A Comprehensive Exploration of Languages for Parallel Computing

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Software-intensive systems in most domains, from autonomous vehicles to health, are becoming predominantly parallel to efficiently manage large amount of data in short (even real-) time. There is an incredibly rich literature on languages for parallel computing, thus it is difficult for researchers and practitioners, even experienced in this very field, to get a grasp on them. With this work we provide a comprehensive, structured, and detailed snapshot of documented research on those languages to identify trends, technical characteristics, open challenges, and research directions. In this article, we report on planning, execution, and results of our systematic peer-reviewed as well as grey literature review, which aimed at providing such a snapshot by analysing 225 studies.

CCS Concepts: • **Software and its engineering → Parallel programming languages**; **Concurrent programming languages;**

Additional Key Words and Phrases: Parallel computing, programming, modelling, languages, frameworks, systematic literature review

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1 INTRODUCTION

There is an ever increasing demand for computational power, which has enabled us to do things that were once considered science fiction: an example is self-driving cars, which require large amounts of computing to do the necessary real-time processing of streaming data from sensors, cameras and so on, and make decisions in real-time based on these data.

Software parallelism, where multiple computations are carried out at the same time, has become the most common way to provide higher levels of computational power leveraging massively

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parallel hardware computational units. Parallel hardware was first introduced in supercomputers, e.g., in the ILLIAC-IV [22]. As of the time of writing (July 2020), the supercomputer with the highest peak performance is the Japanese Fugaku [233], with 7.3 million cores, giving it a maximal speed of 514 petaFLOPS. Besides increment of performance, parallelism can be used to reduce energy consumption too; this role is becoming more and more important, as shown by several secondary studies on energy awareness [221], how to best achieve energy efficiency [122], and which energy predictive models are available [181], in HPC.

We are facing a situation where software-intensive systems have become predominantly parallel. Parallelism appears in many forms, at multiple levels, and it is supported by a variety of hardware architectures. This raises the issue how to *program* these systems. Parallel programming was known to be hard already 30 years ago [126], and it has hardly become easier since then. The programming language is an important link in the software production chain. Many parallel programming languages have been invented over the years, and there is an incredibly rich literature. Due to the importance of the topic and its breadth, we believe that the time is ripe to create a structured and detailed snapshot of this research area, to identify trends, technical characteristics, and potentially open challenges.

In this article, we report on the planning, execution, and results of our systematic literature review, which aims at providing such a snapshot. From an initial set of 3,476 papers and 72 languages, we identified 225 *primary* studies, which we analysed in detail following a precise data extraction, analysis, and synthesis process. A summary of the resulting highlights of our study is as follows:

- Since 1988, effort in this research area has been steadily growing;
- Most languages are high-level and general-purpose;
- Most languages are defined in terms of extensions of existing languages; C/C++ and Java are the most popular programming languages and UML the most popular modelling language;
- Imperative and object-oriented programming are the most popular paradigms, in that order;
- Explicit parallelism is the most commonly supported;
- Task- and data-parallelism are the most common problem decomposition approaches, possibly supported by lower-level forms of parallelism, e.g., pipeline;
- The majority of languages are compiled and the target is usually a high-level language;
- CPUs (multi- and many-core) represent by large the most commonly targeted architectures; interestingly, over 30% of the languages are not tailored to any specific target architecture;
- Support for data-parallelism and multiple hardware platforms (also heterogeneously mixed) are the most longed for features for existing languages;
- Languages and related tooling are in most cases at a prototypical level.

The remainder of the article is organised as follows. We describe our research method in Section 2. The results of our study are unwound in Sections 3 and 4. In Section 5, we provide a further discussion of the results focusing on projecting open challenges into what we believe, supported by our results, to be the most urgent matters to solve in the area. An analysis of the potential threats to the validity of our study, and how we handled them, is reported in Section 6. Works related to our study are described in Section 7, and the article is concluded with Section 8.

2 RESEARCH METHOD

This study was designed and carried out by following guidelines for systematic literature reviews [133]. To carry out this study, we followed the process depicted in Figure 1, which can be divided into the three common phases of planning, conducting, and documenting.

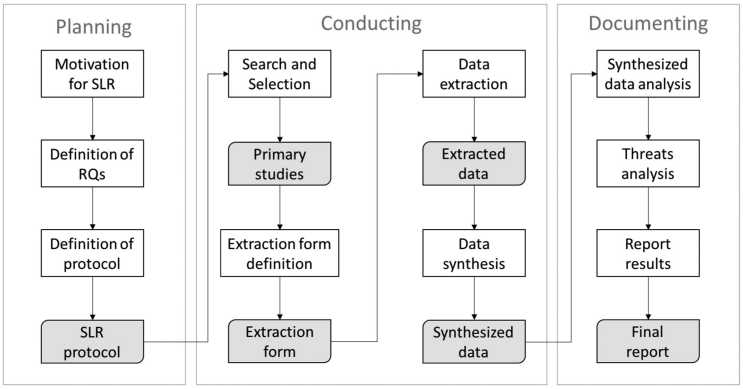


Fig. 1. Overview of the SLR process.

Planning. The objective of this phase was to

- establish the need for a review of languages for parallel computing.
- identify research goal and more importantly questions, and
- define the protocol to be followed by the research team for carrying out the work in a systematic and pinpoint manner.

The output of the planning phase is a detailed review protocol.

Conducting. The objective of this phase was to perform the SLR by carrying out all the steps defined in the review protocol, as follows:

- *Search and selection*: we performed an automatic search in the peer-reviewed literature on a set of four databases and a manual search in the so called *grey literature* (e.g., web-pages, forums) on the Google search engine. Then, identified candidate entries were filtered in order to obtain the final list of primary studies[1] to be considered in later activities of the review. After selection, we carried out an exhaustive backward and forward snowballing as integration to the search and selection process.
- *Data extraction form definition and classification framework*: we defined the set of parameters to compare and classify the primary studies based on the research questions. This was done systematically by applying a standard keywording process [186]. The set of parameters constitutes a classification framework, which was used for data extraction in our study and can be used for the classification of languages for parallel computing.
- *Data extraction*: we went into the details of each primary study, thus filling the corresponding data extraction form. Filled forms were collected and aggregated to be analyzed and synthesised.
- *Data analysis and synthesis*: we provided a comprehensive summary and analysis of the data extracted in the previous activity. The main goal of this activity was to elaborate on the extracted data in order to address each research question of the SLR. This activity involved

[1]For the sake of simplicity, in the remainder of this document, we will refer to included studies and languages from either source as *primary studies*, and will use different terms only when strictly needed to differentiate between papers and languages.

Table 1. Goal of This Study

Purpose	Identify, classify, and evaluate
Issue	the publication trends, technical characteristics, provided evidence, and limitations
Object	of existing languages for describing parallel software
Viewpoint	from researcher's and practitioner's points of view.

both quantitative and qualitative analysis of the extracted data, achieved via vertical and orthogonal analysis.

Documenting. In this phase, we thoroughly analysed and synthesised the extracted data as well as carried out a detailed analysis of possible threats to validity. Eventually, we wrote this article, which describes the performed study. We also provided a complete and public *replication package*[2] for independent replication and verification of our study. In the package, we provide the raw data of search and selection, the complete list of primary studies, as well as the raw data from data extraction.

2.1 Research Goal and Questions

When carrying out a systematic literature review, clearly defining the research goal, and questions are pivotal tasks [41]. The goal of this study was to

> *identify, classify, and evaluate trends, focus, and open challenges in existing research on (modelling and programming) languages for parallel computing in the scope of software engineering.*

The goal was defined by using the Goal-Question-Metric perspectives [24] (see Table 1). Since our aim is to classify languages for the direct use of software engineers, we discard intermediate and lower languages, which are usually employed for automatic transformations such as compilation and optimisation, or as pivot languages, as well as languages for analysis and V&V purposes only. Instead, we focus on high-level languages, that is to say third-generation programming languages and above, intended to be used by engineers to describe parallel software. We will call them **parallel languages** in the remainder of this article.

Our focus is on general-purpose and external domain-specific languages (defined as standalone languages extending or based on an existing language) [127]. These could be also be defined in terms of standalone libraries, which we consider in this study. On the other hand, we do not consider embedded/internal domain-specific languages since the focus would have become too broad and loose (embedded/internal domain-specific languages have several other interesting aspects in relation to their design/implementation and relation to the host language that would need attention).

Our goal can be refined into the following **research questions** (**RQ**), for each of which we also provide primary objective of investigation:

RQ1: *What are the **publication trends** of research on parallel languages?*
Objective: to classify primary studies in order to assess interests, relevant venues, and contribution types; depending on the number of primary studies, trends are assessed over time.

[2]The replication package is available at https://github.com/federicoCiccozzi/CSUR_parallel_languages_replicationPackage.

RQ2: *What are the **technical characteristics** of parallel languages?*
Objective: to identify and classify existing languages in terms of their technical characteristics.

- RQ2.1: *What are the **properties** of parallel languages?*
  Objective: to classify languages in terms of their core properties (e.g., programming paradigm).
- RQ2.2: *What are the characteristics concerning the **programming model** of parallel languages?*
  Objective: to classify languages according to the characteristics of the programming model that they implement (e.g., memory model).
- RQ2.3: *What are the characteristics concerning the **execution, run-time layer and implementation** of parallel languages?*
  Objective: to classify languages in terms of how they are executed (e.g., interpretation), their run-time characteristics (e.g., target architecture), and how they are implemented (e.g., standalone)

RQ3: *What are the **limitations** of parallel languages?*
Objective: to identify current gaps and limitations with respect to the state-of-the-art in languages for parallel computing.

Answering RQ1 gives us a detailed snapshot of publication trends, venues, and types. Based on the classification results obtained by answering research question RQ2, we provide a solid foundation for a thorough comparison of existing and future solutions for languages for parallel computing. Finally, answering RQ3 helps the community in understanding whether there is space for improvement in this research area.

This contribution is useful for both (i) researchers to further contribute to this research area by defining new approaches or refining existing ones, and (ii) practitioners to better understand existing methods and techniques and thereby to be able to adopt the one that better suites their business goals.

2.2 Search and Selection Strategy

In this phase, we gathered the set of research studies and languages that are relevant and representative for our purposes. Figure 2 shows our search and selection process.

