

Highlights

A Comprehensive Evaluation of SZZ Variants Through a Developer-informed Oracle

Giovanni Rosa, Luca Pascarella, Simone Scalabrino, Rosalia Tufano, Gabriele Bavota, Michele Lanza, Rocco Oliveto

- Developer-informed annotated dataset for the evaluation of SZZ, composed of 2,304 instances;
- Empirical evaluation of 9 different SZZ variants, where R-SZZ is the best performing;
- Definition of a heuristics to improve SZZ by allowing to processing of added lines in fix commits;
- Definition of a filtering heuristics for revert commits to improve SZZ;

A Comprehensive Evaluation of SZZ Variants Through a Developer-informed Oracle

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Abstract

Automatically linking bug-fixing changes to bug-inducing ones (BICs) is one of the key data-extraction steps behind several empirical studies in software engineering. The SZZ algorithm is the *de facto* standard to achieve this goal, with several improvements proposed over time. Evaluating the performance of SZZ implementations is, however, far from trivial. In previous works, researchers (i) manually assessed whether the BICs identified by the SZZ implementation were correct or not, or (ii) defined oracles in which they manually determined BICs from bug-fixing commits. However, ideally, the original developers should be involved in defining a labelled dataset to evaluate SZZ implementations. We propose a methodology to define a “developer-informed” oracle for evaluating SZZ implementations, without requiring a manual inspection from the original developers. We use Natural Language Processing (NLP) to identify bug-fixing commits in which developers explicitly reference the commit(s) that introduced the fixed bug. We use the built oracle to extensively evaluate existing SZZ variants defined in the literature. We also introduce and evaluate two new variants aimed at addressing two weaknesses we observed in state-of-the-art implementations (*i.e.*, processing added lines and handling of revert commits).

Keywords: SZZ, Defect Prediction, Empirical Study

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¹ **1. Introduction**

² The revision history of long-lived software projects features plenty of *cor-*
³ *rective changes*, *i.e.*, modifications aimed at fixing bugs. For each corrective
⁴ change – or *bug-fixing commit* – it exists a non-empty set of commits that in-
⁵ troduced the addressed bug. While the performed bug-fixing activity is often
⁶ explicitly documented in the commit message, the same obviously does not
⁷ happen for the commits introducing bugs. Therefore, while such a linking
⁸ can be useful to conduct empirical studies on the characteristics of changes
⁹ that introduce bugs (Bavota and Russo, 2015; Tufano et al., 2017; Aman
¹⁰ et al., 2019; Chen and Jiang, 2019) or to validate defect prediction tech-
¹¹ niques (Hata et al., 2012; Tan et al., 2015; Pascarella et al., 2019; Yan et al.,
¹² 2020; Fan et al., 2019), it is challenging to establish.

¹³ In 2005, Śliwerski et al. (2005) proposed the SZZ algorithm to address
¹⁴ such a problem. Given a bug-fixing commit C_{BF} , the SZZ algorithm identifies
¹⁵ a set of commits that likely introduced the error fixed in C_{BF} . These commits
¹⁶ are named “bug-inducing” commits. In a nutshell, SZZ identifies the last
¹⁷ change (commit) to each source code line changed in C_{BF} (*i.e.*, changed to
¹⁸ fix the bug). This is done by relying on the annotation/blame feature of
¹⁹ versioning systems. The identified commits are considered as the ones that
²⁰ later on triggered the bug-fixing commit C_{BF} .

²¹ Since the original work was published, several researchers have proposed
²² variants of the original algorithm, with the goal of improving its accuracy
²³ (Kim et al., 2006; Williams and Spacco, 2008a; Davies et al., 2014; Da Costa
²⁴ et al., 2016; Neto et al., 2018, 2019). For example, a limitation of the original
²⁵ SZZ algorithm is that it considers changes to code comments and whitespaces
²⁶ like any other change. Therefore, if a comment is modified in C_{BF} , the lat-
²⁷ est change to such a comment is mistakenly considered as a BIC. Therefore,
²⁸ Kim et al. (2006) introduced a variant which ignores such changes. Simi-
²⁹ larly, other variants ignore non-executable statements (*e.g.*, `import` state-
³⁰ ments) (Williams and Spacco, 2008a), meta-changes (*e.g.*, merge commits)
³¹ (Da Costa et al., 2016), and refactoring operations (*e.g.*, variable renaming)
³² (Neto et al., 2018, 2019).

³³ Despite the growth of the number of SZZ variants introduced to achieve
³⁴ higher and higher levels of accuracy, Da Costa et al. (2016) highlighted that
³⁵ the performed accuracy evaluations mostly rely on manual analysis performed
³⁶ on the output of the proposed SZZ variants (Śliwerski et al., 2005; Kim
³⁷ et al., 2006; Williams and Spacco, 2008a; Davies et al., 2014). Researchers

38 themselves usually perform such a validation, despite not being the original
39 developers of the studied systems and, thus, not always having the knowledge
40 needed to correctly identify the bug introducing commit. Other researchers,
41 instead, defined a ground truth to evaluate the performance of their variants
42 (Neto et al., 2019). Also in these cases, however, researchers completed such
43 a task. Therefore, there is a clear need for oracles defined by exploiting
44 the knowledge of people who worked on the system (Da Costa et al., 2016).
45 Still, directly involving them to manually evaluate a large sample of BICs is
46 impractical (Da Costa et al., 2016).

47 In this paper, we extend our previous paper (Rosa et al., 2021) in which we
48 addressed this problem by introducing a methodology to build a “developer-
49 informed” oracle for the evaluation of SZZ variants. To explain the core idea,
50 let us take as an example commit 31063db from the `mrc0mmand/systemd`
51 GitHub project, accompanied by a commit message saying: “*sd-device: keep*
52 *escaped strings in DEVLINK= property. This fixes a bug introduced by*
53 *87a4d41. Fixes systemd#17772*”. The developer fixing the bug is explicitly
54 documenting the commit that introduced such a bug. Based on this observa-
55 tion, we defined strict NLP-based heuristics to automatically detect messages
56 of bug-fixing commits in which developers explicitly reference the commit(s)
57 that introduced the fixed bug. We call such commits “referenced bug-fixing
58 commits”. It is worth noting that such a process is not meant to be exhaus-
59 tive, *i.e.*, we do not aim at finding *all* the referenced bug-fixing commits.
60 Instead, we mainly aim at obtaining a high-quality dataset of commits that
61 are very likely induced a bug-fix.

