

Collaborative Model-Driven Software Engineering: A Systematic Update

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Abstract—Current software engineering practices rely on highly heterogeneous and distributed teams working in a collaborative setting. Between 2013–2020, the publication output in the field of collaborative Model-Driven Software Engineering (MDSE) has significantly increased. However, the only systematic mapping study available is limited to studies published until 2015. In this paper, we provide an update on that study for the complementing 2016–2020 period, and report the latest results, challenges, and trends. Our analysis led to selecting 29 clusters of 54 new peer-reviewed publications on collaborative MDSE. Based on the novel developments in the field, we have extended and improved the original classification framework, making it applicable to recent and future research contributions on collaborative MDSE. The insights in this paper relate to the changing trends in the field and present new relevant information.

Index Terms—model-driven engineering, collaborative modeling, systematic mapping study, systematic update

I. INTRODUCTION

Current software engineering practices rely on highly heterogeneous and distributed teams, required to work together to deliver the software system correctly and efficiently. Thus, collaboration across team members, and often across multiple teams, is needed [1]. The combination of computer-aided collaboration, and model-driven software engineering (MDSE) presents its own benefits and challenges [2]–[4]. In the past decade, collaborative MDSE has become a prominent feature of today’s software engineering practice, e.g., in agile methodologies and low-code platforms [5]–[7].

The field of collaborative MDSE is rapidly expanding and maturing. The only comprehensive study in the field has been provided by Franzago et al. [8]¹, encompassing the 20-year period of 1996–2015. Considering the recent improvements in collaborative MDSE, however, we found that a systematic update of the study on the 5-year period of 2016–2020 will provide valuable insights. Apart from the intensive academic research, this period witnessed various editions of workshops on collaborative modeling [9] [10], a thematic special issue on the topic [4], and numerous international research and development projects, most notably [11]–[13].

In this paper, we report the results of our systematic update. By following the guidelines of Mendes et al. [14], we found 54 relevant new primary studies. On average, this accounts for 10 studies per year, twice as much as the 5 studies per year measured by the original study. Although these numbers

might already hint to a need for an update, we further motivate our work by a systematic qualitative assessment. Additionally, we have surveyed the field for secondary studies to enhance the classification framework of the original study. Eventually, three secondary studies were considered, out of which we retained [15], as it complemented the original classification with relevant information.

This update is strongly coupled with the original study. It takes assumptions from it, and follows its methodology [16]. Accordingly, the goals of this paper are aligned with those of the original study: to identify, classify, and understand collaborative MDSE approaches that have emerged since the original study, i.e., between 2016–2020. An additional goal of this update is to enhance the classification framework of the original study, in response to the developments in the field. Our research is not limited to tools or technological stakeholders. Instead, we approach the research questions from a holistic standpoint. However, we restrict our investigation to approaches which are (i) model-driven (or at least model-based); (ii) consider a meaningful set of collaborating stakeholders; and (iii) provide appropriate means of communication.

There are two kinds of information reported in this paper. First, we reflect on the takeaways and trends of the original study, and report any changes from the 2016–2020 period. Second, we identify new trends based on the newly sampled papers, and the newly introduced classification categories.

II. RELATED WORK

The only systematic review on collaborative MDSE is the original study of this update by Franzago et al. [8]. They rigorously reviewed and analyzed 48 primary studies collected until mid-2015. In this systematic mapping study, they elaborated a classification framework along three main dimensions. *Model management* is the dimension to manage the life cycle of models in a collaborative setting through, for example, repositories to persist models, modeling tools to manipulate models, and interchange formats to share models across stakeholders. *Collaboration* is the means for stakeholders to collectively work on models and coordinate themselves with, for example, versioning systems, conflict management systems, model comparison engines, and development and managerial processes. *Communication* ensures that stakeholders of each other’s work and can exchange and interact with one another by, for example, sharing design decisions, tracking discussions, and notifying changes. The mapping study details a taxonomy

¹Referred as the *original study* in the remainder of the paper.

for each dimension from which they draw various conclusions on the topic of collaborative MDSE. In this paper, we update the original study with numerous papers that have appeared since then. Methodologically, we meticulously follow their protocol, but also update the classification framework with new characteristics that have appeared since then.

While retrieving publications for this update, we identified three secondary studies related to collaborative MDSE. Masson et al. [15] performed a feature analysis of over 10 collaborative modeling tools. They discuss various features already supported by existing tools and identify unavailable, yet desirable, collaborative features. Since their study is well-aligned with our scope, we have included the relevant characteristics in our classification framework. Stephan [17] reports temporal trends of keywords in 103 collaborative MDSE papers between 2012–2017. Although this information is not sufficient to incorporate in our study, we confirm that all the top keywords found appear in our data extraction form. Ertugrul and Demirors [18] analyzed three role-based collaborative business process modeling approaches. Their work is specific to process modeling which is a narrower scope than the one we are concerned with in this paper.

Many modeling tools have recently shifted to support different forms of collaboration. Just to name a few, AToMPM [19] provides a purely in-browser interface for multi-paradigm modeling activities. WebGME [20] also supports web-based collaboration where users can work on the same model thanks to a branching scheme similar to Git. MetaEdit+ [P13] has also released a collaborative environment that incorporates Git to provide offline collaboration. GenMyModel [21] provides an in-browser client to model collaboratively with various model management utilities. OBEO Designer [22] also enables collaborative modeling within Eclipse with a locking mechanism.

III. ASSESSING THE NEED FOR AN UPDATE

Mendes et al. [14] report that many systematic studies are potentially outdated; thus affecting the aggregated understanding of the state-of-the-art through those systematic studies. In order to facilitate a factual decision whether an update of a study is required, they provide a systematic assessment framework. In this section, we apply the framework to our case, and report the results of the assessment.

The framework defines a three-step decision process. In the first step, we must assess if the original study is still of current interest by answering three specific questions. If we can answer positively to all three questions, then we can proceed to the second step. Here, we identify if new relevant methods, studies or information are available with respect to the topic of the original study by answering two specific questions. If at least one is answered positively, we can proceed to the third step. There, we assess if updating the review has an effect on the findings, conclusion or credibility of the original study by answering two specific questions. If at least one is answered partially positively, the original study is deemed as a good candidate for an update. The remainder of

this section demonstrates with quantitative evidence that there is a clear need to update the original study [8].