Before performing the actual search and selection of relevant studies, we manually selected a set of seven pilot studies. They were selected based on the authors' knowledge of the targeted research domain (i.e., languages and frameworks for parallel programming) and on an informal preliminary screening that we performed on the available literature on the topic. Selected pilot studies fulfil our selection criteria (see below) and were selected to cover a fairly long time-span, they are presented in Table 2. Pilot studies were used to validate our search and selection strategy; more specifically, we used them to have quick feedback about the goodness of our search string to be used for the automatic search and for guiding the refinement of the selection criteria.

Two parallel activities were carried out: the *review of the peer-reviewed literature*, and the *review of the grey literature*. These activities yielded in a set of (i) papers describing languages and (ii) languages of interest.

We followed the same overall process when reviewing the peer-reviewed and grey literature. For the sake of simplicity, in the remainder of this document, we will refer to included studies and languages from either source as *primary studies*, and will use different terms only when strictly needed to differentiate between papers and languages.

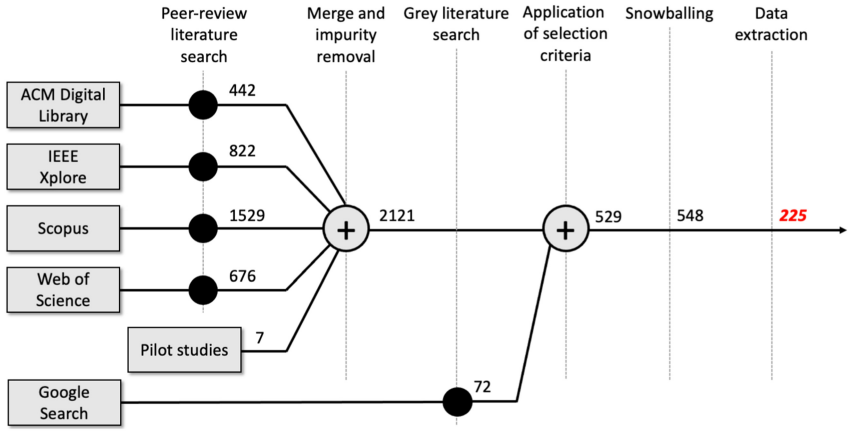


Fig. 2. Search and selection process.

Table 2. Pilot Research Studies

ID	Title	Year	References
P01	ParaSail: A Pointer-Free Pervasively-Parallel Language for Irregular Computations	2019	[223]
P02	Futhark: Purely Functional GPU-Programming with Nested Parallelism and In-Place Array Updates	2017	[116]
P03	Pencil: A platform-neutral compute intermediate language for accelerator programming	2015	[20]
P04	Halide: a language and compiler for optimizing parallelism, locality, and recomputation in image processing pipelines	2013	[190]
P05	A Model-Driven Design Framework for Massively Parallel Embedded Systems	2011	[91]
P07	HPJava: a data parallel programming alternative	2003	[49]
P08	Parallel programming in Split-C	1993	[70]

Table 3. Electronic Databases and Indexing Systems Considered in This Research

Name	Type	URL
IEEE Xplore Digital Library	Electronic database	http://ieeexplore.ieee.org
ACM Digital Library	Electronic database	http://dl.acm.org
SCOPUS	Indexing system	http://www.scopus.com
Web of Science	Indexing system	http://webofknowledge.com

2.2.1 Automatic Search. In this stage, we performed automatic searches on the electronic databases and indexing systems [133] listed in Table 3. As suggested in [133], in order to cover as much relevant literature as possible, we chose four of the largest and most complete scientific databases and indexing systems in software engineering, that are: IEEE Xplore Digital Library, ACM Digital Library, SCOPUS, and Web of Science. The selection of these electronic databases and indexing systems was guided by (i) their high accessibility, (ii) their ability to export search results to well-defined, computation-amenable formats, and (iii) the fact that they have been recognised as being an effective means to conduct systematic literature reviews in software engineering [41].

To create the search string, we considered (i) the research questions and (ii) the set of pilot studies. Then we extracted a list of relevant concepts, their synonyms, abbreviations, and alternative spellings, and we combined them into the final search string by using logical ANDs and ORs. The search string, shown in Listing 2.2.1 was tested by executing pilot searches on the four sources, and checked against all the pilot studies, which had to be part of the obtained results. The actual search strings used for each database were obtained by syntactically adapting them to the characteristics of the specific database; the four specific strings can be found in the replication package. We sought the search string on title, abstract, and keywords of papers; the automatic searches gave us a total of **3,469** potential primary studies.

```
("data parallel" OR "task parallel" OR "process parallel" OR "control parallel" OR
    "collection oriented" OR "multi thread*" OR "parallel programming")
AND
("model* language" OR "model* framework" OR "programming language" OR "programming
    framework")
```

Listing 1. Search string used for automatic searches.

2.2.2 Impurity and Duplicates Removal. Due to the nature of the electronic databases and indexing systems, search results may include also elements that are clearly not research papers, such as conference and workshop proceedings, international standards, textbooks, book series, and so on, and duplicates. In this stage, we manually removed impurities and merged duplicates, reaching **2,121** potential primary studies.

2.2.3 Grey Literature Search. To harvest the grey literature, we targeted the *Google Search Engine*, in accordance to the guidelines for including grey literature in software engineering multivocal reviews [93]. We started with an automatic search using the same search string as for the peer-reviewed literature and completing by manual searches based on our knowledge in the field. The combination of automatic and manual searches helped us identifying relevant *lists* (e.g., Wikipedia's "List of concurrent and parallel programming languages" and *language-specific pages* (e.g., language-specific web-pages or blog posts about how specific languages are used). We selected the relevant languages using a mixture of expert knowledge, browsing the web-pages of well-known languages from the primary studies, and using lists such as Wikipedia's page on "Concurrent and parallel programming languages". The grey literature gave us 72 potential parallel languages to be included.

2.2.4 Application of Selection Criteria. Once removed impurities and duplicates, we applied our inclusion and exclusion criteria on all remaining studies to decide on their potential inclusion in the set of primary studies. Each study was analysed in two steps: first by considering its `title`, `keywords`, and `abstract`; second, if the analysis did not result in a clear decision, by `introduction`, and `conclusion` sections. The selection criteria were the following:

Inclusion Criteria for Peer-reviewed literature

(ICP1) Studies proposing a modelling/programming language/framework for parallel programming.
(ICP2) Studies proposing a formalisation and/or implementation of the proposed language.
(ICP3) Studies subject to peer review [254].
(ICP4) Studies written in English.
(ICP5) Studies available as full-text.

Inclusion Criteria for Grey literature

(ICG1) Web-pages reporting on a modelling/programming language/framework for parallel programming.
(ICG2) Web-pages reporting on a formalisation and/or implementation of the proposed language.
(ICG3) Web-pages in English.
(ICG4) Web-pages freely accessible.

Exclusion Criteria for Peer-reviewed literature

(ECP1) Secondary and tertiary studies (e.g., systematic literature reviews, surveys).
(ECP2) Studies in the form of tutorial papers, short papers (≤3 pages), poster papers, editorials, manuals, because they do not provide enough information.

Even if secondary/tertiary and other studies were excluded from the set of primary studies (see the ECP1/ECP2 exclusion criteria), we considered them as follows:

- for checking the completeness of our set of primary studies (i.e., if any relevant paper was missing from our study);
- for providing a summary of what is already known about languages for parallel programming;
- for identifying any important issues to be considered in our study;
- for defining what the contribution of our study to the literature could be;
- for identifying potential new ideas and preliminary results related to our topic.

Exclusion Criteria for Grey literature

(ECG1) Web-pages reporting exclusively on the basic principles of the language.
(ECG2) Web-pages reporting exclusively on the application of the language.
(ECG3) Peer-reviewed literature, since this type of studies is considered in a different search activity.
(ECG4) Videos, webinars, books, and so on. Since they are too time-consuming to be considered for this study.

To select studies objectively, four researchers—the selection team—actively participated in this phase. More specifically, by following the method proposed in [9], each potentially relevant study was classified by the four researchers as *relevant*, *uncertain*, or *irrelevant* according to the selection criteria above. Studies classified as *irrelevant* were immediately excluded, while those marked as *relevant* were preliminary included. For the *uncertain* cases, the selection team discussed with the mediation of a fifth researcher, the mediator. The selection team members classified a certain number of common studies (∼15%) in order to check agreement, achieving a Cohen's kappa [28] of **0.87**.[3] Out of the gathered 2,122 peer-reviewed studies and 72 languages, we eventually selected **529** potential primary studies.

2.2.5 Snowballing. To minimise potential bias with respect to construct validity of our study, we complemented the automatic search with a snowballing activity [103]. We performed a closed recursive backward and forward snowballing activity [253]. We found 19 relevant studies, which led to a total of **548** preliminary primary studies.

[3]Cohen suggested the Kappa result be interpreted as follows: values ≤ as indicating no agreement and 0.01–0.20 as none to slight, 0.21–0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as substantial, and 0.81–1.00, which represents our case with 0.87, as almost perfect agreement.

2.3 Data Extraction

At the beginning of this phase, we created a *data extraction form*, or classification form, to be used to collect data extracted from each preliminary primary study. The data extraction form, provided in Tables 5 and 6, was composed of four facets, one for each research question. Specifically, for answering RQ1, we considered standard information such as title, authors, and publication details of each study. For RQ2, RQ3, and RQ4, we followed a systematic process based on *keywording* for: (i) defining the parameters of each facet of the data extraction form, and (ii) extracting data from the primary studies accordingly.

The goal of the keywording was to effectively develop an extraction form that could fit existing studies and took their characteristics into account [186]. More precisely, we collected keywords and concepts by reading the full text of the pilot studies. Then, we performed a clustering operation on collected keywords and concepts in order to organise them according to the identified categories. The clustering operation is very similar to the sorting phase of the grounded theory methodology [57]. During the actual extraction phase, we collected any kind of additional information that was deemed relevant but that did not fit within the data extraction form. We reviewed the collected additional information and, when needed, we refined the data extraction form to better fit the collected information; previously analysed primary studies were re-analysed according to the refined data extraction form. This process was complete only when all primary studies were analysed. The final total number of included and analysed primary studies was **225** (see Table 4).

2.4 Data Analysis and Synthesis

In this phase we gathered, analysed and synthesised the extracted data to understand and classify the current state of the art in the area of languages for parallel programming [134, § 6.5]. We designed and carried our data analysis and synthesis by following the guidelines presented by Cruzes et al. in [69]. More specifically, we focused on vertical and orthogonal (or horizontal) analysis.