62 We used our NLP-based heuristics to filter all the commits done on
63 GitHub public repositories between March 2011 and the end of January
64 2021 by relying on GitHub Archive (Grigorik, 2012), a public service which
65 archives all public events occurred on GitHub. Compared to our previous
66 paper, we have analyzed 9 additional months of GitHub events. From a set
67 of 24,042,335 (*i.e.*, 4.4M more than our previous paper), our heuristics iden-
68 tified 4,585 possible referenced bug-fixing commits. To further increase the
69 quality of our dataset, we manually validated such commits, aiming at verify-
70 ing whether the commit message was clearly documenting the bug-inducing
71 commit. Besides, we annotated possible issues from the issue-tracker explic-
72 itly referenced by developers since such a piece of information is exploited by
73 some SZZ variants. In the end, we obtained a dataset including 2,304 refer-
74 enced bug-fixing commits (*i.e.*, 22% more than our previous paper), with 212
75 also including information about the fixed issue(s). This means that develop-

76 ers keep annotating the BIC in the commit messages, thus our methodology
77 can be used to build and then update, over time, an extensive dataset for
78 the evaluation of SZZ.

79 After manually analyzing cases in which all SZZ variants failed to detect
80 the correct BIC, we found two main limitations of existing approaches: (i)
81 they do not take into account added lines, but only deleted lines, since those
82 are the ones on which it is possible to use the `blame` command; (ii) they are
83 confused by revert commits, which reset previous changes not allowing SZZ
84 to find the actual BICs. Therefore, we introduce two novel heuristics that
85 aim at overcoming such limitations. In the first, given the set of added lines,
86 we detect the lines directly affected by them by relying on Definition-Use
87 chains. Then, we detect changes that introduced such lines. In the second
88 heuristic, we detect revert commits by using NLP-based heuristics, and we
89 discard them when they are selected as candidate BICs.

90 We tested the new heuristics we introduced in isolation, to understand to
91 what extent they affect the accuracy. Our results show that the Definition-
92 Use heuristic allows finding BICs in cases in which other SZZ variants do not
93 work. On the other hand, the revert heuristics for revert commits provides
94 a small advantage in terms of precision (+1%), without paying any price in
95 terms of recall.

96 To summarize, the novel contributions provided in this paper with respect
97 to our previous paper (Rosa et al., 2021) are the following:

- 98 1. We extended the dataset by including 9 additional development months
99 on GitHub, resulting in 4.4M additional commits analyzed and 421 new
100 instances in the final dataset;
- 101 2. We replicated our experiments on the new dataset;
- 102 3. Based on our findings, we introduced and evaluated two new heuristics
103 for SZZ, showing that both of them slightly improve its effectiveness.

104 2. Background and Related Work

105 We start by presenting several variants of the SZZ algorithm (Śliwerski
106 et al., 2005) proposed in the literature over the years. Then, we discuss how
107 those variants have been used in SE research community.

108 2.1. SZZ Variants

109 Several approaches have been proposed to identify bug introducing com-
110 mits, such as those based on history slicing (Servant and Jones, 2011, 2012,

Approach	Reference	Based on	Used by	Oracle def.	# P.	# B.F.
B-SZZ	Śliwerski et al. (2005)		(Palomba et al., 2018; Pasarella et al., 2019; Caglayan and Bener, 2016; Wen et al., 2016; Posnett et al., 2013; Kim et al., 2008; Tan et al., 2015; Kononenko et al., 2015; Wehaibi et al., 2016; Lenarduzzi et al., 2020a)	//	//	//
AG-SZZ	Kim et al. (2006)	B-SZZ	(Tufano et al., 2017; Bernardi et al., 2018; Hata et al., 2012; Rahman et al., 2011; Eyolfson et al., 2014; Misirli et al., 2016; Canfora et al., 2011; Prechelt and Pepper, 2014; Bird et al., 2009a)	Manual	2	301
DJ-SZZ	Williams and Spacco (2008a)	AG-SZZ	(Marinescu et al., 2014; Borg et al., 2019; Bavota and Russo, 2015; Tóth et al., 2016; Fan et al., 2019; Karampatidis and Sutton, 2020; Rodríguez-Pérez et al., 2020, 2018)	Manual	1	25
L- & R-SZZ	Davies et al. (2014)	AG-SZZ	(Da Costa et al., 2016)	Manual	3	174
MA-SZZ	Da Costa et al. (2016)	AG-SZZ	(Fan et al., 2019; Neto et al., 2018, 2019; Tu et al., 2020; Aman et al., 2019; Chen and Jiang, 2019)	Automated	10	2,637
RA-SZZ	Neto et al. (2018)	MA-SZZ	(Fan et al., 2019; Neto et al., 2018; Yan et al., 2020)	Manual	10	365
RA-SZZ*	Neto et al. (2019)	RA-SZZ	None	Manual	10	365
A-SZZ	Sahal and Tosun (2018)	B-SZZ	None	Manual	2	251

Table 1: Variants of the SZZ algorithm. For each one, we specify (i) the algorithm on which it is based, (ii) references of works using it, (iii) the oracle used in the evaluation (how it was built, number of projects (# P.) and bug fixes (# B.F.) considered).

111 2017). Among the proposed techniques, SZZ is the one which had the highest
112 adoption when it comes to the detection of bug-inducing changes (Herbold
113 et al., 2022). Table 1 presents the SZZ variants proposed in the literature.
114 We report for each of them its name and reference, the approach it builds
115 upon (*i.e.*, the starting point on which the authors provide improvements),
116 some references to works that used it, and information about the oracle used
117 for the evaluation. Specifically, we report how the oracle was built and the
118 number of projects/bug reports considered.

119 All the approaches that aim at identifying bug-inducing commits (BICs)
120 rely on two elements: (i) the revision history of the software project, and (ii)
121 an issue tracking system (optional, needed only by some SZZ implementa-
122 tions).

123 The original SZZ algorithm was proposed by Śliwerski et al. (2005) (we
124 refer to it as B-SZZ, following the notation provided by Da Costa et al.
125 (2016)). B-SZZ takes as input a bug report from an issue tracking system,
126 and tries to find the commit that fixes the bug. To do this, B-SZZ uses a two-
127 level confidence level: *syntactic* (possible references to the bug ID in the issue
128 tracker) and *semantic* (*e.g.*, the bug description is contained in the commit
129 message). B-SZZ relies on the CVS `diff` command to detect the lines
130 changed in the fix commit and the `annotate` command to find the commits
131 in which the lines were modified. Using this procedure, B-SZZ determines
132 the *earlier* change at the location of the fix. Potential bug-inducing commits
133 performed after the bug was reported are always ignored.

