying online repository [27].

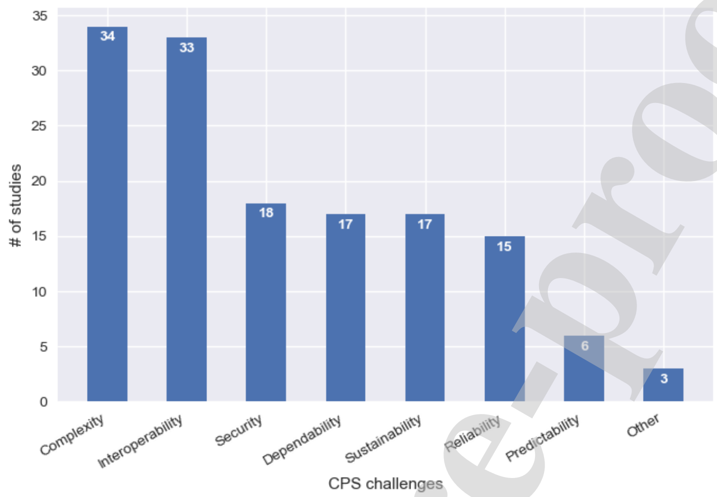

Figure 15: Distribution of the categorized CPS challenges reported by the studies.

4.2.4 Addressed CPS challenges

In this section, the CPS challenges which the primary studies addressed are reported according to the **"RQ4: Does the study address any challenge(s)?"** in addition to its sub-questions.

107 studies out of 140 studies (76.43%) reported the CPS challenge(s) they faced (e.g. challenge on managing complexity, supporting interoperability, dependability and reliability). Number of the reported CPS challenges are shown in (Figure 15). It is worth mentioning that several studies addressed more than one CPS challenge. In order to relate to the challenges presented by the studies to one another, the categorization of CPS challenges introduced in [41] was followed in this study. Moreover, we also added the complexity of CPS development and management as a new category in addition to the existing categorization defined in [41]. Reported CPS challenges and their corresponding studies are listed in Table 8.

- **Complexity:** 34 studies (22.82%) were classified under this category. It is reasonable that complexity was the most reported challenge, due to the nature of the CPS development process that requires complex engineering work. Some of the addressed complexity challenges include: complexity of design, timing behavior specification, execution complexity, co-simulation construction, architecture complexity, interaction complexity, semantics complexity, interdependency complexity and requirements complexity.

- **Interoperability:** also means Heterogeneity. 33 studies (22.15%) were classified under this category. To develop a CPS, the collaboration of different disciplines is a must. Thus, CPS combines different components (i.e. hardware, software, sensors, network, etc.), hence, managing and coordinating all these disciplines and operations are challenging. Scalability and composability are two important types of interoperability challenge. Scalability is quite difficult since the system ought to keep functioning adequately when new features are added. To provide the composability, CPS development should consider combining several components within a system and managing their interrelationships.

- **Security:** Reported by 18 studies (12.08%). Studies in this category are concerned about the 3 security aspects of the CPS. Firstly, integrity needs to be supplied to protect the correctness of information from being manipulated or modified. An example for the CPS integrity problem would be compromising a sensor/actuator and injecting false data. Second aspect is confidentiality, that refers to allowing only authorized individuals to get access to the data. Third aspect is availability which means keeping the CPS components on service, e.g. preventing cyber- attacks (like denial of service) that may limit or block the availability of the system.

- **Dependability:** can be defined as the ability of CPS to keep functioning as required. 17 studies (11.41%) were covered under this category. It encompasses aspects like safety and maintainability. The system must be maintainable simply when a failure occurs.

- **Sustainability:** 17 studies (11.41%) were covered under this category. It refers to the challenges like adaptability, efficiency in using resources, reconfigurability, uncertainty, performance measurement and optimization.

- **Reliability:** 15 studies (10.07%) were covered under this category. Reliability means that the CPS should function correctly not only in closed and fixed environments but also in open and uncertain environments. Challenges to address are; fault tolerance, robustness, timing uncertainty etc.

- **Predictability:** 6 studies (4.03%) were in this group. Predictability refers to the degree to which the system's behavior/functionality and outcomes are predictable and they satisfy the system requirements. For instance; predicting system's stochastic behavior and accuracy, that is, the degree to which the system's measured outcomes need to be accurate.