Vertical analysis aims at finding trends and collect information about each category of the data extraction form. We applied the line of argument synthesis [254], meaning that we first analysed each primary study individually to classify its main features according to each specific parameter of the data extraction form. Then, we analysed the set of studies as a whole, in order to reason about potential patterns, trends and potential gaps.

Orthogonal analysis aims at identifying possible relations across different categories of the data extraction form. We cross-tabulated and grouped extracted data as well as we made comparisons between pairs of categories of the data extraction form. Through contingency tables, we extracted and evaluated relevant pair-wise relations in terms of patterns, trends, and potential gaps.

In both cases, we performed a combination of content analysis [89] (for categorising and coding approaches under broad thematic categories) and narrative synthesis [200] (for detailed explanation and interpretation of the findings coming from the content analysis).

3 RESULTS: VERTICAL ANALYSIS

In this section, we report on the results of the vertical analysis. More specifically, we analysed each primary study individually to classify its main features according to each specific parameter of the data extraction form. Then, we analysed the set of studies as a whole and here we reason and report on potential patterns, trends, and potential gaps. Note that in some cases no value or

Table 4. List of Primary Studies, with Language Name (if Avail.), Reference, and Activity Status of the Language

ID	Name ((✓) = active)	References	ID	Name ((✓) = active)	References	ID	Name ((✓) = active)	References
P01	ParaSail (✓)	[223]	P02	Futhark (✓)	[116]	P03	Pencil	[20]
P04	Halide (✓)	[190]	P05	Gaspard (✓)	[91]	–	–	–
P07	HPJava	[49]	P08	Split-C (✓)	[70]	P993	–	[184]
P1002	APARAPI-FPGA	[206]	P1011	Logtalk (✓)	[171]	P1012	PACXX	[111]
P1034	XPFortran-OpenMP	[261]	P1039	HyperPascal (✓)	[31]	P1041	IAL	[66]
P105	CARPET	[211]	P1097	AJWS (✓)	[139]	P1101	ClassiC	[175]
P1103	X-KLAIM (✓)	[30]	P1105	SuperPascal	[113]	P1113	Tetra (✓)	[84]
P1116	Seymour	[168]	P1118	IPC++	[216]	P1131	JavaNOW	[229]
P1136	Java4P	[178]	P114	JUMP (✓)	[115]	P116	ECP-C	[23]
P1172	Lemonade (✓)	[76]	P1175	Linda (✓)	[205]	P1200	NestStep	[130]
P1233	–	[189]	P1254	Modula-P (✓)	[244]	P1260	Molecule (✓)	[258]
P1285	MULTILISP	[112]	P1288	XcalableMP (✓)	[236]	P1291	Musket (✓)	[197]
P1293	NANO-2	[16]	P1304	Node.Scala	[37]	P1312	–	[208]
P1313	OP++	[220]	P1317	C++-with-Ease	[158]	P132	AMPLE (✓)	[137]
P134	LSP	[213]	P1351	–	[260]	P1371	OpenRCL	[149]
P138	P^3L	[71]	P1388	Orgel	[180]	P1389	Vector Pascal (✓)	[63]
P1395	Force	[5]	P140	–	[21]	P1412	Parallel C	[109]
P1425	–	[177]	P143	ASTOR (✓)	[238]	P1433	–	[59]
P1437	Encore (✓)	[40]	P1442	PPM	[43]	P1452	Chapel (✓)	[52]
P1464	Ensemble (✓)	[114]	P1467	Morpho (✓)	[4]	P147	–	[73]
P998	OIL (✓)	[97]	P1480	Delirium	[157]	P1495	–	[219]
P1511	ParCel-1	[242]	P1514	ParoC++	[176]	P155	Fortran M	[54]
P1550	PGASUS (✓)	[110]	P1565	Pooma	[179]	P1572	Prelude (✓)	[64]
P1586	Qlisp	[100]	P1620	Modula-2*	[187]	P1632	Arvo (✓)	[247]
P1636	PyCOMPSs (✓)	[226]	P1641	Quasar (✓)	[101]	P1649	Real-time Mentat	[106]
P1669	RELACS (✓)	[191]	P168	–	[72]	P1681	NCX	[10]
P1691	C^n	[154]	P1695	River Trail (✓)	[117]	P1700	–	[90]
P1705	SAC (✓)	[104]	P171	–	[78]	P1710	–	[36]
P1711	– (✓)	[224]	P1717	OmpSs-OpenCL	[77]	P1736	Scootr (✓)	[140]
P1738	Scout (✓)	[165]	P1752	Glasgow paral. Haskell	[153]	P1764	SHMEM+ (✓)	[3]
P1771	Sigma C (✓)	[102]	P1804	Spar (✓)	[241]	P1844	Swift/T	[255]
P1849	SyncCharts	[245]	P1867	FastFlow (✓)	[7]	P1894	Atomos (✓)	[48]
P1906	ZPL (✓)	[209]	P1910	Jade (✓)	[198]	P1912	CGIS	[156]
P1916	DSPL	[169]	P1923	ForeC (✓)	[259]	P1924	Fork95	[131]
P1928	II	[74]	P1930	JavaSymphony	[8]	P1931	JStar (✓)	[240]
P1940	OpenTM	[19]	P1941	parallel C (✓)	[47]	P1944	ParCel-2 (✓)	[46]
P1970	LM (✓)	[67]	P1976	–	[192]	P198	Polymorphic Parallel C	[162]
P1988	GridNestStep	[164]	P1991	TCF++ (✓)	[159]	P2023	TPascal	[45]
P2036	Trellis	[222]	P2055	UTC (✓)	[150]	P2072	iOberon	[135]
P208	SVM-Fortran	[96]	P2094	VersaPipe (✓)	[263]	P2113	Wysteria (✓)	[194]
P2120	Yada	[95]	P215	–	[203]	P232	Orca	[26]
P240	MANIFOLD	[17]	P252	A-NETL	[18]	P268	Accelerator	[225]
P281	mpC	[145]	P284	VPR	[65]	P292	Qu-Prolog (✓)	[60]
P296	AL1	[161]	P297	ALBA	[118]	P334	EL*	[193]
P344		[138]	P347	XMP (✓)	[147]	P36	–	[34]
P360	Gaspard2 (✓)	[201]	P363	DAPL	[250]	P364	Promoter	[29]
P367	PObC++ (✓)	[188]	P380	ALWAN	[88]	P392	Agora (✓)	[33]
P408	Augur (✓)	[235]	P415	CCMs	[107]	P443	Balinda C++	[249]
P444	Bamboo (✓)	[264]	P446	Beehive (✓)	[234]	P457	Booster	[182]
P460	Braid (✓)	[252]	P465	BSGP (✓)	[121]	P472	C**	[144]
P476	CaKernel	[35]	P479	CAOPLE (✓)	[257]	P48	DPML	[86]
P480	CAPP (✓)	[62]	P498	Chestnut	[215]	P51	–	[108]
P52	V	[141]	P545	SEPCom (✓)	[251]	P581	Delta Prolog	[185]
P586	Rolez (✓)	[80]	P605	COOL	[53]	P608	Copperhead (✓)	[50]
P619	CuPit-2	[120]	P62	Visper	[212]	P633	Firebird (✓)	[232]
P636	Dataparallel C	[173]	P650	Declarative Ada	[231]	P651	CLM (✓)	[68]
P656	Aida	[155]	P658	CL/1	[42]	P665	812	[167]
P669	OpenMPD	[146]	P692	TACT	[214]	P72	STING (✓)	[124]
P726	DPX10 (✓)	[248]	P728	DryadLINQ (✓)	[83]	P734	ICE (✓)	[98]
P735	Mentat	[105]	P736	EastFJP (✓)	[163]	P748	Skil	[39]
P764	Flat X10 (✓)	[32]	P768	ELMO (✓)	[196]	P786	MFL (✓) (✓)	[210]
P787	eskimo	[6]	P800	Eve	[85]	P805	KL	[136]
P824	StreamMDE (✓)	[217]	P825	HPF	[27]	P840	Aspen	[239]
P846	–	[148]	P852	–	[12]	P866	FastPara	[160]
P87	– (✓)	[92]	P886	FSPPL (✓)	[142]	P891	ForkLight	[132]
P90	Ellie (✓)	[13]	P907	FPMR (✓)	[207]	P910	HOE^2 (✓)	[152]
P930	Gemma in April	[256]	P931	GEMS (✓)	[38]	P949	Go!	[61]
P954	Gossamer	[199]	P964	GraphGrind (✓)	[218]	P968	GraphIt (✓)	[262]
P972	Habanero Java (✓)	[51]	P980	Ly (✓)	[237]	G1	Open MPI (✓)	[228]
G2	Joule	[128]	G3	LabVIEW (✓)	[172]	G5	Sisal	[94]
G6	Bloom (✓)	[195]	G7	Julia (✓)	[227]	G8	Limbo	[243]
G9	Sequoia++	[25]	G10	Clojure (✓)	[119]	G11	Erlang (✓)	[79]
G12	Rust (✓)	[202]	G13	Charm++ (✓)	[56]	G14	Join Java(✓)	[246]
G15	Chapel (✓)	[55]	G16	Coarray Fortran (✓)	[123]	G17	Ateji PX (✓)	[183]
G18	Scala(✓)	[204]	G19	Go (✓)	[99]	G20	JoCaml	[125]