134 Kim et al. (2006) noticed that B-SZZ has limitations mostly related

135 to formatting/cosmetic changes (*e.g.*, moving a bracket to the next line).
136 Such changes can deceive B-SZZ: B-SZZ (i) can report as BIC a revision
137 which only changed the code formatting, and (ii) it can consider as part of
138 a bug-fix a formatting change unrelated to the actual fix. They introduce a
139 variant (AG-SZZ) in which they used an annotation graph, a data structure
140 associating the modified lines with the containing function/method. AG-
141 SZZ also ignores the cosmetic parts of the bug-fixes to provide more precise
142 results.

143 Williams and Spacco (2008a) improved the AG-SZZ algorithm in two
144 ways: first, they use a line-number mapping approach (Williams and Spacco,
145 2008b) instead of the annotation graph introduced by Kim et al. (2006);
146 second, they use DiffJ (Pace, 2007), a Java syntax-aware diff tool, which
147 allows their approach (which we call DJ-SZZ) to exclude non-executable
148 changes (*e.g.*, `import` statements).

149 Davies et al. (2014) propose two variations on the criterion used to select
150 the BIC among the candidates: L-SZZ uses the largest candidate, while
151 R-SZZ uses the latest one. These improvements were done on top of the
152 AG-SZZ algorithm.

153 MA-SZZ, introduced by Da Costa et al. (2016), excludes from the candi-
154 date BICs all the *meta-changes*, *i.e.*, commits that do not change the source
155 code. This includes (i) branch changes, which are copy operations from one
156 branch to another, (ii) merge changes, which consist in applying the changes
157 performed in a branch to another one, and (iii) property changes, which only
158 modify file properties (*e.g.*, permissions).

159 To further reduce the false positives, two new variants were introduced
160 by Neto *et al.*, RA-SZZ (Neto et al., 2018) and RA-SZZ* (Neto et al.,
161 2019). They exclude from the BIC candidates the refactoring operations,
162 *i.e.*, changes that should not modify the behavior of the program. Both ap-
163 proaches use state-of-the-art tools: RA-SZZ uses RefDiff (Silva and Valente,
164 2017), while RA-SZZ* uses Refactoring Miner (Tsantalis et al., 2018), with
165 the second one being more effective (Neto et al., 2019).

166 The presented variants of SZZ do not parse lines added in bug-fixing
167 commits (*e.g.*, an added `if` statement checking for `null` values). This is
168 because a line added does not have a change history when processed by
169 SZZ using the Annotation Graph (Kim et al., 2006) or the Line-Number
170 mapping (Śliwerski et al., 2005). As we discussed in our previous work (Rosa
171 et al., 2021), there are however cases in which lines added while fixing a
172 bug can point to the correct bug-inducing change. Sahal and Tosun (2018)

173 proposed the first approach to include in SZZ support for added lines (from
174 here on A-SZZ). Specifically, when the bug-fixing changes add new lines, A-
175 SZZ identifies the code blocks encapsulating them. Then, A-SZZ considers
176 the set of lines in the block and discards the cosmetic changes and comment
177 lines. Finally, it runs the original SZZ algorithm as if the remaining lines of
178 the block were modified in the commit.

179 Recently, Bao et al. (2022) proposed a new variant of SZZ, namely V-
180 SZZ, which is specialized in the detection of vulnerability-inducing commits.
181 V-SZZ is not included in our study since we consider generic bugs (not nec-
182 essarily security-relevant ones).

183 Another interesting variant is PR-SZZ, proposed by Bludau and Pretschner
184 (2022), which uses pull requests and the associated data to find the bug in-
185 ducing commits. Also this work is excluded from our work since we do not
186 study the issue extraction step of SZZ, but rather its ability to identify the
187 bug-inducing commit given the fixing commit.

188 Concerning the empirical evaluations performed in the literature, the orig-
189 inal SZZ was not evaluated (Śliwerski et al., 2005). Instead, all its variants,
190 except MA-SZZ, were manually evaluated by their authors. One of them,
191 RA-SZZ* (Neto et al., 2019), used an external dataset, *i.e.*, Defect4J (Just
192 et al., 2014). MA-SZZ was evaluated using automated metrics, namely *earli-*
193 *est bug appearance, future impact of a change, and realism of bug introduction*
194 (Da Costa et al., 2016).

Tool name	Approach	Public repository
SZZ Unleashed (Borg et al., 2019)	~DJ-SZZ (Williams and Spacco, 2008a)	https://github.com/wogscpar/SZZUnleashed
OpenSZZ (Lenarduzzi et al., 2020b)	~B-SZZ (Śliwerski et al., 2005)	https://github.com/clowee/OpenSZZ
PYDRILLER (Spadini et al., 2018)	~AG-SZZ (Śliwerski et al., 2005)	https://github.com/ishepard/pydriller

Table 2: Open-source tools implementing SZZ.

195 In Table 2 we list the open-source implementations of SZZ. SZZ Unleashed
196 (Borg et al., 2019) partially implements DJ-SZZ: it uses line-number map-
197 ping (Williams and Spacco, 2008a) but it does not rely on DiffJ (Pace, 2007)
198 for computing diffs, also working on non-Java files. It does not take into
199 account meta-changes (Da Costa et al., 2016) and refactorings (Neto et al.,
200 2019).

201 OpenSZZ (Lenarduzzi et al., 2020b) implements the basic version of the
202 approach, B-SZZ. Since it is based on the git blame command, it implicitly
203 uses the annotated graph (Kim et al., 2006).

204 PYDRILLER (Spadini et al., 2018), a general purpose tool for analyzing
205 git repositories, also implements B-SZZ. It uses a simple heuristic for ignoring
206 C- and Python-style comment lines, as proposed by Kim et al. (2006). We
207 do not report in Table 2 a comprehensive list of all the SZZ implementations
208 that can be found on GitHub, but only the ones presented in papers.

209 *2.2. SZZ in Software Engineering Research*

210 The original SZZ algorithm and its variations were used in a plethora of
211 studies. We discuss some examples, while for a complete list we refer to the
212 extensive literature review by Rodríguez-Pérez et al. (2018), featuring 187
213 papers.