- **Other:** This category contains other challenges which are concurrency, latency and remote monitoring.

Further, a correlation analysis of the CPS domains and its challenges is scrutinized so as to provide an understanding of the challenges addressed in each CPS application domain, (see Table 9). Despite the fact that the correlation analysis cannot indicate the CPS domain wholly, for instance, one can see that in the smart manufacturing application domain, most research works converged

Table 8: CPS challenges and their corresponding studies.

CPS challenges	#	**Relevant studies**
Complexity	34	[P91, P92, P23, P15, P93, P94, P81, P84, P95, P58, P33, P7, P96, P60, P4, P97, P20, P98, P85, P25, P99, P100, P101, P102, P3, P103, P104, P29, P63, P105, P106, P107, P108, P69]
Interoperability	33	[P91, P24, P23, P16, P26, P84, P95, P33, P27, P109, P97, P110, P98, P111, P61, P18, P62, P52, P89, P103, P73, P112, P22, P54, P64, P56, P113, P114, P115, P107, P116, P79, P117]
Security	18	[P12, P70, P118, P49, P65, P66, P119, P120, P48, P1, P121, P122, P123, P124, P125, P57, P126, P21]
Dependability	17	[P80, P26, P58, P47, P5, P86, P99, P127, P88, P48, P100, P128, P129, P37, P130, P17, P69]
Sustainability	17	[P32, P83, P49, P131, P81, P34, P132, P60, P133, P88, P51, P62, P134, P135, P2, P136, P55]
Reliability	15	[P94, P131, P26, P65, P58, P34, P132, P45, P77, P86, P61, P67, P51, P123, P63]
Predictability	6	[P6, P34, P110, P67, P137, P114]
Other	3	[P138, P19, P53]

on interoperability and sustainability challenges. Similarly, in the critical infrastructure application domain, most research works concentrated on security, sustainability, and interoperability challenges. However, it is interesting to notice that the latency and the predictability challenges of both domains were not addressed by any of the examined papers.

RQ4.2: Did the study reports challenges addressed while developing the MDE approach/tool?

Only 15%, that is, 21 studies out of the 140 studies reported about the limitations they faced. Studies reported limitations faced are; [P12, P118, P16, P84, P34, P139, P109, P5, P86, P61, P140, P121, P53, P122, P63, P114, P57, P115, P107, P69, P8].

Table 9: Correlation analysis between CPS application domains and its challenges

	Complex -ity	Depend -ability	Flex -ibility	Interoper -ability	Latency	Predict -ability	Reli -ability	Remote monitoring	Security	Sustain -ability
Air Transportation (AT)	[P25]	[P26]		[P26, P73]	[P19]		[P26]			
Building Automation (BA)	[P15]								[P12]	
Critical Infrastructure (CI)	[P29, P63]	[P48]		[P61, P62, P64]			[P65, P61, P63]		[P65, P66, P48, P1]	[P32, P62, P2]
Health Care and Medicine (HC&M)	[P4, P69]	[P69]				[P34, P67]	[P34, P67]		[P70]	[P34]
Safety-critical Systems				[P79]			[P77]			
Self-adaptive CPS	[P81]	[P80]				[P6]				[P81]
Smart Environment (SE)	[P3]									
Smart Manufacturing (SM)	[P58, P60]	[P58]		[P24, P16, P27, P52, P22, P54, P56]			[P58, P45, P51]	[P53]	[P49, P57]	[P49, P60, P51, P55]

5 Discussion and Threats to the Validity

In this section, discussion of the findings achieved as the result of the applied research workflow of this SM study is given along with its implications. Threats to the validity of the study is also discussed in this section. At first, the quantitative analysis revealed that the number of published research papers in this field continues to increase year after year. USA affiliated researchers are the most interested researchers in this field (39 studies), followed by China (23 studies). Moreover, most preferred publication venues are conferences (64.75%, 90 studies) by far.

RQ1.1 revealed that the metamodeling is the most used approach by the researchers. Model-based and DSL approaches follow the metamodeling. Also, modeling approaches were correlated with the authors' affiliation country in an attempt to determine which of the modeling approaches are mostly used in different countries. The study found out that, DSL-based approach is mainly adopted by US-associated researchers, while meta-modeling and model-based approaches are mostly adopted by European-associated researchers.