A. Assessing the currency of the original study

1) *Does the original study still address the current question?*: Since the publication of the original study, three editions of a workshop on collaborative modeling [9] have been organized between 2016–2018. A special issue on collaborative MDSE has been published in the IEEE Software journal in 2018 [4]. A recent article [23] firmly places collaborative modeling as one of the future grand challenges in MDSE. Another recent article [1] establishes that collaborative features will retain their prominent role in modeling environments in the future. Therefore, we confirm that collaborative MDSE is still a current mainstream topic in the community.

2) *Has the original study had good access or use?*: Mendes et al. suggest that a secondary study should be cited at least 6 times per year to be considered for an update. This is based on [24], where the authors report that software engineering papers are cited on average of 6.82 times per year ($n = 71\ 668$). At the time of writing, the original study has accumulated 47 citations over the 2-year period since its publication, resulting in 23.5 citations per year. This ranks the original study in the top third of the list of studies investigated by Mendes et al. Furthermore, the original study is currently the highest-cited publication by the search term “*collaborative model-driven*” in all major scientific databases. Therefore, we confirm that the original study has had a good access and use.

3) *Has the original study used valid methods and was well conducted?*: The original study rigorously followed the guidelines to conduct systematic mapping studies [25], [26], and scored above average, at 61.5%, in the quality checklist of Petersen et al. [27]. Therefore, we confirm that the methods of the original study are well-constructed and executed.

B. Relevant new methods, studies and other information

1) *Are there any new relevant methods?*: As outlined in Section II, new studies have been published since the publication of the original study. In particular, the work of Masson et al. [15] has a relevant classification method complementary to the original one. The authors provide a feature model for collaborative modeling environments, focusing on the implementation details of such systems. The feature model could serve as an aid for extending and updating the classification framework of the original study.

2) *Are there any new studies, or new information?*: We have evaluated the search string of the original study² over the time range the study has focused on (1996–2015), and over the time range since then (2016–2020). The search string yields 17 300 hits for the original 20-year range and nearly as much, 16 800 hits, for the 5-year range of 2016–2020. This is a substantial increment in annual publications by a factor

²(collaborat* OR coordinat* OR cooperat* OR concur* OR global) AND (MDE OR MDD OR MDA OR MDS* OR EMF OR DSL OR DSML OR "model driven" OR "eclipse modeling framework" OR "domain specific language" OR "domain specific modeling language")

of 3.88. As this study update shows, a significant amount of work has been dedicated to collaborative modeling following the publication date of the original study.

C. Assessing the effect of the update

1) *Will the adoption of new methods change the findings/conclusions or credibility?*: The adoption of the feature model of [15] alone could improve at least the credibility of the findings, as it provides a complementary technical set of information to the original study. Other studies might be encountered during the search phase that could further influence the findings and conclusions.

2) *Will the inclusion of new studies/information/data change the findings/conclusions or credibility?*: Multiple papers on advanced collaborative techniques have been published since the publication of the original study. Typical topics include property-based locking [28], semantic inconsistency management [29], and other advanced techniques [P01]. Therefore, we are confident that the inclusion of new studies will most probably update and extend the classification framework drawn in the original study.

Given the positive answers above, we deem it justified and required to update the original study. As a rule of thumb, Mendes et al. [14] suggest that the maturation time between the publication of the original study and its update should be longer than two years. In our case, this time is 5 years.

IV. STUDY DESIGN

Our study was carried out in accordance with well-established guidelines in the realm of empirical software engineering [26], systematic mapping studies [27], and updates of systematic literature studies [30], [31]. For the sake of consistency, we keep the design of this study aligned with the one of the original study as much as possible. (For example, by using the same research questions, same selection criteria, etc.) In the following, we give an overview of the design of this study, emphasizing its variation points with respect to the original one. Further details about the common parts can be found in the original study. A complete *replication package* is publicly available [32] for independent replication and verification of our study. The replication package includes the raw data of our search and selection phase, the list of selected primary studies, the raw data extracted from each primary study, the R scripts for data exploration and analysis, and the list of changes in the classification framework.

A. Goal and Research questions

We formulate the goal of this study using the Goal-Question-Metric perspectives [33]. The purpose of this study is to identify, classify, and understand issues related to the characteristics, challenges, and publication trends of existing collaborative MDSE approaches, in the period between 2016–2020, and that, from a researcher’s point of view.

We use the same research questions as the original study.

RQ1: *What are the characteristics of collaborative MDSE approaches?*

RQ2: *What are the challenges and shortcomings of existing collaborative MDSE approaches?*

RQ3: *What are the publication trends that can be deduced from the scientific publications about collaborative MDSE approaches over time?*

By answering these research questions we provide an *up-to-date map* that classifies recent approaches for collaborative MDSE with respect to: (i) their model management, collaboration, and communication characteristics; (ii) their limitations, faced challenges, and future work; and (iii) publication trends such as publication year, and targeted scientific venues. Our map allows current and prospective researchers to understand the evolution of this research field in the past years, thus allowing the scientific community to better reason about research interests, and unexplored research directions. Fig. 1 outlines the process and main phases of this study.

B. Search and selection

The success of a systematic study strongly depends on the retrieval of the relevant primary studies that are representative enough of the topic being considered [25]. As recommended in the guidelines for updating a systematic literature study by Wohlin et al. [30], we have based our search strategy entirely on forward snowballing, starting from (i) the set of primary studies of the original study, and (ii) the original study itself. Although the authors suggest one iteration is sufficient for mapping the increment of the state of the art, we have opted for a fully recursive forward snowballing to improve the quality of the search. In accordance with [30], we relied on Google Scholar as the source of retrieval. Google Scholar is considered a comprehensive academic search engine [34], and adequate for updates of systematic literature studies [30].