Table 5. Data Extraction form Facets, Clusters and Categories

Facet	Cluster	Category	Description
RQ1	Publication details	Authors	identifies the list of authors
		Venue name	identifies the title of the study
		Venue type	identifies the type of venue
		Year	identifies the year of publication
RQ2	Language properties	Language name	reports the name of the language that is defined in the study
		Language abstraction	identifies the level of abstraction at which the language is defined
		Purpose	identifies whether the language is generic or domain-specific
		Parallel primitives	identifies whether the language provides implicit or explicit parallelism
		Abstract syntax	identifies how the abstract syntax is defined
		Concrete syntax	identifies how the concrete syntax is defined
		Program. paradigm	identifies the specific programming paradigm
		Communication type	identifies whether communication is synchronous or not
		Synchronisation type	if synchronous, identifies the sync. type
	Programming model	Parallel architecture	identifies the class of parallel architecture targeted in the study
		Problem decomposition inspired by Thoman et al.'s taxonomy [230]	identifies the type of parallelism. Task parallelism: a form of parallelism where the work at hand is broken down into smaller work units, called tasks, which are scheduled to run in parallel. Pipeline parallelism: form of parallelism where the computation of each task is divided into a fixed sequence of stages, the same for all tasks, and the tasks are computed in a partially parallel fashion where a task can start executing initial stages before the preceding task has finished executing its final stage. Data parallelism: a form of parallelism where operations over whole data structures are performed in parallel over the individual elements of the structures. Nested parallelism: a form of parallelism where the parallelism is exploited at several levels. An example is a cluster of powerful nodes where some parallelism appears between the nodes and some internally in the nodes, e.g., in a GPU internal to the node.
		Communication model inspired by Thoman et al.'s taxonomy [230]	identifies the the communication model. Shared memory: a form of communication where processes, or threads, communicate through writing and reading a shared memory area. Message passing: a form of communication where processes communicate, and often synchronise, by sending and receiving messages. Data flow: a computing paradigm where the nodes in a so-called Data Flow Graph communicate by passing data tokens over the edges in the graph. Shared events: a form of communication where processes/threads communicate via shared events. FIFO buffer: a form of communication via data buffering in FIFO manner.
		Memory model inspired by Thoman et al.'s taxonomy [230]	identifies the memory model. Distributed: a memory model where each processor has its own private memory, and has exclusive access to this memory. Shared: memory model where several processors share the same address space, and can read and write to the same memory area. Stack-based: way to handle memory for function calls in a structured fashion by allocating and deallocating local data and actual function arguments. Region-based: an alternative to stack-based memory handling where memory is allocated and deallocated in larger memory areas, so-called regions.
	Execution, run-time and implementa-tion	Execution mode	identifies how programs conforming to the language can be executed
		Target language (if compiled)	if compiled, identifies the compilation target language(s)
		Target architecture	identifies the hardware processor(s) targeted for execution
		Implementation type	identifies how the language is implemented
		Extended language	identifies the name of base language extended (or tailored) to define the language presented in the study
RQ3		Limitations	identifies gaps and open challenges as reported in the studies

Table 6. Category Values and Multiplicity

Category	Values	Mult.
Authors	string	1
Venue name	string	1
Venue type	Workshop, Conference, Journal, Book chapter	1
Year	numeric value (e.g., 2010)	1
Language name	string	0..1
Language abstraction	Modelling language, High-level programming language	1
Purpose	General-purpose, Domain-Specific	1
Parallel primitives	Explicit, Implicit	0..*
Abstract syntax	Metamodel, Formal specification, Context-free grammar, Informal specification	1
Concrete syntax	Textual, Diagrammatic, Graph-based, Tree-based	0..*
Programming paradigm	Object-oriented, Imperative, Declarative, Event-driven, Multi-paradigm (representing a language featuring several paradigms)	0..*
Communication type	Synchronous, Asynchronous	0..*
Synchronisation type	Rendezvous, Monitor, Lock-free data structure, Lock, Dynamic interfaces, Dependency graph, Channel, Barrier	0..*
Parallel architecture	Single instruction single data (SISD), Single instruction multiple data (SIMD), Multiple instruction single data (MISD), Multiple instruction multiple data (MIMD), Single program multiple data (SPMD), Architecture independent	0..*
Problem decomposition	Task parallelism, Data parallelism, Nested parallelism, Pipeline parallelism	0..*
Communication model	Shared memory, Message passing, Data-flow, User-defined, Shared events, FIFO buffer	0..*
Memory model	Stack-based, Distributed, Shared, Region-based	0..*
Execution mode	Compiled, Interpreted, Hybrid	0..*
Target language type (if compiled)	High-level, low-level	0..1
Target architecture	Multi-core CPU, Many-core CPU, GPU, GPGPU, FPGA, DSA, Target-independent	0..*
Implementation type	Standalone, Extension	0..1
Extended language (if extension)	string	0..1

multiple values could be extracted from the studies for specific categories. This means that the total number of occurrences in the related plots may not sum up to or be greater than the total number of primary studies (225). Note that we also provide summary tables (Tables 9–24) in supplementary material where each analysed article is connected to each specific category and its characterising value(s).

3.1 Publication Trends (RQ1)

To answer RQ1, we analysed the extracted data to identify publication trends in terms of (i) trend over time and (ii) venue types. The first, shown in terms of the number of primary studies published over the years, is depicted in Figure 3. It is interesting to note that the first study included in our investigation was published back in 1981. After that, the research area did not receive much

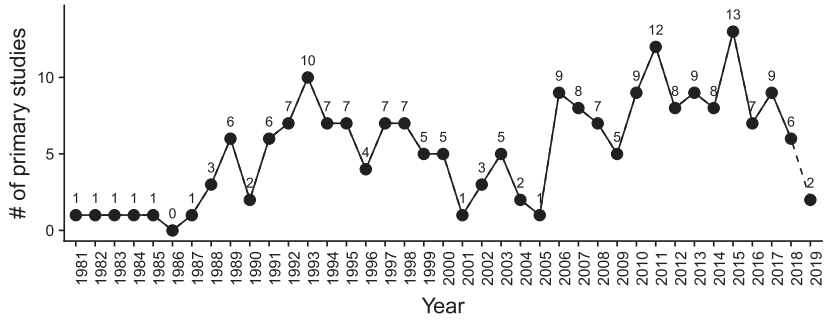


Fig. 3. Trend of publications over time.

attention for six years, which is indicated by a maximum of one primary study per year until 1987, as shown in Figure 3. Since 1988, effort in this research area started to steadily grow. This is evident from the 10-, 12- and 13-fold increase in the number of primary studies in 1993, 2011, and 2015 with respect to 1981. The growing interest of the community seems to have peaked in 2011 with 13 primary studies. Furthermore, based on the extracted data, we observe that the average number of primary studies is approximately six per year from 1981 to 2019, and approximately nine per year in the last decade (2009–2019). Given the steady increment in the last decade, we expect this trend to continue in the future. We also noted drops in the number of primary studies in 2001 and 2005; however, we could not find any clear reason for that.

We also classified the number of primary studies with respect to the type of publication venue, namely, Journal, Conference, Workshop, and Book chapter. We notice that Conference is the most common venue type, with 54% of primary studies belonging to it. The second most common venue type is Journal, which holds almost 36% of the primary studies. Workshop and Book chapter stand for 9.5% and 0.5% of the primary studies, respectively.

The top 10 venues in terms of number ($\geq$4) of primary studies are listed in Table 7. It is interesting to note that these venues only stand for 22.8% of the 225 primary studies, whereas the remaining ones are published in 134 other venues. The **International Conference on Parallel Processing** (**ICPP**) has published the highest portion (3.65%) of the primary studies. The second ranked venue, with 3.2% is the International European Conference on Parallel and Distributed Computing (Euro-Par). The ACM SIGPLAN Symposium on **Principles and Practice of Parallel Programming** (**PPOPP**) and the **International Conference on Functional Programming** (**ICFP**) published 2.74% of primary studies each. The **International Parallel and Distributed Processing Symposium** (**IPDPS**), the Conference on **Object-Oriented Programming Systems, Languages, and Applications** (**OOPSLA**), and ACM **Transactions on Programming Languages and Syste**ms (**TOPLAS**) published 2.28% of studies each. Finally, the ACM SIGPLAN Conference on **Programming Language Design and Implementation** (**PLDI**), the **Hawaii International Conference on System Sciences** (**HICSS**) and the International Workshop on High-Level Parallel Programming Models and Supportive Environments (HIPS) published 1.82% of studies each.

These results could be helpful in guiding new researchers in this area to identify the most relevant publication venues for searching the related work as well as publishing their research results. However, it should be noted that apart from the top nine venues (which also display a rather low concentration of published primary studies), the widely dispersed distribution of relevant publications over other venues (134) shows that the research community does not strongly favour any specific venue.

Table 7. Venues Featuring ≥4 Primary Studies

Venue name	Acronym	Type	#Papers
International Conference on Parallel Processing	ICPP	C	8
International European Conference on Parallel and Distributed Computing	Euro-Par	C	7
ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming	PPOPP	C	6
International Conference on Functional Programming	ICFP	C	6
International Parallel and Distributed Processing Symposium	IPDPS	C	5
Conference on Object-Oriented Programming Systems, Languages, and Applications	OOPSLA	C	5
ACM Transactions on Programming Languages and Systems	TOPLAS	J	5
ACM SIGPLAN Conference on Programming Language Design and Implementation	PLDI	C	4
Hawaii International Conference on System Sciences	HICSS	C	4
Workshop on High-Level Parallel Programming Models and Supportive Environment	HIPS	W	4

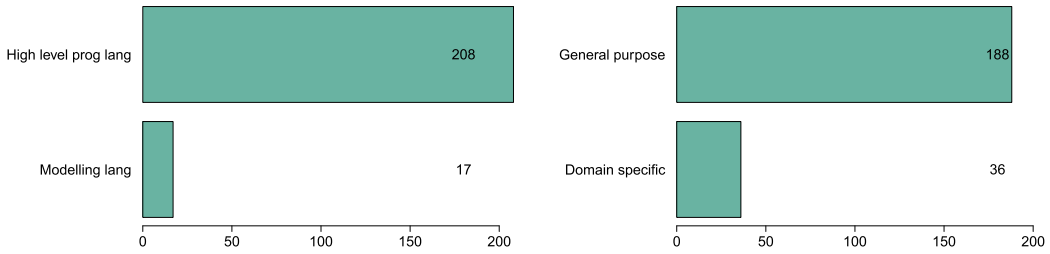
Highlights – RQ1 Publication trends

- Since 1988, effort in this research area has been steadily growing; a steady increment in the last decade suggests a continuation of this trend in the near future.
- The widely dispersed distribution of relevant publications across venues suggests that the research community does not strongly favour any specific one.
- The HIPS workshop has been continuously running for 25 years, showing an interesting continuity in the community's effort towards high-level parallel programming and related tools.