214 SZZ has been used to run several empirical investigations having different
215 goals (Çaglayan and Bener, 2016; Lenarduzzi et al., 2020a; Wehaibi et al.,
216 2016; Tufano et al., 2017; Bernardi et al., 2018; Eyolfson et al., 2014; Misirli
217 et al., 2016; Canfora et al., 2011; Prechelt and Pepper, 2014; Bird et al.,
218 2009a; Rodríguez-Pérez et al., 2018; Aman et al., 2019; Chen and Jiang, 2019;
219 Posnett et al., 2013; Karampatsis and Sutton, 2020; Bavota and Russo, 2015;
220 Kononenko et al., 2015; Palomba et al., 2018; Rodríguez-Pérez et al., 2020;
221 Petruolio et al., 2022; Herbold et al., 2022). For example, Aman et al. (2019)
222 studied the role of local variable names in fault-introducing commits and
223 they used SZZ to retrieve such commits, while Palomba et al. (2018) focused
224 on the impact of code smells, and used SZZ to determine whether an artifact
225 was smelly when a fault was introduced. Many studies also leverage SZZ
226 to evaluate defect prediction approaches (Kim et al., 2008; Rahman et al.,
227 2011; Hata et al., 2012; Tan et al., 2015; Tóth et al., 2016; Wen et al., 2016;
228 Fan et al., 2019; Pascarella et al., 2019; Fan et al., 2019; Tu et al., 2020; Yan
229 et al., 2020; Zeng et al., 2021). For example, Zeng et al. (2021) presented a
230 study to evaluate the effectiveness of CC2Vec, a state-of-the-art Just-in-Time
231 (JIT) defect prediction tool which uses deep learning. They use SZZ to label
232 the defect-fixing commits for the training and evaluation of the model. Also,
233 the main usage of SZZ in industry is for the evaluation of defect prevention
234 approaches (Bowes et al., 2017; Senchenko et al., 2022).

235 Looking at Table 1 it is worth noting that, despite its clear limitations
236 (Kim et al., 2006), many studies, even recent ones, still rely on B-SZZ
237 (Palomba et al., 2018; Pascarella et al., 2019; Çaglayan and Bener, 2016;
238 Wen et al., 2016; Posnett et al., 2013; Kim et al., 2008; Tan et al., 2015;
239 Kononenko et al., 2015; Wehaibi et al., 2016; Lenarduzzi et al., 2020a) (the
240 approaches that use git implicitly use the annotation graph defined by Kim

et al. (2006)). Improvements are only slowly adopted in the literature, possibly due to the fact that some of them are not released as tools and that the two standalone tools providing a public SZZ implementation were released only recently (Lenarduzzi et al., 2020b; Borg et al., 2019).

The studies most similar to ours are the one by Da Costa et al. (2016), the one by Rodríguez-Pérez et al. (2020), and the one by Herbold et al. (2022). All of them report a comparison of different SZZ variants. Da Costa et al. (2016) defined and used a set of metrics for evaluating SZZ implementations without relying on a manually defined oracle. However, they specify that, ideally, domain experts should be involved in the construction of the dataset (Da Costa et al., 2016), which motivated our study. Rodríguez-Pérez et al. (2020) introduced a model for distinguishing bugs caused by modifications to the source code (the ones that SZZ algorithms can detect) and the ones that are introduced due to problems with external dependencies. They also used the model to define a manually curated dataset on which they evaluated SZZ variants. Their dataset is created by researchers and not domain experts. In our study, instead, we rely on the explicit information provided by domain experts in their commit messages. Herbold et al. (2022) conducted an empirical analysis on the defect labels (*i.e.*, bugfix commits) identified by SZZ and the impact on commonly used features for defect prediction. Their results, evaluated on a dataset of 38 Apache projects, show that SZZ is able to correctly identify only half of the bug fixing commits, and using more features is not significant for defect prediction. In our study, we mainly focus on the construction of an evaluation dataset for SZZ, comparing the main variants proposed in literature.

3. Defining a Developer-informed Dataset for SZZ

In this section, we present a methodology to build a dataset of bug-inducing commits by exploiting information provided by developers when fixing bugs. Our methodology reduces the manual effort required for building such a dataset and more important, does not assume technical knowledge of the involved source code on the researchers' side.

The proposed methodology involves two main steps: (i) automatic mining from open-source repositories of bug-fixing commits in which developers explicitly indicate the commit(s) that introduced the fixed bug, and (ii) a manual filtering aimed at improving the dataset quality by removing ambiguous commit messages that do not give confidence in the information

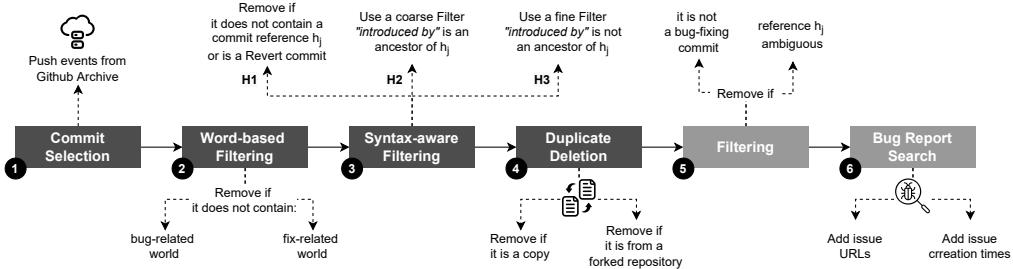


Figure 1: Process used for building the dataset. Steps 5 and 6 are the result of a manual evaluation.

277 provided by the developer. In the following, we detail these two steps. The
 278 whole process is depicted in Fig. 1.

279 3.1. Mining Bug-fixing and Bug-inducing Commits

280 There are two main approaches proposed in the literature for selecting
 281 bug-fixing commits. The first one relies on the linking between commits
 282 and issues (Bissyande et al., 2013): issues labeled with “bug”, “defect”, etc.
 283 are mined from the issue tracking system, storing their issue ID (*e.g.*, sys-
 284 temd#17772). Then, commits referencing the issue ID are mined from the
 285 versioning system and identified as bug-fixing commit. While such a heuristic
 286 is fairly precise, it has two important drawbacks that make it unsuitable
 287 for our work. First, the link to the issue tracking system must be known and
 288 a specific crawler for each different type of issue tracker (*e.g.*, Jira, Bugzilla,
 289 GitHub, etc.) must be built.

290 Second, projects can use a customized set of labels to indicate bug-related
 291 issues. Manually extracting this information for a large set of repositories is
 292 expensive. The basic idea behind this first phase is to use the commit mes-
 293 sages to identify bug-fixing commits: we automatically analyze bug-fixing
 294 commit messages searching for those explicitly referencing bug-inducing com-
 295 mits.