As shown in Table I, in the first iteration of snowballing, we obtained a total of 631 potentially relevant studies. For each study, we have applied a set of selection criteria. If a paper was included, snowballing was applied iteratively on it. The procedure eventually concluded after three iterations. By this phase, we analysed a total of 886 potentially relevant studies.

TABLE I: Statistics of the snowballing rounds

Snowballing	All	Excluded	Included
1st round	631	592	39 (6.18%)
2nd round	228	214	14 (6.14%)
3rd round	27	26	1 (3.70%)
Total	886	832	54 (6.09%)

The selection criteria are identical to the ones of the original study. We included studies that propose an MDSE approach for supporting the collaborative work of multiple stakeholders. The study has to cover the three complementary dimensions of model management, collaboration, and communication. The primary artifacts within the collaboration process must be models. The studies should provide either validation or evaluation. We only considered studies written in English, available in full-text and subject to peer-review. We excluded studies that discuss only business processes and collaboration

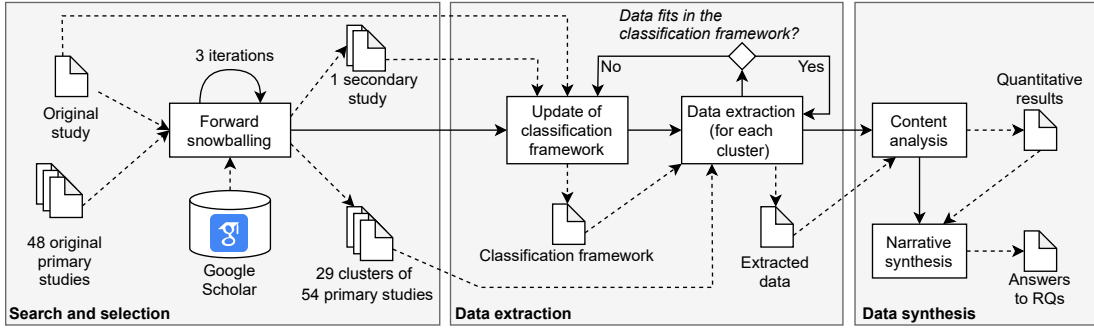


Fig. 1: The process of updating the systematic mapping study

practices, without proposing a specific method or technique. Secondary studies and other forms (e.g., tutorials, extended abstracts, posters, editorials) were also excluded.

We used ReLiS [35] to perform the iterative screening of the studies among three researchers. Each of the 886 studies were screened by two researchers independently. For each potentially relevant study, we applied an *adaptive reading depth* [27], [36]. The resulting 0.86 Cohen’s kappa indicates a nearly perfect agreement among the researchers. This makes us reasonably confident about the objectivity of our selection phase. Among the 886 studies, only 69 conflicts (7.7%) have emerged. We resolved each conflict by including the third researcher, and engaging in a hands-on discussion and collective decision making exercise. We have anticipated the first iteration having the most impact on the eventual set of included papers, and therefore, at the end of the first iteration, a fourth researcher validated all included studies, and 20% of the excluded ones. Eventually, we included 54 primary studies.

Consistent with the original study, we clustered the included studies in order to group the papers pertaining to the same approach. (For example, a conference paper extended into a journal version.) In accordance with [26], usually it was the most recent journal version of each cluster that was selected to represent the cluster during the investigation of RQ1 and RQ2. In the analysis of RQ3 (publication trends), however, we used each study separately. In the end, we grouped the 54 primary studies into a total of 29 clusters. For independent verification, the raw data related to each phase of our search and selection process is available in the replication package.

C. Data extraction

The goal of this phase is to extract data from each primary study to properly answer our research questions. Following the guidelines [14], we built on the data extraction procedure from the protocol of the original study. Specifically, we started from the same classification framework of the original study. Then, in order to accommodate the recent developments in collaborative MDSE, we updated the classification framework based on the secondary studies we have identified during snowballing. The only relevant secondary study was the feature model of collaborative modeling tools by Masson et al. [15]. Eventually, we included 11 new categories (one in the model management dimension, 9 in the collaboration dimension, and one in the

communication dimension), and updated 7 categories of the original study by extending and aligning their parameters with the ones defined in [15]. Three researchers extracted all the data from the primary studies according to the updated classification framework; and all the data from the primary studies of the original study for the newly defined categories. A fourth researcher validated all the extracted data and solved conflicts or doubts as they emerged. For independent verification, the complete classification framework and the extracted data are available in the replication package of this study. The resulting classification framework is shown contextually to the results of this study in Sections V, VI, and VII.

D. Data synthesis

In this phase, we extracted and reported the main findings emerging from the classification framework. We performed a combination of *content analysis* and *narrative synthesis* [37]. Content analysis relies on the quantitative assessment of the extracted data (e.g., the frequency of web-based vs. desktop-based modeling editors), while narrative synthesis refers to the systematic method where a textual narrative summary is adopted to explain the quantitative information emerging from the content analysis and identifying emerging patterns and trends [37]–[39]. All authors collectively carried out this phase via a series of dedicated group sessions. We grouped the results of our data synthesis according to the research questions. These are reported in the following section. Furthermore, similarly to the original study, we used contingency tables to find new orthogonal insights which span multiple categories. The orthogonal findings are reported in Section VIII.

V. CHARACTERISTICS (RQ1)

In this section, we report the results of our study, with respect to the three dimensions of collaborative MDSE: model management, communication, and collaboration.