Although, in terms of the number of studies, metamodeling is the most adopted modeling approach, yet component-based approach is the most reported modeling approach in terms of the number of the activities it is used for, which covered 9 activities namely: Adaptability, Analysis, Correctness, Development, Efficiency, Flexibility, Security, Simulation, and V&V.

As far as the purpose of modeling is concerned (RQ1.2), the most-reported CPS modeling purpose was the development, that is, developing either DSL, metamodel, tool or automating the development process of a CPS. Other reported modeling purposes were Analysis (like safety analysis, performance analysis, requirement analysis, etc.), V&V (DSML validation, metamodel verification, behavior verification, etc.), and Security (threat modeling, attack modeling, cyber-attack analysis, etc.).

Results for RQ2 showed that 63 studies out of 140 (45%) addressed a specific CPS application domain. Smart manufacturing is the most addressed CPS domain by the researchers (26.98%, 17 studies out of 63). Remaining popular domains are Critical Infrastructure, Health Care and Medicine, Air Transportation, Smart Environment, Building Automation, Safety-critical Systems, and Self-adaptive CPS respectively.

For the evaluation method, RQ3 results revealed that the majority of the studies (54.26%, 70 studies) presented case study(s) as the major evaluation method for their proposed MDE solution. On the other hand, only 17 studies (13.18%) presented an empirical evaluation for their MDE based CPS development. That is, conducting empirical evaluations in this field is mostly missing which is critical on the assessment of the proposed modeling approaches especially on their usability for both the construction and the execution of CPS. This research area still requires much attention.

Results for RQ4 showed that a variety of CPS challenges were addressed. However, the most addressed challenges were complexity and interoperability. The much focus for these two challenges can be related to the heterogeneous nature of CPS. CPS combines different components and requires the interaction of different researchers from different backgrounds. Thus, it informs why researchers interested in this field should pay more attention to reducing the complexity and interoperability aspects of CPS. Other challenges addressed were: Security, Dependability, Sustainability, Reliability, Flexibility and Predictability.

From the growing adoption of MDE approaches (specifically metamodeling, DSL, and model-based approaches) in the development of CPS, it can be deduced that MDE has shown considerable maturity in reducing code sophistication and keeping the system at a high level of abstraction. However, this maturity has been examined mostly in the academic studies in comparison with the efforts originating from the industry. Among 140 primary studies, only 3 of them are provided by the industry. The reason can be either the application of MDE in CPS development is not widely adopted across the industry currently, or MDE is being applied to CPS development, but there are not enough publications reflecting the level of its maturity in the industry.

Furthermore, the solutions brought in the primary studies on the application of MDE in CPS development are exemplified with a number of case studies in various CPS application domains. We may expect that many of the approaches discussed in these studies can naturally be extended to cover other application domains of CPS in near future, i.e. an MDE solution brought for smart manufacturing can be used to derive new MDE approaches to enable automation and control for the buildings. Finally, the complexity and interoperability challenges will still keep their importance in the CPS modeling while more MDE studies are expected to appear on addressing the sustainability issues since the evolving nature of the future's CPS will require an extensive maintenance of CPS components and their configurations as well as the efficient use of the resources inside the fast changing CPS environments.

5.1 Threats to the validity

Threats to validity for this SM study are classified according to categories proposed by Wohlin et al. [42], and hence they include four types, namely construct, internal, external and conclusion validity threats.

Construct validity

It represents how the SM study truly reflects the intent of the researchers, and what is asked by the research questions. To define the research questions, it is important to stress that the process proposed by [24] and [25] and using guidelines defined by [26] were followed in this study.

Furthermore, another aspect of construct validity is to assure that all relevant studies on the selected topic are found adequately. The possibility of missing primary studies is a common threat to the validity of any SM. Both the terms MDE and CPS are well-established concepts, and thus, the terms are sufficiently good enough to be used as keywords. Therefore, to mitigate this risk, a good-enough search string through several iterations was formed, and adequate coverage of literature was achieved. General publication databases, which index most of the well-reputed publication venues, were extensively searched in this study as well. The complete list of the publication venues shown in the technical report [27] indicates that the coverage of the search is enough. Also, to improve the results, the forward snowballing sampling method was used, and it has proved to be effective.