296 As a preliminary step, we mined GH ARCHIVE (Grigorik, 2012) which
 297 provides, on a regular basis, a snapshot of public events generated on GitHub
 298 in the form of JSON files.

299 We mined the time period going from March 1st 2011 to January 28th

300 2021¹, extracting 24,042,335 commits performed in the context of *push* events:
301 such events gather the commits done by a developer on a repository before
302 performing the *push* action. Considering the goal of building an oracle for
303 SZZ algorithms, we are not interested in any specific programming language.
304 We performed three steps to select a candidate set of commits to manually
305 analyze in the second phase: (i) we selected a first candidate set of bug-fixing
306 commits, (ii) we used syntax-aware heuristics to refine such a set, and (iii)
307 we removed duplicates.

308 *3.1.1. Word-Based Selection of Bug-Fixing Commits*

309 To identify bug-fixing commits, we first apply a lightweight regular ex-
310 pression on all the commits we gathered, as done in a previous work (Fischer
311 et al., 2003; Tufano et al., 2019). We mark as potential bug-fixes all com-
312 mits accompanied by a message including at least a fix-related word² and a
313 bug-related word³. We exclude the messages that include the word *merge* to
314 ignore merge commits. Note that we do not need such a heuristic to be 100%
315 precise, since two additional and more precise steps will be performed on the
316 identified set of candidate fixing commits to exclude false positives (*i.e.*, a
317 NLP-based step and a manual analysis).

318 *3.1.2. Syntax-Aware Filtering of Referenced Bug-Fixing Commits*

319 We needed to select from the set of candidate bug-fixing commits only
320 the ones in which developers likely referenced the bug-inducing commit(s)
321 (*i.e.*, referenced bug-fixing commits). We used the syntax-aware heuristics
322 described below to do this. The first author defined such heuristics through
323 a trial-and-error procedure, taking a 1-month time period of events on GH
324 Archive to test and refine different versions of the heuristics, manually in-
325 specting the achieved results after each run. The final version has been
326 consolidated with the feedback of two additional authors.

327 As a preliminary step, we used the `doc.sents` function of the SPACY⁴
328 Python module for NLP to extract the set S_c of sentences composing each
329 commit message c .

330 For each sentence $s_i \in S_c$, we used SPACY to build its word dependency
331 tree t_i , *i.e.*, a tree containing the syntactic relationships between the words

¹ Compared to the previous paper (Rosa et al., 2021) which this manuscript extends, we analyze nine additional months of development, resulting in 4.4M additional commits.

² *fix* or *solve* ³ *bug*, *issue*, *problem*, *error*, or *misfeature* ⁴ <https://spacy.io/>

332 composing the sentence. Fig. 2 provides an example of t_i generated for the
 333 sentence “*fixes a search bug introduced by 2508e12*”.

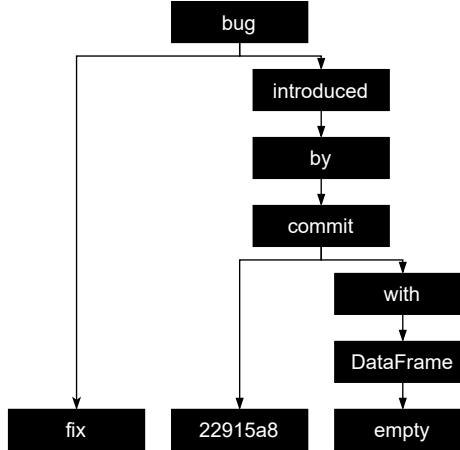


Figure 2: Example of word dependency tree built by SPACY.

334 By navigating the word dependency tree, we can infer that the verb “fix”
 335 refers to the noun “bug”, and that the verb “introduced” is linked to commit
 336 id 2508e12 through the “by” apposition.

337 **H1: Exclude Commits Without Reference and Reverts.** We split
 338 each $s_i \in S_c$ into words and we select all its commit hashes $H(s_i)$ using
 339 a regular expression⁵. We ignore all the s_i for which $H(s_i)$ is empty (*i.e.*,
 340 which do not mention any commit hash). Similarly, we filter out all the s_i
 341 that either (i) start with a commit hash, or (ii) include the verb “revert”
 342 referring to any $h_j \in H(s_i)$. We keep all the remaining s_i . We exclude the
 343 commits that do not contain any valid sentence as for this heuristic. We use
 344 the $H(s_i)$ extracted with this heuristic also for the following heuristics.

345 **H2: Coarsely Filter Explicit Introducing References.** If one of the
 346 ancestors of h_j is the verb “introduce” (in any declension), as it happens in
 347 Fig. 2, we consider this as a strong indication of the fact that the developer
 348 is indicating h_j as (one of) the bug-inducing commit(s). In this case, we
 349 check if h_j also includes at least one of the fix-related words² **and** one of the
 350 bug-related words³ as one of its ancestors or children. At least one of the
 351 two words (*i.e.*, the one indicating the fixing activity or the one referring
 352 to a bug) must be an ancestor. We do this to avoid erroneously selecting

⁵ [0-9a-f]{6,40}

353 sentences such as “*Improving feature introduced in 2508e12 and fixed a bug*”,
354 in which both the fix-related and the bug-related word are children of h_j .

355 For example, the h_j in Fig. 2 meets this constraint since it has among its
356 ancestors both *fix* and *bug*. We also exclude the cases in which the words
357 *attempt* or *test* (again, in different declensions) appear as ancestors of h_j . We
358 do this to exclude false positives observed while experimenting with earlier
359 versions of this heuristic.

360 For example, the sentence “*Remove attempt to fix error introduced in*
361 *2f780609*” belongs to a commit that aims at reverting previous changes. Simi-
362 larly, the sentence “*Add tests for the fix of the bug introduced in 2f780609*”
363 most likely belongs to the message of a test-introduction commit.

364 **H3: Finely Filter Non-Explicit Introducing References.** If h_j
365 does not contain the verb “introduce” as one of its ancestors, we apply a
366 finer filtering heuristic: both a word indicating a fixing activity **and** a word
367 indicating a bug must appear as one of h_j ’s ancestors. Also, we define a list
368 of stop-words that must not appear either in the h_j ’s ancestor as well as in
369 the dependencies (*i.e.*, ancestors and children) of the “fixing activity” word.
370 Such a stop-word list, derived through a trial-and-error procedure, includes
371 eight additional words (*was*, *been*, *seem*, *solved*, *fixed*, *try*, *trie* (to capture
372 *tries* and *tried*), and *by*), besides *attempt* and *test* also used in H2. This
373 allows, for example, to exclude sentences such as “*This definitely fixes the*
374 *bug I tried to fix in commit 26f3fe2*”, meets all selection criteria for H3, but
375 it is a false positive.