A. Model management

The model management dimension is responsible for managing the lifecycle of models, including their creation, manipulation, and storage. Table II lists the categories of the extended classification framework, the frequency of their values in the original study, the frequency of their values in this update, and an indication of the difference between the two studies. For

TABLE II: Support for Model Management

Supported modeling artifacts			
Value	Original (2003–2015)	Update (2016–2020)	Δ
Model	48 (100%)	29 (100%)	→
Metamodel	4 (8.3%)	9 (31.03%)	↑
Meta-metamodel	-	1 (3.45%)	↗
Language independence			
Independent	21 (43.75%)	24 (82.75%)	↑
Specific	27 (56.25%)	5 (17.24%)	↓
Validation			
Supported	15 (31.25%)	15 (51.7%)	↑
Editor type			
Graphical	38 (79.16%)	18 (62.07%)	↓
Textual	5 (10.41%)	6 (20.69%)	↑
Tabular	2 (4.16%)	5 (17.24%)	↑
Tree-based	14 (29.16%)	4 (13.79%)	↓
Sketch-based	7 (14.58%)	1 (3.45%)	↓
External	6 (12.5%)	1 (3.45%)	↓
Modeling framework – New category.			
Custom	40 (83.33%)	21 (72.41%)	↓
EMF	8 (16.67%)	8 (27.58%)	↑
Client type			
Desktop	31 (64.58%)	15 (51.72%)	↓
Web	18 (37.5%)	14 (48.28%)	↑
Mobile	-	4 (13.79%)	↑
Multi-view scenarios – New category.			
Multi-user single-view	38 (79.17%)	19 (65.52%)	↓
Multi-view single-model	7 (14.58%)	5 (17.24%)	↗
Multi-view multi-model	3 (6.25%)	5 (17.24%)	↑
Single-view multi-model	-	1 (3.45%)	↗
Multi-View support			
Synthetic	6 (12.5%)	5 (17.24%)	↗
Projective	8 (16.67%)	5 (17.24%)	↗

↑ Increase ↗ Slight increase → No change ↘ Slight decrease ↓ Decrease

the new categories, we manually extracted the corresponding data from the corpus of the original studies (blue); for the previously existing categories, we use the data from the original study (red).

The focus of collaboration in terms of the *supported modeling artifacts* has shifted in 2016–2020 towards the: metamodel (9 occurrences) and meta-metamodel (1) level. With this shift, collaborative techniques have become more *language independent* as well. The ratio of language-independent techniques has nearly doubled, from 43.75% to 82.75%. *Validation* has become a more integral part of collaborative frameworks. More than half of the sampled approaches support the user with some form of validation, showing an increase from 31.25% to 51.7% since the original study. The lack of validation can significantly hinder collaboration, especially at higher levels of abstraction [40]. The increased support for validation, therefore, could be a result of the increased number of tools supporting collaborations at higher meta-levels.

The most notable changes in *editor types* are the decrease in use of graphical editors (from 79.16% to 62.07%), and the increased number of textual (from 10.41% to 20.69%) and tabular editors (from 4.16% to 17.24%). The vast majority of approaches, more than 70%, use their own custom *modeling frameworks*. For example, authors used a custom framework in [P13] to combine multi-user modeling with any external version control system without performing any merging or

locking. The most widely used generic modeling framework, EMF [41] has improved its support from 16.67% to over 27%.

We observed relevant changes in the *type of client software* for collaborative modeling. The ratio of desktop clients has decreased (from 64.58% to 51.72%) in favor of frameworks that provide either web (48.28%) or mobile client interfaces (13.79%). This shift highlights how users are becoming more mobile, and modeling is becoming less resource-intensive. For instance, [P26] presents a tool that facilitates the creation and use of graphical DSLs on mobile devices; the mobile-based editor was applied in a case study on wind turbines control applications development where the modeling activities were performed on-site in a wind farm.

Regarding the *multi-view scenarios* in collaborative approaches, the majority, nearly two third of the approaches operate in a multi-user single-view fashion [42], while true multi-view scenarios are supported only by a third of the frameworks. Nevertheless, multi-view approaches still have become more widespread overall. While only 20.83% of the approaches in the original study support multiple views, this has increased to 34.48% between 2016–2020, especially due to the strong increase in the ratio of multi-view multi-model techniques [43]. There is no real change in the trend of the ratio of synthetic (views built with different concrete syntaxes) and projective (views built with same concrete syntaxes) approaches [43] for multi-view support.

B. Collaboration

Collaboration features are responsible for enabling an effective and efficient groupwork across the involved stakeholders. Typical means of collaboration in MDSE include versioning systems with merging and branching support, consistency management mechanisms and conflict resolution algorithms.

As shown in Table III, real-time collaboration ("synchronous", in the original study) is becoming increasingly popular as compared to off-line ("asynchronous", in the original study) *types of collaboration*. This could be the result of the increased use of web- and mobile clients, which align well with real-time principles, such as in the case of [P05], [P18] and [P22]. There is noticeable decrease in the ratio of approaches that operate over strictly *prescribed workflows* (from 89.58% to 51.72%). This means collaboration becoming less sequential, and featuring less distinctively defined roles. The three typical *consistency models* are still the strong, the eventual, and strong eventual models. Strong consistency ensures the identical state of distributed nodes, but due to its underlying mechanisms, it significantly hinders the scalability and user experience of collaborative modeling tools [44]. Eventual consistency provides the weaker guarantee that changes will be eventually observed across each node [45]. Strong eventual consistency combines the benefits of both models and, consequently, it is very suitable for underpinning collaborative applications [46]. We see a prominent decrease in the popularity of strong consistency, changing from 56.25% to 34.48%; while the strong eventual model is gaining popularity. Over 27% of approaches support strong eventual consistency,

TABLE III: Support for Collaboration

Collaboration types – The parameters of this category have been renamed.

Value	Original (2003–2015)	Update (2016–2020)	Δ
Real-time	28 (58.33%)	19 (65.52%)	↑
Off-line	24 (50.00%)	12 (41.37%)	↓

Prescribed workflow

Supported	43 (89.58%)	15 (51.72%)	↓
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Consistency model – New category.

Eventual	17 (35.42%)	11 (37.93%)	↗
Strong	27 (56.25%)	10 (34.48%)	↓
Strong eventual	3 (6.25%)	8 (27.59%)	↗

Conflict management approach

Allow & Resolve	27 (56.25%)	11 (37.93%)	↓
Preventive	12 (25.00%)	8 (27.59%)	↗

Conflict awareness (user) – New category.

Warning	11 (22.92%)	21 (72.41%)	↑
Prompt action	3 (6.25%)	2 (6.9%)	→

Locking – The parameters of this category have been renamed.