3.2 Technical Characteristics (RQ2)

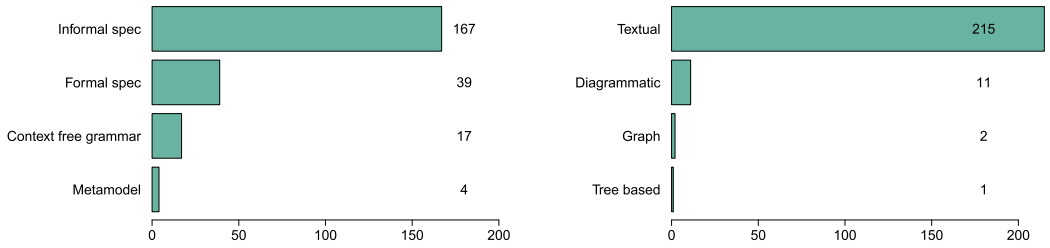
This research question focuses on a set of technical aspects of the languages proposed in the analysed primary studies. The technical aspects were either mentioned explicitly in the papers or could be easily inferred from the specification of the languages discussed in the papers.

3.2.1 Language Properties (RQ2.1). From the primary studies, we extracted and analysed some high-level features such as level of language abstraction, its purpose, and the kinds of abstract and concrete syntax of the languages. As it can be seen in Figure 4(a), most languages (208/225) are defined as *high-level programming languages*. This has to do with the syntactic abstractions provided by the language, the different kinds of data and control flow abstraction and the level of dependency on the underlying platform, such as hardware and operating systems. These languages range from *third generation* to *fifth generation* programming languages. A small number of languages (17/225) are defined as canonical *modelling languages*, in order to provide an even more abstract, and often diagrammatic, representation (i.e., model) of a program. The purpose of these modelling languages include providing efficient platform for data analytics, supporting multilevel modelling on various parallel platforms and accelerators. Interestingly, we found one concurrent constraint programming language (P633) targeting massively parallel SIMD computers. As shown in Figure 4(b), except for a few domain-specific or special-purpose languages (36/225), the majority of the studies (188/225) proposed general-purpose languages.



(a) Language abstraction (b) Purpose

Fig. 4. Language properties: language abstraction and purpose.



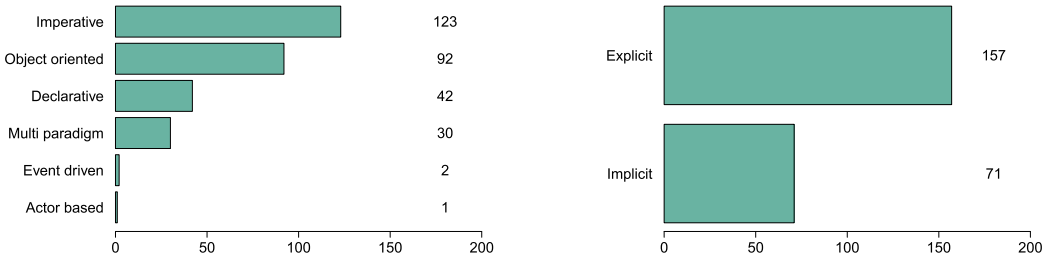
(a) Abstract syntax (b) Concrete syntax

Fig. 5. Language properties: abstract and concrete syntax.

As expected, and shown in Figure 5(b), the concrete syntax of most languages (215/225) is specified in terms of textual notations. For modelling languages in particular, diagrammatic, tree-based, or graph-based concrete syntax is provided in most cases too (14/17). The abstract syntax of most languages (approximately 73%) is provided only informally, as shown in Figure 5(a). In several studies, proposed languages are built on top of existing languages without providing the complete abstract syntax of the extended languages. The abstract syntax of modelling languages is described by means of canonical metamodel specifications only in four cases out of 17.

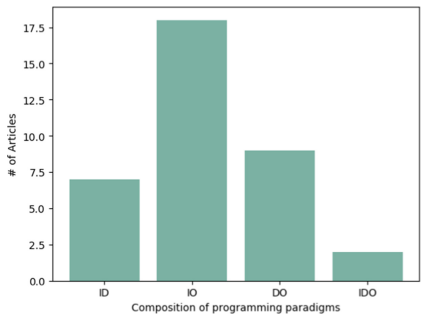
With regards to languages' programming paradigm, as it can be seen in Figure 6(a), it is evident that the procedural imperative paradigm is the most studied and used 123/225, whereas object-oriented and declarative paradigms rank second and third with 92 and 42 occurrences, respectively. Among those, a fair number of languages (30/225) support multiple programming paradigms; out of them, eighteen support imperative and object-oriented, seven support declarative and imperative, nine support declarative and object-oriented, two support combined imperative, declarative, and object-oriented, and one supports event-driven and object-oriented. The figure and table[4] in Figure 7 depicts the combination of the major programming paradigms and the associated programming languages. One event-driven programming language, called *Eve* (P800), is proposed to support the event-loop and task-based parallelism in achieving high concurrency. An interesting case is represented by *Node.Scala*, which is a dynamic multi-paradigm language and framework for enhancing the Java Virtual Machine by introducing safe stateful event-driven programming (P1304). Quite surprisingly, given the suitability of the paradigm for

[4]The table exclude languages that was not given a name in the study.



(a) Programming paradigm (b) Parallel primitives

Fig. 6. Language properties: programming paradigm and parallel primitives.



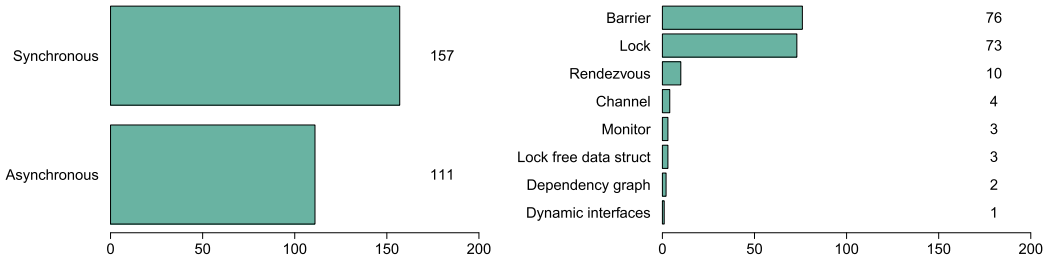
Paradigms	Languages
ID	PyCOMPSs, Scootr, DryadLINQ, Skil, FastPara, OIL, Julia
IO	PACXX, AJWS, C++-with-Ease, OpenRCL, Morpho, Pooma, Bamboo, CAPP, DryadLINQ, Mentat, GraphGrind, HPJava, Open MPI, Julia, Join Java, Chapel, Ateji PX
DO	Logtalk, Qu-Prolog, DryadLINQ, Go!, Habanero Java, Julia, Scala, JoCaml
IDO	DryadLINQ, Julia

Fig. 7. Multi-paradigm parallel languages. ID—Imperative and Declarative, IO—Imperative and Object-oriented, DO—Declarative and Object-oriented, IDO—Imperative, Declarative, and Object-oriented.

describing parallelism, only three object-oriented languages are *actor-based* (P1991, P296, and P1916).

Regarding the supported type of parallel primitives (Figure 6(b)), most languages (157/225) support *explicit* primitives for describing parallelism. Nevertheless, a noteworthy number of languages (71/225) focus on *implicit* primitives. Not so surprisingly, support for explicit or implicit primitives is in most cases mutually exclusive; only three languages (P01, P1970, and P1550) provide support for both. An interesting case is represented by Glasgow parallel Haskell (P1752), which exploits so-called *semi-explicit* parallelism, meaning that potential parallelism is explicitly annotated in the program, while all aspects of coordination are delegated to the runtime environment.

Regarding the types of communication among parallel activities offered by the languages (Figure 8(a)), we found that 42/225 studies offer both synchronous and asynchronous communication; the rest support either synchronous (157/225) or asynchronous communication (111/225). Among those supporting synchronous communication (Figure 8(b)), we found that lock- and barrier-based synchronizations are the most popular choices to synchronise parallel activities, with 76 and 73 occurrences each. A few languages (10/157) use rendezvous-based synchronisation instead. However, there exist some languages that use specialised synchronisation mechanisms, such as: channel-based (4/157), monitor-based (3/157), lock-free data structures (3/157), dependency graphs (2/157), and dynamic interfaces (1/157). Note that some languages exploit multiple types of synchronisation.



(a) Communication type (b) Synchronisation type

Fig. 8. Language properties: communication and synchronisation types.

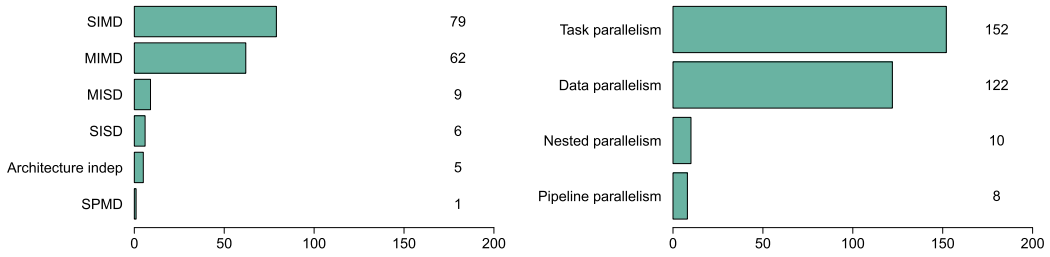
Highlights – RQ2.1 Language properties

- Most languages are high-level and general-purpose, their formal abstract syntax is often not explicitly given, and their concrete syntax is in most cases textual.
- Imperative and object-oriented programming are the most popular paradigms, in that order;
- Explicit parallelism is the most commonly supported.
- Distribution of synchronous and asynchronous communication is rather even, with lock- and barrier-based are the most common synchronisation means.

3.2.2 Programming Model (RQ2.2). The analysis of RQ2.2 covers four aspects of parallel programming models: target hardware architecture, problem decomposition, communication model, and memory model. As expected, most studies target **single instruction multiple data** (**SIMD**) or **multiple instruction multiple data** (**MIMD**) architectures, with 79/225 and 62/225 occurrences, respectively. Very few studies target **single instruction single data** (**SISD**) or **multiple instruction single data** (**MISD**) architectures, with 6/225 and 9/225 occurrences, respectively. Furthermore, five languages (P02, P03, P05, P1906, P1118, and P1136) provide *architecture-independent* solutions, meaning that their programming model is not tailored nor dependent on any specific target machine. One language (P1988) supports **single program multiple data** (**SPMD**) architecture.