376 3.1.3. *Deletion of Duplicate Commits*

377 We saved the list of commits including at least one sentence s_i meeting H1
378 and either H2 or H3 in a MySQL database. Since we analyzed a large set of
379 projects, it was frequent that some commits were duplicated due to the fact
380 that different forks of a given project are available, or else they are cherry-pick
381 commits. This means that we consider as duplicates the commits that (i)
382 have the same commit message, (ii) reference the same BIC, and (iii) apply
383 the same change to the code. As a final step, we removed such duplicates,
384 keeping only the commit of the main project repository.

385 Out of the 24,042,335 parsed commits, the automated filtering selected
386 4,585 commits. Our goal with the above described process is not to be
387 exhaustive, *i.e.*, we do not want to identify all bug-fixing commits in which
388 developers indicated the bug-inducing commit(s), but rather to obtain a high-
389 quality dataset of commits that were certainly of the bug-inducing kind. The

390 quality of the dataset is then further increased during the subsequent step of
391 manual analysis.

392 *3.2. Manual Filtering*

393 Four of the authors (from now on, evaluators) manually inspected the
394 4,585 commits produced by the previous step. The evaluators have differ-
395 ent backgrounds (graduate student, faculty member, junior and a senior re-
396 searcher with two years of industrial experience). The goal of the manual
397 validation was to verify (i) whether the commit was an actual bug-fix, and
398 (ii) if it included in the commit message a non-ambiguous sentence clearly
399 indicating the commit(s) in which the fixed bug was introduced. For both
400 steps the evaluators mostly relied on the commit message and, if available,
401 on possible references to the issue tracker. Those references could be issue
402 IDs or links that the evaluators inspected to (i) ensure that the fixed issue
403 was a bug, and (ii) store for each commit the links to the mentioned issues
404 and, for each issue, its opening date.

405 The latter is an information that may be required by an SZZ implemen-
406 tation (*e.g.*, SZZ Unleashed (Borg et al., 2019) and OpenSZZ (Lenarduzzi
407 et al., 2020b) require the link to the issue) to exclude from the candidate
408 list of bug-inducing commits those performed after the opening of the fixed
409 issue.

410 Indeed, if the fixed bug has been already reported at date d_i , a commit
411 performed on date $d_j > d_i$ cannot be responsible for its introduction. Since
412 the commits to inspect come from a variety of software systems, they rely
413 on different issue trackers. When an explicit link was not available, but an
414 issue was mentioned in the commit message (*e.g.*, see the commit message
415 shown in the introduction), the evaluators searched for the project’s issue
416 tracker, looking on the GitHub repository for documentation pointing to
417 it (in case the project did not use the GitHub issue tracker itself). If no
418 information was found, an additional Google search was performed, looking
419 for the project website or directly searching for the issue ID mentioned in
420 the commit message.

421 The manual validation was supported by a web-based application we de-
422 veloped that assigns to each evaluator the candidate commits to review,
423 showing for each of them its commit message and a clickable link to the
424 commit GitHub page. Using a form, the evaluator indicated whether the
425 commit was relevant for the oracle (*i.e.*, an actual bug-fix documenting the
426 bug-inducing commit) or not, and listing mentioned issues together with

427 their opening date. Each commit was assigned by the web application to two
428 different evaluators, for a total of 8,231 evaluations. To be more conserva-
429 tive and to have higher confidence in our oracle, we decided to not resolve
430 conflicts (*i.e.*, cases in which one evaluator marked the commit as relevant
431 and the other as irrelevant): we excluded from our oracle all commits with
432 at least one “irrelevant” flag.

433 *3.3. The Resulting SZZ Oracle*

434 Out of the 4,585 manually validated commits, 2,304 (50%) passed our
435 manual filtering, of which 212 include references to a valid issue (*i.e.*, an issue
436 labeled as a bug that can be found online). For these, we also automatically
437 checked if the issue date is valid considering the extracted bug commit (*i.e.*,
438 the bug commit date must be before the issue date). This indicates that SZZ
439 implementations that rely on information from issue trackers can only be run
440 on a minority of bug-fixing commits. Indeed, the 2,304 instances we report
441 have been manually checked as true positive bug-fixes, and only 212 of these
442 (13%) mention the fixed issue. The dataset is available in our replication
443 package (Rosa et al., 2023).

444 These 2,304 commits and their related bug-inducing commits impact files
445 written in many different languages. All the implementations of the SZZ al-
446 gorithm (except for B-SZZ) perform some language-specific parsing to ignore
447 changes performed to code comments.

448 In our study (Section 4.1) we experimented several versions of the SZZ
449 including those requiring the parsing of comments. We implemented sup-
450 port for the top-8 programming languages present in our oracle (*i.e.*, the
451 ones responsible for more code commits): C, C++, C#, Java, JavaScript,
452 Ruby, PHP, and Python. This led to the creation of the dataset we use in
453 our experimentation, only including bug-fixing/inducing commits impacting
454 files written in one of the eight programming languages we support. This
455 dataset is also available in our replication package (Rosa et al., 2023). Ta-
456 ble 3 summarizes the main characteristics of the *overall* dataset and of the
457 *language-filtered* one. Note that the *language-filtered* dataset contains a lower
458 number of instances also for repositories having as a main language one of
459 the eight supported ones because some of their commits were related to un-
460 supported languages (*e.g.*, fixing a bug in a Maven pom file).

461 It is worth noting that a repository, or even a commit, can involve several
462 programming languages: for this reason, the *total* may be lower than the

Language	Overall			Language-filtered		
	#Repos	#Commits	#Issues	#Repos	#Commits	#Issues
C	406	520	62	343	430	43
Python	311	348	43	276	307	29
C++	187	223	25	159	189	19
JS	186	207	29	138	155	16
Java	92	106	14	74	83	8
PHP	65	73	6	57	64	3
Ruby	47	52	6	40	42	5
C#	31	38	3	25	32	1
Others	833	1077	99	0	0	0
Total	1,854	2,364	246	1,059	1,258	119

Table 3: Features of the *language-filtered* / *overall* datasets.

463 sum of the per-language values (*i.e.*, a repository can be counted in two or
464 more languages).