No support	35 (72.92%)	22 (75.86%)	↗
Pessimistic	12 (25.00%)	5 (17.24%)	↓
Optimistic	1 (2.08%)	2 (6.9%)	↗

Conflict resolution type

(Semi)automated	10 (20.83%)	13 (44.83%)	↑
Manual	17 (35.42%)	8 (27.59%)	↓

Diff/merge domain – New category.

Syntactic	46 (95.83%)	22 (75.86%)	↓
Semantic	2 (4.17%)	5 (17.24%)	↑

Versioning – The parameters of this category have been renamed.

External: generic VCS	4 (8.33%)	4 (13.79%)	↑
Internal	9 (18.75%)	3 (10.34%)	↓
External: model-driven	5 (10.42%)	3 (10.34%)	→

Network architecture – The parameters of this category have been restructured.

Centralized single server	40 (83.33%)	19 (65.52%)	↓
Centralized multiple srvrs	3 (6.25%)	6 (20.69%)	↑
Mixed	3 (6.25%)	3 (10.34%)	↗
P2P	2 (4.17%)	3 (10.34%)	↗

↑ Increase ↗ Slight increase → No change ↘ Slight decrease ↓ Decrease

a sharp increase from the previous 6.25%. For example, [P18] addresses collaborative conflicts on the data level by relying on conflict-free replicated datatypes [46].

Conflicts arise inevitably when several collaborators work in parallel, for instance, during merging of collaborative models. Similar to the benefits of finding problems earlier in the software development process, adopting preventive approaches to *manage conflicts* during collaboration activities saves the effort to be spent in resolving conflicts later in the modeling process. We see a slightly increasing trend (from 25% to 27.59%) for preventive conflict management approaches in the primary studies. Most of the preventive approaches warn the modelers beforehand (72.41%), when there are potential chances of conflicts. However, managing those conflicts is left up to the users. Only [P14], [P29] take a prompt action and eliminate the chances for conflict among the modeling artifacts. *Locking* mechanisms also prevent the conflicts during collaboration, where pessimistic locking allows only a single modeler to work on (part of) a model at once and optimistic locking gives modelers the freedom to decide for proceeding with an update at the time of commit [47]. A small number of primary studies supported locking mechanism, with pessimistic approaches (17.24%) superseding the optimistic one (6.9%). Though pessimistic approaches eliminate the chances of con-

flicts completely, optimistic approaches can be a better choice for maintaining efficiency of overall modeling process. The only change we observed since the original study, is the strong decrease in the reliance on pessimistic locks, with a change from 25% to 17.24%. The overall trend shows that locking-based collaborative techniques are getting less popular. Finally, if the conflicts are allowed, the modeling frameworks need to provide support means to *resolve these conflicts*. Compared to the original study, a good number of primary studies provide (semi-) automated support for resolution of conflicts, with an increase from 20.83% to 44.83%. Conflict resolution, and specifically, *diff/merge*, is mainly addressed on the syntactic level (75%). The support for semantic techniques, however, has increased from 4.17% to 17.24%. Especially in approaches emphasizing collaboration across disparate domains, semantic techniques (semantic conflict detection, resolution, *diff/merge*) are crucial. Examples include [P20] and [P24], [P25].

External generic *version control* systems, and especially Git, are the most common among the approaches providing *versioning* support. Approaches such as MetaEdit+ [P13] and MONDO [P06] directly address well-known industrial requirements by this choice. Internal versioning techniques have lost popularity, and their support has decreased from 18.75% to 10.34%. WebGME [P14] and Collaboro [P10] are examples of such approaches.

The ratio of centralized *network architectures* has slightly decreased overall. The detailed view of the centralized cases shows that it is the single-server model (e.g., [42], [P29]) that experienced a strong decrease, from 83.33% to 65.52%; while the centralization with multiple servers has strongly increased (e.g., [P06], [P19], [P26]), from 6.25% to 20.69%. A slight increase in P2P and mixed (P2P with centralization) architectures can be observed. Such distributed architectures require more intricate data-level consistency considerations, as demonstrated in [P18] (by conflict-free replicated datatypes), and [P08] (by blockchains).

C. Communication

Communication features are responsible for allowing a semantically rich exchange among the involved stakeholders, to augment the information carried by the models they collaborate over. Typical means of communication are chats, wikis, model annotations, comments, change proposals, and forums.

As shown in Table V, we observe a significant shift from synchronous to asynchronous *communication* support. Asynchronous communication has increased from 33% to 72%, as compared to the original study, while synchronous communication, has gotten less supported, strongly decreasing from 41.67% to 27.59%. This trend is somewhat counter-intuitive, considering the increased support for real-time collaboration and its good fit for synchronous communication. The categories *Client type*, *Collaboration type* and *Communication type* from Model management, Collaboration and Communication dimension respectively have strong ties together. Synchronous communication is always supported in real-time collaboration; and appeared more relevant for web-

TABLE IV: Support for Communication

Communication type – New category.

Value	Original (2003–2015)	Update (2016–2020)	Δ
Asynchronous	16 (33.33%)	21 (72.41%)	↑
Synchronous	20 (41.67%)	8 (27.59%)	↓
Built-in communication means (with at least 3 occurrences)			
Chat	18 (37.5%)	8 (27.59%)	↓
Comments	8 (16.67%)	5 (17.24%)	→
Call-for-attention	1 (2.08%)	5 (17.24%)	↑
Annotations	13 (27.08%)	3 (10.34%)	↓
Other	8 (16.67%)	8 (27.59%)	↑
Stakeholder types			
Technical	47 (97.92%)	28 (96.55%)	↘
Non-technical	7 (14.58%)	11 (37.93%)	↑
Workspace awareness score			
High	11 (22.91%)	11 (37.93%)	↑
Medium	8 (16.67%)	5 (17.24%)	→
Low	29 (60.41%)	13 (44.83%)	↓

↑ Increase ↗ Slight increase → No change ↘ Slight decrease ↓ Decrease

and mobile-based clients in our primary studies, as only [P16], [P21] provided synchronous communication for desktop-based clients.