The results concerning the supported problem decomposition types confirm the historical predominance of task- and data-parallelism (Figure 9(b)), with 152/225 and 122/225 entries, respectively. Task-parallelism is compatible with applications for various domains, e.g., from web applications to system programming, and often used to implement implicit (data) parallelism. In contrast, data-parallelism is generally preferred for high-performance computing applications. Lower-level forms of parallelism, nested (10/225), and pipeline parallelism (8/225) appear too, often as secondary form of parallelism. Figure 10 depicts the number of studies proposing languages supporting various composition of problem decomposition categories. In 64/225 primary studies, languages provide support for both task- and data-parallelism. Other problem decomposition combinations are proposed in relatively small number of studies: (7/225) for task and nested parallelism, (4/225) for pipeline and data parallelism, (6/225) for nested and data parallelism, (3/225) for task, nested, and data parallelism, and (1/225) for each of the combination of task and pipeline parallelism, and task, pipeline, and data parallelism.

Regarding the communication model (Figure 11(a)), message-passing is the most popular choice of communication (111/225). The use of shared memory, i.e., more or less implicitly regulated accesses to common regions of memory, is the second most popular medium of communication (107/225). Another, less common, communication means is data-flow-based (23/225), employed



(a) Parallel architecture (b) Problem decomposition

Fig. 9. Programming model: parallel architecture and problem decomposition.

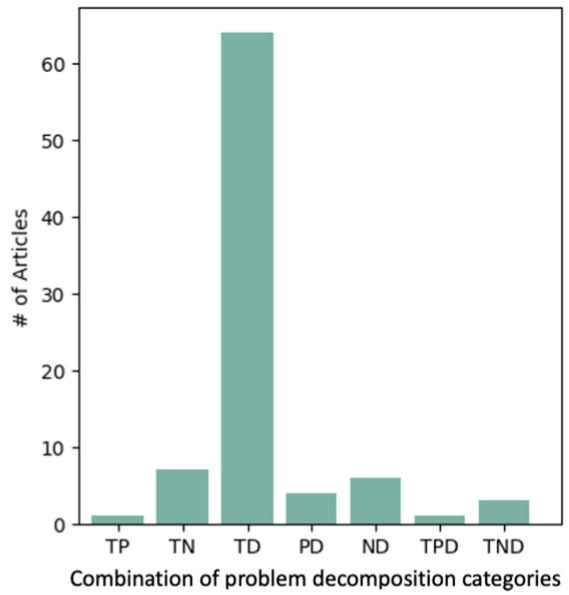
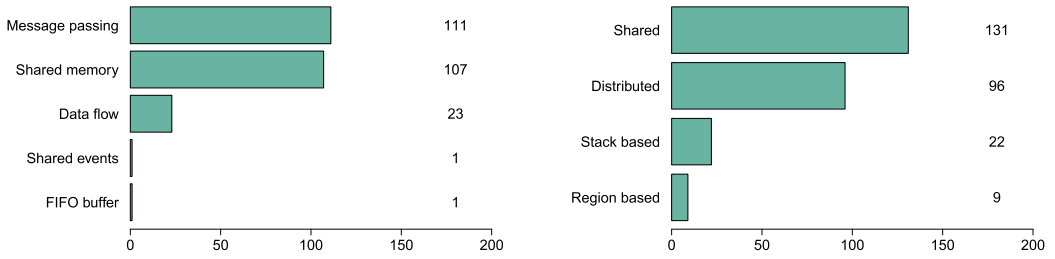


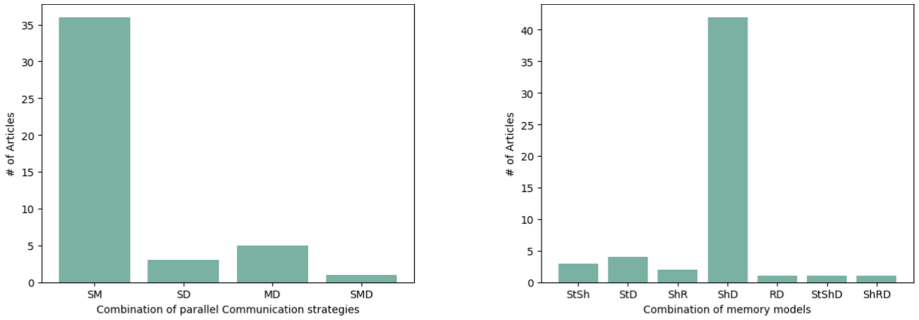
Fig. 10. Number of Languages supporting multiple problem decomposition strategies. T—Task parallelism, P—Pipeline parallelism, N—Nested parallelism, and D—Data parallelism.

by so-called data-flow languages. Communication via shared events (P1976) and via FIFO buffers (P998) occurs in one study each. As illustrated in Figure 12(a), 36/225 studies proposed languages providing parallel communication mechanism via shared memory and message passing mechanism, (3/225) proposed shared memory and data flow communication, 5/225 proposed message passing and data flow, and one study proposed the *split-C* language offering shared memory, message passing, and data flow based communication. Concerning the memory model (Figure 11(b)), the majority of languages target shared memory architectures (131/225). It is worth noticing that, in contrast with its virtual abstraction role in communication models, memory here is meant as "physical" memory. To exemplify, languages featuring shared memory in their communication model do not necessarily target architectures with shared physical memory. Distributed memory architectures, such as clusters, are also commonly targeted (96/225). Finally, these models might be enhanced by advanced variations, as in stack-based (22/225) and region-based (9/225) approaches. As with the previous categories, a given language might target



(a) Communication model (b) Memory model

Fig. 11. Programming model: communication and memory models.



(a) Combination of communication models. S - Shared memory, M - Message passing, D - Data flow

(b) Combination of memory models. St - Stack based, Sh - Shared, R - Region based, D - Distributed

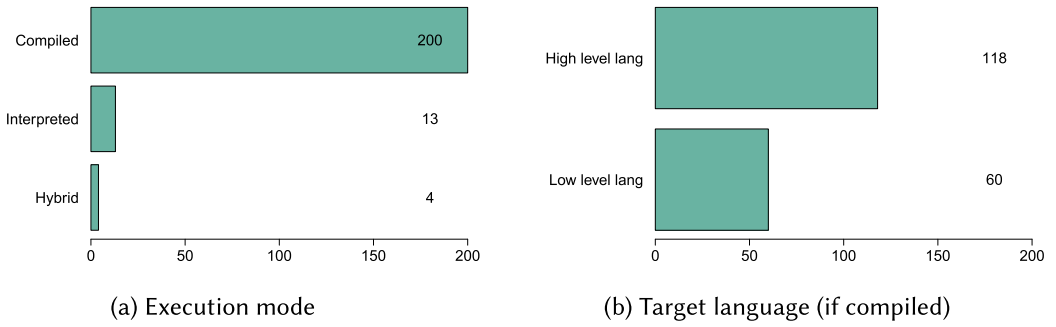
Fig. 12. Programming model combinations: communication and memory models.

more than one memory model, especially in those cases where memory access is abstracted through language constructs, i.e., implicit communication and data allocation. As depicted in Figure 12(b), in 42 primary studies, languages target both shared and distributed memory. Other combination of memory models include 3/225, 4/225, and 2/225 studies that proposed languages having stack-based and shared, stack-based and distributed, and shared and region-based memory models. There exists one study for each of the combinations of region-based and distributed, stack-based, shared, and distributed, and shared, region-based, and distributed memory models.

Highlights – RQ2.2 Programming model

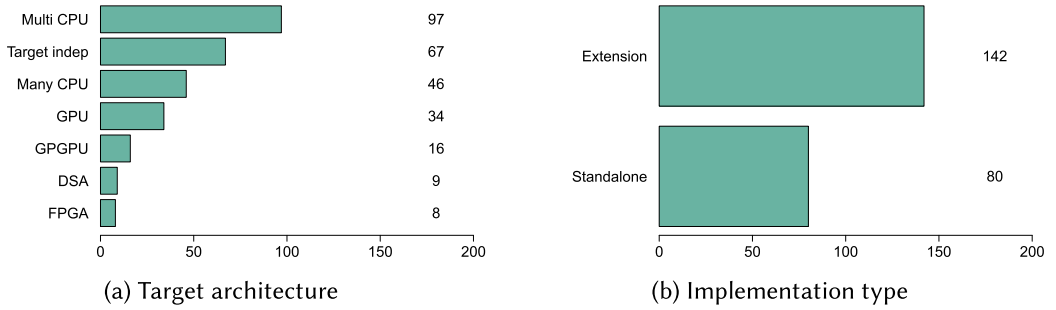
- Most languages target SIMD and MIMD architectures, while very few provide *architecture-independent* solutions.
- Task- and data-parallelism are the most common problem decomposition approaches, possibly supported by lower-level forms of parallelism, e.g. pipeline.
- Shared-memory, message-passing and data-flow are the most common communication models, in that order.
- The majority of languages target shared or distributed memory architectures, possibly enhanced into more advanced models, e.g. region-based approaches.

3.2.3 Execution, Run-time and Implementation (RQ2.3). Research question RQ2.3 concerns languages with respect to their run-time characteristics, more specifically how languages are implemented and executed. First, we classified the languages according to how they are executed, namely



(a) Execution mode (b) Target language (if compiled)

Fig. 13. Execution: mode and target language.



(a) Target architecture (b) Implementation type

Fig. 14. Target architecture and implementation type.

via interpretation, compilation or hybrid approaches. If compiled, we investigated whether the language(s) targeted by the compiler are low- or high-level languages. Eventually, we analysed which architectures are specifically targeted by the languages and how the language is implemented.

With regards to the execution mode (Figure 13(a)), it is evident that the community has heavily focused on developing compilation strategies (200/225); interpretation strategies were provided in 13 studies, while in four cases execution was achieved via hybrid approaches (e.g., mix of interpretation and JIT compilation). Looking at Figure 13(b), we can see how, in most cases (118/200), work on compilers focuses on generating programs in high-level languages (including compiler internal/intermediate languages). This shows that the bulk of the community's effort is devoted to so called front- and middle-ends, while back-ends tend to be reused. Nevertheless, there is a fair amount of compilation works (60/200) targeting low-level languages, thus focusing more on back-ends.

Regarding target architectures (Figure 14(a)), many approaches (97/225) focus on multi-core CPUs. Interestingly, the second biggest share of studies (67/225) focus on target-independent languages, followed by those focusing on many-core CPUs (46/225). GPUs are targeted by 34 studies, while GPGPUs by 16; DSAs, and FPGAs are mentioned as target architectures in nine and eight studies, respectively. Note that a number of studies (62/225) propose languages that are meant to support multiple target architectures. Concerning how languages are implemented (Figure 14(b)), the majority of the primary studies (142/225) present languages as extension of existing languages. In Table 8, we list the base languages extended to implement the languages reported in the primary studies. The most leveraged family of programming languages is C-based (49/142) followed by Java-based (20/142). On the modelling languages side, the UML family of languages is exploited in eight studies.