465 Besides sharing the datasets as JSON files, we also share the cloned repos-
466 itories from which the bug-fixing commits have been extracted. This enables
467 the replication of our study and the use of the datasets for the assessment of
468 future SZZ improvements.

469 4. Study 1: Evaluating SZZ Variants

470 In this section we report the updated results of our first study, in which
471 we use the oracle we built to evaluate state-of-the-art SZZ variants and tools.

472 4.1. Study Design

473 The *goal* of this study is to experiment different variants of the SZZ
474 algorithm. The *perspective* is that of researchers interested in assessing the
475 effectiveness of the state-of-the-art implementations and identify possible im-
476 provements that can be implemented to further improve the accuracy of the
477 SZZ algorithm. To achieve such a goal, we aim to answer the following
478 research question:

479 ***RQ₁*:** *How do different variants of SZZ perform in identifying*
480 *bug-inducing changes?* With this research question we want to
481 compare the various state-of-the-art SZZ implementations using
482 our dataset.

Table 4: Characteristics of the SZZ implementations we compare in the context of RQ₁. We mark with a “ \dagger ” our re-implementations.

Acronym	Fix Line Filtering	BIC Identification Method	BIC Filtering	BIC Selection	Differences w.r.t. the original paper
B-SZZ \dagger	-	Annotation Graph (Kim et al., 2006)	-	-	We use git <code>blame</code> instead of the CVS <code>annotate</code> , <i>i.e.</i> , we implicitly use an annotation graph (Kim et al., 2006). We do not filter BICs based on the issue creation date
AG-SZZ \dagger	Cosmetic changes (Kim et al., 2006)	Annotation Graph (Kim et al., 2006)	-	-	No differences
MA-SZZ \dagger	Cosmetic changes (Kim et al., 2006)	Annotation Graph (Kim et al., 2006)	Meta-Changes (Da Costa et al., 2016)	-	No differences
L-SZZ \dagger	Cosmetic Changes (Kim et al., 2006)	Annotation Graph (Kim et al., 2006)	Meta-Changes (Da Costa et al., 2016)	Largest (Davies et al., 2014)	We filter meta-changes (Da Costa et al., 2016)
R-SZZ \dagger	Cosmetic Changes (Kim et al., 2006)	Annotation Graph (Kim et al., 2006)	Meta-Changes (Da Costa et al., 2016)	Latest (Davies et al., 2014)	We filter meta-changes (Da Costa et al., 2016)
RA-SZZ* \dagger	Cosmetic Changes (Kim et al., 2006); Refactorings (Neto et al., 2019)	Annotation Graph (Kim et al., 2006)	Meta-Changes (Da Costa et al., 2016)	-	We use Refactoring Miner 2.0 (Tsantalis et al., 2020)
SZZ@PYD	Cosmetic Changes (Kim et al., 2006)	Annotation Graph (Kim et al., 2006)	-	-	We implement a wrapper for PyDRILLER (Spadini et al., 2018).
SZZ@UNL	Cosmetic Changes (Kim et al., 2006)	Line-number Mapping (Williams and Spacco, 2008a)	Issue-date (Sliwerski et al., 2005)	-	We implement a wrapper for SZZ Unleashed (Borg et al., 2019).
SZZ@OPN	-	Annotation Graph (Kim et al., 2006)	-	-	We implement a wrapper for OpenSZZ (Lenarduzzi et al., 2020b).

483 4.1.1. SZZ Implementations Compared

484 We used for our experiment different variants of the SZZ algorithm.
485 Specifically, re-implemented all the main approaches available in the liter-
486 ature (presented in Section 2) in a publicly available tool named `pyszsz`⁶
487 which also includes an adapted version of the PyDRILLER SZZ implemen-
488 tation (Spadini et al., 2018). Moreover, we adapted existing Open Source
489 tools (*i.e.*, SZZ Unleashed (Borg et al., 2019), and OpenSZZ (Lenarduzzi
490 et al., 2020b)) to work with our dataset. We provide a replication package
491 (Rosa et al., 2023) containing all the tools involved in the experiment with
492 instructions on how to run them.

493 We report the details about all the implementations we compare in Ta-
494 ble 4 and, for each of them, we explicitly mention (i) how it filters the lines
495 changed in the fix (*e.g.*, it removes cosmetic changes), (ii) which method-
496 ology it uses for identifying the preliminary set of bug-inducing commits
497 (*e.g.*, annotation graph), (iii) how it filters such a preliminary set (*e.g.*, it
498 removes meta-changes), and (iv) if it uses a heuristic for selecting a single
499 bug-inducing commit and, if so, which one (*e.g.*, most recent commit). We
500 also explicitly mention any difference between our implementations and the

⁶ <https://github.com/grosa1/pyszsz>

501 approaches as described in the original papers presenting them.

502 As most of the bug-fix pairs in our dataset do not contain the reference to
503 the bug-report ($\sim 91\%$), all our re-implementations are independent from the
504 issue-tracker systems. This is the reason why we did not set the “Issue-date”
505 as a default BIC filtering technique, despite it is reported in the respective
506 papers (*e.g.*, for B-SZZ). However, since we have extracted this information
507 where present, we experiment all of the variants with and without such a
508 filtering applied. Note that git tracks both the *author’s date* (*i.e.*, when
509 the commit was performed in the first place) and the *commit’s date*, which
510 the latter changing every time the commit is being modified (*e.g.*, due to a
511 rebasing of the branch). For the issue date filter we use the author’s date
512 since the commit’s date might make SZZ erroneously filter out some legit
513 bug-inducing commits. For example, let us consider an issue I reported at a
514 date d_I , and its bug-inducing commit C having an author’s date $da_C < d_I$
515 and a commit’s date $dc_C > d_I$. This indicates a situation in which the issue
516 was reported after the change was performed in the first place, but before
517 C has been modified due, for example, to a rebase. If we considered the
518 commit’s date, we would have discarded C as a bug-inducing commit as
519 performed after the issue was reported.

520 For the Open Source tools, instead, we did not modify their implemen-
521 tation of the BIC-finding procedures: *e.g.*, we did not remove the filtering
522 by issue date from SZZ Unleashed. However, our wrappers for such tools
523 allow to run them with our dataset. For example, SZZ Unleashed depends
524 on a specific issue-tracker system (*i.e.*, Jira) for filtering commits done after
525 the bug-report was opened. We made it independent from it by adapting
526 our datasets to the input it expects (*i.e.*, Jira issues in JSON format). It is
527 worth noting that, despite the complexity of such files, SZZ Unleashed only
528 uses the issue opening date in its implementation. For this reason, we only
529 provide such field and we set the others to `null`.