Our primary studies include a variety of both built-in and external communications tools. *Built-in communication* is integrated into the collaborative MDSE approach [8]: chat, comments, call-for-attention and annotations were used more frequently (see Table IV). External communication is only prescribed by the collaborative MDSE approach: e-mails and face-to-face discussions were usually preferred for external communication. We observe that, despite being of cardinal importance, the use of external communication tools is either not discussed or only mentioned very implicitly. For instance, [P27] states that the moderator invites the collaborators but does not mention how this invitation is sent. Similarly [P24] does not explain how the document is forwarded (and notified) to next reviewer during sequential collaboration.

Collaboration support for non-technical *stakeholders* has increased in the last years. This might be an indication that there is an increasing trend of having tight collaborations between technical (e.g., engineers and developers) and non-technical stakeholders (e.g., business analyst, domain expert). Most of the approaches are dedicated to specific stakeholders, mainly involving developers, designers, users, modelers, and business stakeholders. We did not find approaches designed for non-technical stakeholders only; this is in line with the scope of the study (i.e., collaborative MDSE approaches for performing software engineering activities), which requires some level of technical proficiency at least for part of the team of collaborators. Interestingly, [P16] included a chatbot as a stakeholder, showing the integration of automated conversation in collaborative modeling activities.

The original study suggested further research to enhance the support for updating stakeholders about each others' actions in a shared workspace, that is, to increase the *workspace awareness* among stakeholders. It is encouraging to report that we observed an increase in the proportion of studies with a high awareness level, which shows that researchers have taken up this line of research. Especially version control system

TABLE V: Recurring limitations

Cluster	Original (2003–2015)	Update (2016–2020)	Δ
1. Model management	1	27	↑
2. Evaluation	0	25	↑
3. Collaboration	30	23	↓
4. NFP	13	11	↘
5. Tool improvement	4	5	↗
6. Communication	6	3	↘
Total	63	97	↑

↑ Increase ↗ Slight increase → No change ↘ Slight decrease ↓ Decrease

based mechanisms (e.g., in [P03] and [P06]), and real-time model updates (e.g., in [P22], [P28]) are common.

VI. CHALLENGES AND SHORTCOMINGS (RQ2)

In this section, we report the results of our update regarding RQ2, i.e., the challenges and shortcomings of collaborative MDSE approaches researchers are facing and have either identified them as actual limitations or suggested addressing the shortcoming as a future work. For each primary study, we have collected the limitations and future works by a thorough analysis of the full text, and applied a card sorting technique [48] to cluster this information.

We have extracted a total number of 97 unique shortcomings from the 29 studies, an average of 3.34 per study. This number is nearly three times as much as the average number of shortcomings identified in the original study (63 limitations in 48 papers, 1.31 average). Plausible explanations to this phenomenon can be the overall better quality of publications in the update (studies appropriately detailing the shortcomings of the approach they describe); or the improved overall maturity of the field (improving publication standards and practices).

Five relevant clusters have emerged from the card sorting, four of them consisting of at least 11 studies, as shown in Table V. Three clusters are identical to the dimensions of collaborative MDSE: model management (with 27 unique limitations identified), collaboration (23), and communication (3); one cluster is related to non-functional properties (11); and one cluster is related to the lack or extensiveness of evaluation (25). The original study identifies the first four clusters. Evaluation-related shortcomings, however, are completely new, and emerged as the second most frequently encountered type of shortcomings.

Model management and collaboration are the most frequently encountered shortcomings related to the three dimensions of collaborative MDSE. The third dimension, communication draws significantly less attention, and shows a decreasing trend. Given the takeaways of Section V-C, we find it likely that communication support, as a dimension of collaborative MDSE, does not draw enough attention in general. Only [P10], [P16], and [P24] report communication-related shortcomings. Within *model management*, the low number of supported languages (e.g., [P10]), and their expressiveness (e.g., [P23]) is the leading limitation. The lack or restricted support for meta-modeling and multi-view modeling is the second most frequent limitation, e.g., in [P08] and [P28]. As discussed in Section V, the shift towards higher meta-levels has been noticeable during

the past five years and, as such, seeing the lack of meta-level support as a limitation might be justified.

In terms of *evaluation*, collaborative approaches have a systemic issue with, in some cases, the complete lack of proper evaluation. It is important to note, that these are self-declared limitations by the authors of primary studies. Typical examples include: evaluation being done on synthetic or academic examples (e.g., [P05], [P29]), and the size of the case being considered not representative (e.g., [P27]). Another recurring theme is the desire to test the prototype in more realistic settings, often labeled as “industrial” (e.g., [P14], [P15]) or “real” [P28].

Out of the limitations related to *collaboration*, conflict detection and automation of collaboration are the most relevant clusters. Some approaches completely ignore conflict detection and plan it as future work [P01]. More advanced approaches, such as [P07], aim to extend their capabilities with AI-based and semantic conflict detection techniques. As discussed in Section V, semantic techniques are rarely encountered, and thus, this direction allows significant room to grow.

Non-functional properties are a prominent cluster of identified shortcomings as well. Scalability has been identified as the leading non-functional limitation or desired future work (e.g., [P05], [P11], [P23]). The focus on scalability as a limitation seems to be justified in the case of collaborative tools, potentially supporting the work of distributed, large-scale teams.

The remaining limitations are related to tool development and integration tasks (e.g., [P09], [P23]); and approach-specific concerns, such as supporting crowd modeling in [P26], and supporting abbreviations in the NLP technique of [P22].

VII. PUBLICATION TRENDS (RQ3)

In this section, we report the results of our update regarding RQ3: the publication trends in the domain of collaborative MDSE. For the sake of completeness, we analyze the included publications on an individual basis, rather than in a clustered way. For each primary study we extracted the publication year and type. The results are shown in Fig. 2.