We did not apply backward snowballing in addition to forward snowballing since some references achieved by the backward snowballing would be out of our search range, i.e. it would cause access and force to examine the papers published before 2010. Elimination of these old-dated papers would have an additional cost with probably very limited benefits. We already had a large pool of papers. The limitation on the selected year range (between 2010 - 2018) of the primary studies may also be considered as a threat since the conducted SM does not cover the primary studies published before 2010. However, we believe that selecting this range was quite accurate, especially when the publication trend in this range of years is taken into account. In Section 4.1.1., it is clearly shown that the number of papers on the application of MDE for CPS development increased continuously and significantly compared with the numbers of the papers published at the beginning of 2010. Specifically, the primary studies published in the recent years constitute the vast majority of our pool of papers. The choice of this range of years also enabled us to perform an SM study on most recent primary studies in addition to prevent an overlap with the related work.

Internal validity

This relates to the degree to which the design and the conduct of the SM study are likely to prevent systematic errors. Internal validity is a prerequisite for external validity [26]. Therefore, both qualitative and quantitative analysis were used to minimize threats. The use of a rigorous protocol and data extraction form mitigates this kind of threats to validity. Moreover, threats originating from personal bias or lack of understanding of the study were reduced by conducting data extraction phase iteratively. For this purpose, one researcher extracted data from the primary studies and answered quality and self-assessment questions. The other two researchers (expert in CPS and MDE) reviewed the extracted data from studies with low self-assessment rates under 50%.

External validity

According to [42], external threats concern the generalizability of the SM study results, that is, the degree to which the primary studies is representative of the reviewed topic. In this study, the set of primary studies may not be representative of the entire set of existing studies on the topic, MDE for CPS. However, this threat was mitigated as follows; Firstly, the search strategy consisted of manual and automatic search, then followed by the forward snowballing. The forward snowballing enabled finding studies which were not captured by the search strings in the digital libraries. Secondly, the inclusion and exclusion criteria of the protocol created in this study support refining the set of primary studies which leads to include only studies which meet the topic. Only studies in English were included. Papers written in other languages concerning the same topic may exist. However, this threat is considered as having minimal effect.

Conclusion validity

All relevant primary studies cannot be identified [26]. To alleviate this threat, the research protocol of this study was designed and validated carefully to minimize the risk of excluding relevant studies. Search strings were formed in a way that only a very small number of relevant studies could be missed, and a manageable quantity of irrelevant studies could be included. Besides the automatic search, a manual search and a forward snowballing were performed. The protocol was rigorously defined to be reusable by other researchers for reproducing the same study, i.e. the data extraction form is available in the accompanying online repository [27].

6 Conclusion

The research on CPS attracts both academics and industry players due to the wide use of these systems and the opportunities they offer. However, the development and management of CPS are challenging tasks originating from their inherent heterogeneity and complexity characteristics, and hence MDE is being used to reduce complexity encountered in these tasks. In this study, we focused on the application of MDE to the different domains of CPS, the presented evaluations and the addressed CPS challenge(s) by the primary studies. To this end, an SM study was conducted for the studies published between 2010 and 2018. Initially, we retrieved 646 papers, 140 of which were included in this study, following a predefined selection strategy through a multi-stage process.

Our study presented a bibliometric analysis to gain an understanding of active researchers, year-on-year publication trends, and publication venues in the field. The results show that MDE for CPS is an active research area with an increasing number of publications over the years. Results also showed that the conferences account for the most frequently used publication venue. Smart manufacturing is currently the most addressed CPS domain, followed by Critical Infrastructure, Health Care and Medicine. The conducted SM study also revealed that the majority of the studies present case studies as their main evaluation method for the proposed MDE solution. Moreover, we determined that the researchers mostly address the complexity and the interoperability challenges to CPS development.

Finally, we believe this SM study may also assist CPS researchers by pointing out the current research gaps which can be considered as the future work. For instance, our study showed that the empirical evaluation of model-based CPS development is mostly missing in the existing studies which may cause a threat on the applicability of the proposed approaches. Hence, research on evaluating MDE of CPS needs further investigation withing this context.

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Appendix: List of the primary studies

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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