Table 8. Extended Languages

# occ.	Languages
25	C
21	C++
15	Java
5	Pascal
5	UML, Fortran
4	OpenMP
3	MARTE
2	Prolog, Ada, Modula-2, Haskell, Lisp, OpenCL, LM, X10
1	APARAPI, XPFortran, IA, C*, PAL, Euclid, Scala, CUDA, PL/1, C#, Insense, XSLT, Python, Mentat, JavaScript, Deterministic Parallel Java, OmpSs-OpenCL, R, SHMEM, JavaSymphony, ParCel-1, NestStep, OpenACC, TNC, Active Oberon, Orca, mpC, ReactoGraph, Qu-Prolog, PLASMA, XMP, MPL, BSP, Cactus, Rolez, CuPit, Habanero Java, occam2, Scheme, LINQ, MFL, HPF, Node.js, April, Cilk, MPI, Caml

Highlights – RQ2.3 Execution, run-time and implementation

- The large majority of parallel languages are compiled and the target is usually a high-level language, indicating a consolidated trend towards implementing front- and middle-ends rather than back-ends for new languages.
- CPUs (multi- and many-core) represent by large the most commonly targeted architectures; interestingly, over 30% of languages is not tailored to any specific target architecture.
- Most languages are defined in terms of extensions of existing languages; C/C++ and Java are the most leveraged programming languages, and UML the most used modelling language, for extension purposes.

3.3 Limitations (RQ3)

The analysis and synthesis of limitations presented in the primary studies were carried out by: (i) extracting text portions from the studies concerning limitations and planned future works, as described by the authors, and (ii) clustering them, if represented by ≥ 3 primary studies, in the comprehensive groups described next in descending order.

The most represented gaps were related to **supported data-parallelism** and expressed by the following needs:

- Support for describing data-parallelism, by providing annotations (P1097), by modelling (P140), or by programming (P268, P852, and P2023);
- Support for structured (P479), complex (P545), or user-defined (P498) data-types;
- Support for a broader set of data-parallel primitives (P608);
- Support for multi-dimensional arrays (P608);
- Support for irregular data structures (P07, P364);
- Support for data-parallelism at compilation level (P460);
- Support for data-parallel garbage collection (P633).

The second cluster of gaps was related to **supported target hardware platforms** and expressed as follows:

- Support for targeting multiple hardware platforms (P1288, P1351, P608, P268, P968, and P1752);

- Support for multi-GPU execution (P408, P2055, P1291, and P1700);
- Support for heterogeneous target platforms (P1717);
- Support for clusters of multi-cores (P1412).

The third cluster was related to **improvement of language and related tooling** and expressed as follows:

- Improvement of the specification and implementation of the language (P1632, P1804, P415, P2055, P480, and P768);
- Improvement of the provided compiler (P90, P1944, and P360);
- Extension of the language to implement full-blown OS running on bare hardware (P72);
- Support for external parallel libraries (P2120);
- Support for runtime execution (P444).

The fourth cluster was related to **provided analyses and optimisations** and expressed as follows:

- Enlargement of the set of provided program analyses, both static and dynamic, and optimisations (P05, P07, P1912, P1940, P968, and P1944);
- Support for advanced memory optimisations (such as usage of fast local memory on GPUs from high-level API in P1700, low-level memory access patterns in P02);
- Support for timing efficiency, through analysis and optimisation (P1923);
- Improvement of currently provided analyses (P846);
- Support for analysing how work-stealing affects energy consumption in power-critical mobile devices (P1097);
- Data-sharing optimisation to minimise overheads (P993).

The fifth cluster regarded the **evaluation** of the language and related tooling and was expressed as follows:

- Need of real-world evaluation (P1695, P805, P846, P980, and P1511);
- Need of scalability proof (P1738, P930, P1511, and P116);
- Need of performance proof (P498);

The sixth cluster concerned **schedulability** issues and was expressed as the need for improvement of scheduling policies (P1940, P446, P1752, and P443), also with support for priority schedulers (P1752). Improvement of **performance** in general (P1442, P2055, and P1291) and communication performance in particular (P114) as well as improvement of **portability** (P930, P116, and P1304) constitute the last two clusters.

Besides the clustered ones, there are a number of other gaps that are worth mentioning, as follows:

- Support for automatic generation of target configuration (P140, P1041), also exploit machine learning for predicting, for a given combination of application and hardware, the best way to execute the application (P1700);
- Enlargement of communication model (P52, P736);
- Trade-off between compatibility with existing compilers and performance gains (P1011, P1636);
- Improvement of usability (P2055);
- Support for interactive handling of exceptions (P1172);
- Support for both dynamic and static (at compile-time) concurrency (P1910).

Highlights – RQ3 Limitations

- Support for data-parallelism seems to be the most wished feature of existing parallel languages;
- Support for multiple hardware platforms (also heterogeneously mixed) is a longed feature too;
- In general, languages and related tooling are in most cases at a prototypical level;
- More support, especially automated, for analysis and optimisation is a common envisioned enhancement;
- There is an evident need of evaluation in real-world settings, especially to assess scalability and performance of languages for large-scale applications.

4 RESULTS: ORTHOGONAL ANALYSIS

In this section, we discuss interesting relations across categories of the extraction data. To do so, we cross-tabulated and grouped extracted data as well as we made comparisons between *pairs* of categories of the data extraction form. Through contingency tables (not included in the text for space reasons), we extracted and evaluated relevant pair-wise relations.

4.1 Problem Decomposition Vs. Parallel Primitives

Most languages offering explicit parallel primitives focus on task-parallelism (115/147). Such a high number of languages supporting explicit task-parallelism is motivated by the great expressive power offered to programmers, i.e., complete control over the parallel choreography; this comes with potential risks related to explicitly describing how tasks shall be synchronised though. In addition, introducing support for task-parallelism using explicit primitives represents a relatively simple solution for extending existing sequential languages. Explicit primitives and data-parallelism represent the second most common combination, although with much fewer occurrences (73/147). Despite being expectedly less frequent than explicit primitives, as seen in the vertical analysis (Figure 6(b)), implicit primitives in combination problem decomposition produces an interesting result. Indeed, the tendency to prefer task-parallelism (61%) rather than data-parallelism (39%) for explicit primitives is inverted when it comes to implicit primitives, where data-parallelism (55%) is slightly more common than task-parallelism (45%). Few languages support pipeline parallelism and code parallelism. Among these, the majority provides explicit primitives. It is interesting to notice that no language supporting nested parallelism provides implicit primitives.

4.2 Communication Model Vs. Memory Model

As seen in the vertical analysis (Figure 11(a)), shared-memory represents the most common communication model; the majority of languages combine this model with the shared memory model (89/105). However, it is interesting to notice that a fair number of languages also combine shared-memory communication model with distributed memory (31/105). Message-passing is the second most common communication model, but its combination with memory models provides inverted results. Most languages featuring message-passing target indeed the distributed memory model (66/99), with shared memory coming right after (41/99). Stack-based memory model is also moderately diffused in combination with shared memory (8/21) and message passing (13/21) communication models. Finally, languages adopting data flow communication tend to prefer the distributed (16/31) and shared memory (10/31) models, with a slight preference for the first.

4.3 Communication and Memory Models Vs. Target Architecture

Shared memory and message passing communication models are the most popular choices among languages targeting multi-core CPU (52/98 and 41/98, respectively). These two communication models are used a lot with many-core CPU architectures too (32/52 and 30/52, respectively). This applies even to target-independent languages (29/70 and 37/70 entries). Shared memory appears

to be the most convenient medium of communication for various accelerator architectures such as DSA, GPU, GPGPU, and FPGA than message passing or data flow. Nevertheless, the presence of data flow communication in all target architectures (including target-independent), even though with a lower number of occurrences than shared memory or message passing communication model, shows its importance as communication model.

The relation between memory model and target architecture is rather symmetric to the one between communication model and target architecture. More specifically, shared and distributed memory models are the most popular choices in languages targeting multi-core CPU (59/98 and 48/98, respectively). A similar distribution applies to languages targeting many-core CPU (31/52 and 30/52, respectively) and target-independent languages (34/70 and 29/70, respectively). As for the shared memory communication model, the shared memory model is the most common choice for accelerator architectures such as DSA, GPU, GPGPU, and FPGA.

5 OPEN CHALLENGES AND PROSPECTS

From our vertical analysis (RQ2), it appeared that languages for parallel computing are in most cases high-level and general-purpose. This is understandable since the first ensures an acceptable abstraction level for the programmer to be able to express his functions without the need to handle machine-specific details. The second makes those languages usable in multiple application domains and for multiple purposes. Nevertheless, since parallel and heterogeneous hardware is getting evermore common in fields where experts do not necessarily have a background in parallel programming (e.g., health, biology), we believe that research should direct more attention toward the definition of languages at **higher-levels of abstraction** (i.e., modelling languages). Moreover, mechanisms for specialising (and thereby shrinking) general-purpose languages to **domain-specific variants** of it would be helpful too, since they would allow domain-specific analyses and optimisations as well as require a less steep learning/training curve.

Most parallel languages provide explicit means to describe parallel computations. On the one hand, this allows experienced programmers to make fine-grained optimisations and provide very efficient parallel algorithms; on the other hand, this makes parallel languages hard to use for the less experienced users. To make parallel programming more accessible to those without parallel programming skills, it would be useful to carry out more research in the provision of **implicit parallelism**, not necessarily as a mutually exclusive alternative to explicit parallel primitives but also in combination. Efficient ways to provide data parallelism is regarded as the most wished feature for existing languages (RQ4); there is definitely space for contributing to the body of knowledge and state of the practice by focusing on **implicit data parallelism**.

Through our analysis (RQ2), we got a confirmation that multi- and many-core CPUs represent the most commonly targeted architectures. Although already growing in number of related publications, there is still space for significant contributions and advances in languages for other architectures, especially FPGAs and GPUs, and even more for languages **targeting multiple architectures**, even in combination. The latter is in fact one of the most commonly mentioned longed feature in the analysed studies (RQ4).