During the period of 2016–2020, we have sampled a total of 51 publications. Additionally, for the year 2015, we have sampled 3 publications which could not be included in the original study due to their later publication date. In sum, 2015 has produced 12 publications. This shows a steady publication trend with the average number of 10 publications between 2016–2020. This average is aligned with the previous 5-year period (2011–2015), which produced an average of 9 papers per year. The original study identifies 2003 as the point when the publication trends have started to increase significantly. In comparison with the past five years, the period between 2003–2015 produced an average of 8.15 papers per year. By looking at the complete period of 2003–2020, our study has further revealed, that there is a statistically significant difference in the publication volume between the periods of 2003–2012 and 2013–2020. (Respective means: 6.8 and 11.125. Independent 2-group Mann-Whitney U Test: $p = 0.01424$). This trend

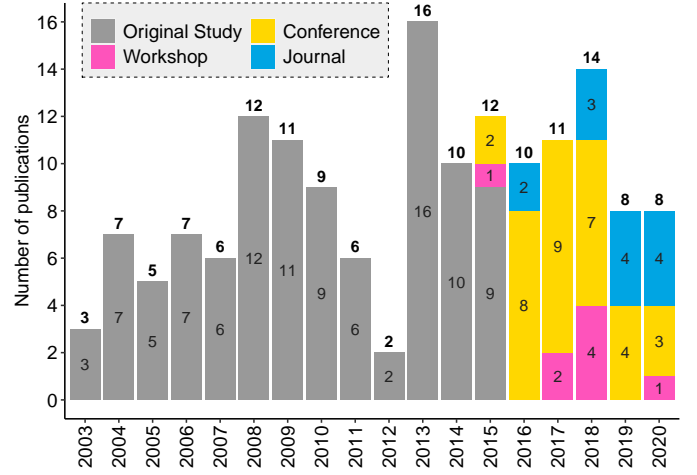


Fig. 2: Publication trends between 2003–2020 with the papers of the current study highlighted.

TABLE VI: Venues with more than one publication

Venue	Publications	Ratio
MODELS	9	16.67%
SOSYM	3	5.56%
ASE, STAF/ECMFA, IEEE Software, ER, MODELSWARD, WET-ICE	2	3.7%
Others	30	55.56%

can be explained by two components: (i) the appearance of novel, web-based modeling tools that inherently embraced collaborative modeling and remained relevant through multiple years, such as AToMPM [19] and Flexisketch [49] in 2013, and WebGME in 2014 [20]; and (ii) the appearance of collaborative frameworks and platforms with multiple applications, such as the Yjs/Syncmeta [50] framework in 2015, the MONDO platform [51] in 2016, and the SOCIO [52] framework in 2017.

The above numbers suggest that the field of collaborative MDSE is relatively steady, with a regular influx of new techniques and approaches. Apart from 2012, which has seen only 2 publications on the topic, there were at least 6 papers produced per year in the past 15 years.

The ratio of journal, conference, and workshop publications suggests that the maturity of the field has slightly evolved in the past five years. The ratio of journal and conference papers has increased from 79.24% in 2011–2015 to 86.27% in 2016–2020. Relevant change can be observed in the venues of publications. Between 2003–2015, the distribution of papers across venues was relatively even, as 8 conferences and workshops have contributed 3–5 papers each to the field. Between 2016–2020 (Table VI), however, over 16% of papers were published at the *International Conference on Model Driven Engineering Languages and Systems – MODELS* (6 conference and 3 workshop papers). The journal on *Software & Systems Modeling – SOSYM* is the second frequent source of publications with only 3 papers (5.56%). Four other conferences, one workshop, and one journal published 2 papers each (3.7%).

VIII. ORTHOGONAL FINDINGS

We have further analyzed the extracted data to find relevant phenomena orthogonal to the vertical analysis, emerging between specific combinations of concepts in the classification framework. By evaluating the orthogonal findings of the original study with the 2016–2020 data, we have found that each of them are still valid. The reader is referred to the original study (Section 10, pp 22–23) for further information. Therefore, in this section, we only focus on our findings from the 2016–2020 period uncovered by the updated classification framework.

1) *Orthogonal findings about Real-time collaboration:*

Real-time collaboration is naturally coupled with *synchronous communication*. This has been demonstrated by the support for synchronous means of communication in real-time settings being 100%, but only 57.89% for asynchronous means. In off-line settings, synchronous and asynchronous means are supported evenly. Real-time communication approaches score higher in *workspace awareness* as compared to off-line approaches. 73.7% of real-time approaches earned a *Medium* or *High* score in this aspect; while this number is 27.3% in off-line approaches. As a potential limitation, real-time collaboration is most frequently supported by a strong notion of model consistency (45.1%). This is somewhat unexpected as eventual (35.5%) and strong eventual (19.4%) consistency models fit the real-time paradigm better [45]. As a typical application of the paradigm, real-time collaboration is much often used in (meta-)meta level collaboration than off-line techniques. 81.8% of higher meta-level collaborations are approached in real-time fashion. On the model level, real-time techniques are used in the 73% of the cases.

2) *Orthogonal findings about Mobile clients:* While mobile clients are naturally restricted in their resources and physical dimensions, they evidently align well with supporting non-technical stakeholders in a collaborative modeling endeavor. We have observed each approach with a mobile client supports both technical and non-technical users. The support for non-technical users is much lower in desktop-based (33.33%) and browser-based (42.86%) approaches. Approaches with mobile clients also tend to focus on more lightweight modeling approaches, where the real-time interaction is important (80% support), but version control and conflict awareness are omitted.

3) *Orthogonal findings about Conflict management and Conflict resolution:* Preventive conflict management is most frequently encountered in single-view settings: 7 such combinations have been identified, while only 1 preventive approach was found in multi-view settings. 87.5% of preventive techniques are found in real-time settings; allow-and-resolve techniques, however, distribute across real-time and off-line settings evenly. The automation of conflict resolution is a stronger trend in single-view settings than multi-view ones. 69.2% of single-view settings provide some means of automation for resolving conflicts; while this number is 50% in multi-view settings. This is likely because of the more intricate nature of conflicts in multi-view settings. While conflicts in

single-view settings are purely syntactic, conflicts in multi-view settings tend to be more semantic, and thus, harder to detect and repair.