In the definition of new languages, we tend to believe that **a balanced mix of concepts from object-oriented and functional programming** could provide a fruitful combination of ingredients for achieving both explicit and implicit parallelism. Moreover, it would allow to push up the level of abstraction, thus making those languages more accessible and less dependent on the target architectures; multiple levels of refinement (e.g., through modelling), could permit to separate functional aspects from allocation, configuration and deployment ones [2]. In addition, we believe that **blending notations** [58] for stakeholders to interact with high-level (modelling) languages in a flexible and personalised manner has the potential to boost the usage and productivity of these

languages [1], thus making a broader set of stakeholders keen on using them, even for multiple purposes—not only programming, but also design and communication across design and developing teams. For instance, while textual notations could be used for algorithmic parts, graphical ones could be employed to model the target architecture and possibly the allocation of functional items to it; this would be particularly useful in case of complex heterogeneous architectures.

As expected, languages and supporting tools are in most cases at a prototypical level. This is a typical issue of academic research where industrial actors are not involved enough to give a hand in taking results a step (or in most cases several steps) further and to reach industrial grade. We believe that, together with classic networks of researchers and practitioners (e.g., HIPEAC[5]), the growing industrial consortia (e.g., Capella[6] and INCOSE[7] in systems engineering), which in the last few years have increasingly focused on open-source solutions, should be leveraged more by academics in this area as a precious vehicle for pushing research results to new heights and to reach a broader audience.

6 THREATS TO VALIDITY

There are two aspects that make us confident on the quality of our study. The first one is that we defined and meticulously followed a detailed research protocol document, which was subject to external reviews by independent researchers. The second one is that we conducted our study by following well-established guidelines for systematic studies. In any case, it is important to discuss the potential threats to the validity of our work and its outcomes, as well as the means undertaken to mitigate them.

6.1 External Validity

External validity refers to the generalisability of causal findings with respect to the desired population and settings [254]. In a systematic review, one of the most severe threats is that the selected set of primary studies is not representative of the state of the art on languages for parallel computing. This potential threat to validity is mitigated by targeting multiple data sources, i.e., ACM Digital Library, IEEE Xplore, Scopus, and Web of Science. The used data sources cover the area of software engineering well [41] and are five of the largest and most complete scientific databases and indexing systems in software engineering. Moreover, we further complement the results of the automatic searches by performing closed recursive backward and forward snowballing.

Only studies published in the English language were included. Although, this decision could result in a possible threat to validity due to potentially missing primary studies published in other languages, English is the de-facto standard language for scientific papers, so the threat can be reasonably considered negligible.

6.2 Internal Validity

Internal validity refers to extraneous variables and inaccurate settings that may have had a negative impact on the design of the study [254]. We mitigated this potential threat by defining meticulously the process to follow and the data extraction form according to well-established guidelines. Concerning the validity of the data analysis and synthesis, threats were minimal since we used descriptive statistics. Moreover, we cross-analysed the different categories of the data extraction form to make a sanity check of the extracted data. This task made us identify and solve potential

[5] https://www.hipeac.net/.
[6] https://www.eclipse.org/capella/.
[7] https://www.incose.org/.

issues on the consistency of the extracted data and make us confident of the internal validity of our study.

6.3 Construct Validity

Construct validity refers to the extent to which an identified causal relationship can be generalised from the particular methods and operations of a specific study to the theoretical constructs and processes they were meant to represent [254]. As already argued for external validity, the initial automated search has been performed on four different data sources and complemented with snowballing. One remaining potential threat to validity may be caused by a malformed search string. We mitigated this potential threat by (i) following a rigorous process for defining it and (ii) piloting the search string in preliminary queries using all four data sources. Once we gathered all relevant studies from the automatic search, we rigorously screened them in a collaborative fashion and according to well-documented inclusion and exclusion criteria. Moreover, the selection team members classified a certain number of common studies (~15%) in order to check agreement, achieving a Cohen's kappa [28] of **0.87** (almost perfect agreement according to Cohen's suggested interpretation).

6.4 Conclusion Validity

This refers to the relationship between extracted data and obtained findings [254]. We mitigated potential threats by systematically applying and documenting well-defined processes; we also provide a publicly accessible replication package,[8] which allows to replicate each step of our study. The data extraction form definition can be a notable threat to conclusion validity if based on own experience or other informal sources. We mitigated this by (i) letting the categories and their values emerge from the pilot studies and refining them throughout the entire data extraction activity, and (ii) making five researchers be actively involved in the definition of the form as well as the extraction and analysis/synthesis of data.

7 RELATED WORK

In the past few years, systematic literature reviews have gained considerable popularity in many research areas, in particular, software engineering [133]. In this article, we conduct a systematic literature review of programming and modeling languages for parallel computing platforms. This topic overlaps with the research areas of software engineering, computer science, and computer engineering. The research area targeted in this article is quite dispersed as there is a large body of research on programming and modelling languages for parallel computing platforms. This is indicated by 219 identified publications as shown in Figure 2 and discussed in Section 3.

There are very few systematic literature reviews, systematic mapping studies, and surveys of the state-of-the-art that discuss some aspects of parallel computing platforms. The most recent one is a survey on parallel programming models by Fang et al. [81], Brodtkorb et al. [44] conduct an investigation of the state-of-the-art in the area of heterogeneous computing. In this study, they limit the scope of their investigation by focusing on only three heterogeneous platforms, namely, the Cell Broadband Engine Architecture, GPU, and FPGA. Similar to the work in [44], Mittal and Vetter [170] present a survey of heterogeneous computing techniques, where they only consider CPU-GPU computing platform. Fernando et al. [82] perform a systematic mapping study to create a structured map of the existing research with respect to parallel computing in various execution platforms such as multi-core, cluster, and GPU. Similarly, Liu et al. [151] conduct a survey of

[8]The replication package is attached as extra files archive to this manuscript for review purposes and will be made public once the manuscript is in press.

software and hardware aspects of heterogeneous computing platforms. In this work, the authors focus only on a specific architecture, namely, the **Heterogeneous System Architecture** (**HSA**). However, these works do not investigate programming and modelling languages for the considered parallel computing platforms. In comparison to the above mentioned works, we conduct a systematic literature review of programming and modelling languages for generally a broad range of parallel computing platforms.

Andrade and Crnkovic [14] conduct a systematic mapping study of software architectures for heterogeneous computing platforms. The authors identify 28 publications of interest and using these they present various trends and identify gaps in the research area. Similarly, Andrade et al. [15] conduct a systematic mapping study that focuses on the deployment of software on heterogeneous computing platforms. In this study, the authors provide an overview of the research area with the aim at identifying and categorising the published research results according to a defined classification. Although the studies in [14, 15] focus on heterogeneous computing platforms, they do not consider programming and modelling languages. In comparison, this article presents a systematic literature review of programming and modelling languages for parallel computing while considering homogeneous as well as heterogeneous computing platforms.

There are a few works that study and survey the existing programming languages and programming models for multi-core and many-core computing platforms. For instance, Diaz et al. [75] present a survey of parallel and distributed programming models for multi-core and many-core processors. Soares et al. [143] present a systematic mapping study of parallel programming on multi-core platforms. However, their core focus is on the programming languages that are used in undergraduate education. Frank et al. [87] conduct a systematic literature review on parallelisation, modelling and performance prediction of applications that are run on multi-core and many-core processors. In this work, the authors identify and analyse 34 relevant publications that mainly focus on providing support for performance prediction of parallel applications on these parallel computing platforms. However, both these works focus only on homogeneous multi-core and many-core computing platforms. In comparison to these works, the systematic literature review conducted in our article identifies and analyses parallel programming and modeling languages for homogeneous as well as heterogeneous parallel computing platforms.

Kessler and Keller [129] review and analyse a few parallel computing models with respect to execution styles, type of parallelism (data and task parallelism), memory and communication models. Memeti et al. [166] perform a comparative evaluation of four parallel programming frameworks, namely OpenMP, OpenCL, OpenACC, and CUDA. The evaluation parameters considered in this study include programming productivity, performance, and energy. In comparison with these works, our study is comprehensive in the sense that it considers a wide range of programming and modelling languages, programming models, target hardware architectures (SISD, SIMD, MISD, and MIMD), communication and memory models, and parallel execution models.

Nestmann [174] performs a systematic literature review with the aim at identifying a taxonomy for parallel programming models. The authors identify five different taxonomies in the existing literature. Based on the identified taxonomies, the authors build a consolidated and consistent taxonomy for parallel programming models. Amaral et al. [11] conduct a systematic mapping study of programming languages for **High-performance Computing** (**HPC**) platforms. In this study, the authors identify 26 programming languages for the HPC platforms that are presented in 33 relevant publications. Although this work is closely related to the work presented in our article, there are a number of key differences between the two works. That is, Amaral et al. [11] present a systematic mapping study focusing on a large-scale cluster of computing nodes that are connected by networks. Furthermore, the heterogeneity in the parallel computing platforms is not explicitly addressed. On the other hand, we present a systematic literature review that considers

programming and modelling languages for a broad range of homogeneous and heterogeneous parallel computing platforms ranging from on-chip and on-board to large-scale cluster platforms.

To the best of our knowledge, the state-of-the-art is lacking a systematic literature review on programming and modelling languages for parallel computing platforms. There is an urgent need for constructing a structured map of the research area, analysing the existing works, and identifying various trends and gaps in the area. The work presented in this paper takes a major step in addressing these needs.

8 CONCLUSIONS AND FUTURE DIRECTIONS

In this article, we reported on the planning, execution, and results of a systematic literature review on languages for describing parallel software. From an initial set of 3,476 papers (3,469 from automatic searches plus seven pilot studies) and 72 languages, after a set of refinements, we selected 225 *primary* studies to represent the treated topic. We extracted data from them according to a thoroughly defined data extraction process; then, we analysed and synthesised the data. The result of this work was a comprehensive, structured, and detailed snapshot of the current landscape on languages for parallel computing, useful for both the more and the less experienced researcher or practitioner. Additionally, based on the study results and our own interpretation of the current and forthcoming trends in relevant application domains, we provided hints on challenges that remain open as well as on what we believe being some of the "hot" research directions to pursue in this research area. An interesting extension to this study could be a separate review of embedded/internal domain-specific languages for parallel computing, where the focus would be on aspects related to their design/implementation and the relation to the host languages. A retrospective on the host languages and the additional features brought by hosted languages could be then synthesised too. Moreover, another direction for extending this study could be represented by an in-depth analysis of the new challenges in HPC systems in terms of programming, such as those related to persistent memory.

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