4) *Orthogonal findings about the Communication type:*

There is a noticeable difference in how much different client types support different communication types. Asynchronous and synchronous means of communication are supported nearly evenly in desktop clients (100% and 86.67% respectively). This ratio, however substantially different in web and mobile clients. In web-based clients, synchronous communication is over 1.5 times more often found than asynchronous (100% and 64.29% support respectively). In mobile clients this ratio is even higher (100% and 25% support respectively). Multi-view approaches distribute evenly across synchronous and asynchronous communication types. Synchronous communication is typically supported by chat, comments, calls for attention and annotations; while asynchronous communication is typically supported by proposals, reviews, annotations and comments. While allow-and-resolve conflict management techniques are equally frequent with both types of communication, preventive conflict management techniques are nearly twice as frequent in synchronous than in asynchronous communication (7 and 4 respectively).

IX. DISCUSSION

With 51 studies published in the last five years, we see a steady trend in publications, as the amount of papers per year has doubled since the 20-year period of the original study. The topic of collaborative MDSE is maturing, witnessed by the improved ratio of journal papers, the number of large-scale research and development projects concerning collaboration [11]–[13], and of focused workshops [9], [10].

A. *Observations*

The most prominent technological trends in the past five years have been the increased support for real-time collaboration and the mobilization of browser and mobile-based applications. The split in the support between real-time and off-line collaboration has increased from 8.33% to nearly 25%. This trend is in line with recent trends in IDEs for software development. As such, we are witnessing the raise of facilities such as Code With Me in JetBrains' IDEs (e.g., IntelliJ IDEA) [53] and Saros in Eclipse [54], which provide shared programming sessions, remote collaborative debugging, embedded chats, etc. However, this trend also comes with a limitation in the analyzed primary studies, with the strong consistency model still being the typically employed one. Approaches such as AToMPM [P05] and Collaboro [P10] support real-time collaboration with a strong consistency model. Eventual and strong eventual models, however are trending upwards, highlighted by approaches such as FLAME [P03], Miw [P14], and Yjs [P18]. About half of these approaches support users by (semi-)automated conflict resolution, and about 40% provide a browser or mobile-based client. We also saw completely new technologies appearing, such as chatbots as means of human-computer collaboration [P22], and

blockchains as the mediating environment for collaborative MDSE endeavors [P27]. On the end-user level, non-technical users are getting more involved in collaborative MDSE (with an increase in their support from 14.58% to 37.93%). This comes with increasing workspace awareness, and improved conflict awareness.

We have observed a strong imbalance among the three dimensions of collaborative MDSE, with communication being severely overlooked both in terms of supported communication techniques and in terms of planned future work. This may be a shortcoming of academic research, but a similarly plausible explanation can be the moderate need for advanced communication facilities. This is even more emphasized for desktop-based tools, as 44.8% do not feature any built-in means of communication, in contrast with the 28% of browser-based tools, and 20% of mobile applications.

B. Lessons learned

From this study, we synthesize the following lessons learned to researchers and practitioners in collaborative MDSE:

- The **maturity** of the field of collaborative MDSE has improved, demonstrated by steady publication trends and the improved quality of publications.
- **Real-time** collaboration is becoming increasingly popular. Currently it is clearly preferred approach over off-line collaboration.
- End-user clients are getting more **mobile** as the support for **browser**-based and mobile applications are experiencing a sharp increase.
- **Consistency models** more suitable for real-time collaboration are trending upwards. Especially eventual and strong eventual models have gained traction recently.
- **Communication** is a seriously overlooked dimension of collaborative MDSE, typically featuring ad-hoc solutions. As such, it should be addressed better in the next generation of collaborative modeling tools.
- The **evaluation** of collaborative MDSE tools is a systemic problem that hinders the applicability of academic results. This issue can be addressed effectively with dedicated initiatives, workshops, and benchmarks.

C. Methodological reflections

The results clearly indicate that this update was needed. However, at the time of deciding to carry out this study, we could only rely on the assessment framework discussed in Section III. In retrospect, we find this framework appropriate, and well-designed to aid such decisions. The decision to carry out a fully recursive forward snowballing, instead of just one iteration suggested by [14], turned out to be a good decision. The first iteration accounted for 72% of all the papers considered in this study. The second iteration contributed to 26% of the papers, and the last iteration added one paper. Therefore, we suggest following the same approach in future systematic updates in the software engineering area.

D. Threats to validity

We conducted the research reported in this paper based on the carefully designed protocol of the original study [16]. Our work has achieved a 54.5% result in the quality checklist defined by Petersen et al. for systematic studies [27]. This quality score is significantly better than the median and absolute maximum scores (33% and 48%, respectively) reported by [27]. The most important threat to the external validity is the search method that was limited to a forward snowballing, as suggested by [14]. In order to mitigate this threat, we have carried out a fully recursive forward snowballing. In terms of internal validity, the most important threat was introduced in our preliminary assessment of the need for an update. When assessing the volume of potentially relevant new literature (Section III-B), we mitigated the threat by measuring the ratio of volumes between the target period and baseline period in a uniform way: by running the same search string on Google Scholar for both periods. A slight threat to validity remained due to the false positive inflation problem of Google Scholar [14]; but eventually, this did not influence the results. A slight threat to the conclusion validity was introduced in Section VII, when carrying out a significance test over relatively small samples of annual research output. We have validated the plausibility of the conclusion by identifying the underlying trends in technical contributions.

X. CONCLUSIONS AND FUTURE WORK

In this paper, we have presented the results of our systematic update on the mapping study by Franzago et al. [16] on collaborative MDSE in the period of 2016–2020. Starting from over 880 studies, we have selected 54 primary and one secondary studies through a rigorous process. We extended the classification framework of the original study based on the newly identified literature, and extracted insightful information. We have identified multiple interesting trends in the field in terms of the characteristics of existing collaborative MDSE solutions, their limitations, the publication trends, and orthogonal phenomena emerging across the different categories of the classification framework. We conclude that the newly encountered information constitute a valuable contribution to the field.

We suggest three future directions. First, we suggest revisiting this study again in five years, and assessing the need for another update, based on the protocol we have defined. Second, we suggest a focused work on the communication dimension of collaborative MDSE, which proved to be by far the most underdeveloped and overlooked dimension of the three. Finally, we suggest conducting the non-academic counterpart of this study, focusing on the state of practice and its needs to identify the gaps and opportunities between research and development.

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