530 Note that some of the original implementations listed in Table 4 can
531 identify bug-fixing commits. In our study, we did not want to test such a
532 feature: we test a scenario in which the implementations already have the
533 bug-fixing commits for which they should detect the bug-inducing commit(s).

534 4.1.2. Study Context

535 To evaluate the described implementations, we defined two version of
536 the datasets extracted from the *language-filtered* dataset: (i) the $oracle_{all}$
537 dataset, featuring 1,258 bug-fixes, which includes both the ones with and

538 without issue information, and (ii) the $\text{oracle}_{\text{issues}}$ dataset, featuring 119 instances,
539 which includes only instances with issue information. Moreover,
540 we defined two additional datasets, $\text{oracle}_{\text{all}}^J$ (81 instances) and $\text{oracle}_{\text{issues}}^J$
541 (8 instances), obtained by considering only Java-related commits from the
542 $\text{oracle}_{\text{all}}$ and $\text{oracle}_{\text{issues}}$, respectively. We did this because two implemen-
543 tations, *i.e.*, RA-SZZ⁷ and OpenSZZ, only work on Java files.

544 *4.1.3. Experimental Procedure*

545 To answer RQ₁, we perform an experiment to compare the different SZZ
546 implementations. The *hypothesis* is that the evaluated SZZ variants provide
547 different performance in terms of detected bug-inducing changes. We have
548 as factor the SZZ variant. The treatments are the different SZZ variants
549 previously described. As a dependent variables, we have the metrics we
550 use to measure their performance (*i.e.*, *precision*, *recall*, *F1-score*). This
551 means that we ran all the implementations on all the datasets on which
552 they can be executed. This means that we run all the state-of-the-art SZZ
553 implementations and tools (Table 4) on $\text{oracle}_{\text{all}}$ and $\text{oracle}_{\text{issues}}$, except for
554 RA-SZZ* and OpenSZZ that are executed on the datasets including Java
555 files only.

556 Another exception is for SZZ Unleashed, that requires the issue date in
557 order to work. Since it would not be possible to run it on the $\text{oracle}_{\text{all}}$
558 dataset, we simulated the best-case-scenario for such commits: we pretended
559 that an issue about the bug was created few seconds after the last bug-
560 inducing commit was done. Consider the bug-fixing commit *BF* without
561 issue information and its set of bug-inducing commits *BIC*; we assumed
562 that the issue mentioned in *BF* had $\max_{b \in \text{BIC}}(\text{date}(b)) + \delta$ as opening date,
563 where δ is a small time interval (we used 60 seconds).

564 Such an experimental design allows us to compare all the implementations
565 in two scenarios: (i) the *realistic* scenario ($\text{oracle}_{\text{issues}}$), in which the issue
566 date is real, *i.e.*, it may be quite far from the BIC dates; (ii) the *best-case*
567 scenario (*i.e.*, $\text{oracle}_{\text{all}}$) in which real issue information would be available
568 only for a very small percentage of the bug-fixes instances, while the others
569 are simulated. Thus, when experimenting the SZZ variants not using the
570 issue opening date, the results we achieve are those one would achieve in re-
571 ality. Instead, when testing the approaches exploiting the issue opening date

⁷ It relies on Refactoring Miner (Tsantalis et al., 2020) which only works on Java files.

572 information, we are showing what would be the hypothetical effectiveness
 573 of such variants in the best case scenario in which all commits refer to an
 574 issue having an identifiable opening date and, for most of the commits, the
 575 opening of the related issue immediately follows the bug introduction.

576 In the end, we obtained a set of bug-inducing commits detected by the
 577 experimented implementations. Based on the oracle from our datasets, we
 578 evaluated their accuracy by using three widely-adopted metrics: recall, pre-
 579 cision, and F-measure (Baeza-Yates and Ribeiro-Neto, 1999).

580 In detail, we computed the such metrics using the following formulas:

$$581 \quad recall = \frac{|correct \cap identified|}{|correct|} \% \quad precision = \frac{|correct \cap identified|}{|identified|} \%$$

582 where *correct* and *identified* represent the set of true positive bug-inducing
 583 commits (those indicated by the developers in the commit message) and
 584 the set of bug-inducing commits detected by the experimented algorithm,
 585 respectively. As an aggregate indicator of precision and recall, we report the
 586 F-measure (Baeza-Yates and Ribeiro-Neto, 1999), defined as the harmonic
 587 mean of precision and recall. Such metrics were also used in previous works
 588 for evaluating SZZ variants (*e.g.*, Neto et al. (2019)).

589 Given the set of experimented SZZ variants/tools $SZZ_{exp} = \{v_1, v_2, \dots, v_n\}$,
 590 we also analyze their complementarity, by computing the following metrics
 591 for each v_i (Oliveto et al., 2010):

$$\begin{aligned} correct_{v_i \cap v_j} &= \frac{|correct_{v_i} \cap correct_{v_j}|}{|correct_{v_i} \cup correct_{v_j}|} \\ correct_{v_i \setminus (SZZ_{exp} \setminus v_i)} &= \frac{|correct_{v_i} \setminus correct_{(SZZ_{exp} \setminus v_i)}|}{|correct_{v_i} \cup correct_{(SZZ_{exp} \setminus v_i)}|} \end{aligned}$$

592 where $correct_{v_i}$ represents the set of correct bug-inducing commits detected
 593 by v_i and $correct_{(SZZ_{exp} \setminus v_i)}$ the correct bug-inducing commits detected by all
 594 other variants but v_i . $correct_{v_i \cap v_j}$ measures the overlap between the set of
 595 correct bug-inducing commits identified by two given implementations. We
 596 computed it by comparing in pairs each of experimented SZZ variants, thus
 597 measuring the percentage of correctly identified instances that are common
 598 for each pair. We reported the results using a heatmap H , where we have as
 599 rows i and columns j the evaluated SZZ variants. Thus, we have at $H[i_n, j_m]$
 600 the overlap measured between the two SZZ implementations corresponding
 601 to the row i_n and column j_m , respectively. $correct_{v_i \setminus (SZZ_{exp} \setminus v_i)}$, instead,
 602 measures the correct bug-inducing commits identified only by variant v_i and
 603 missed by all others experimented in RQ₁. It is worth clarifying that, when

604 we compute the overlap metrics, we compare all the implementations among
 605 them on the same dataset. This means, for example, that we do not compute
 606 the overlap between a variant tested on $oracle_{all}$ and another variant tested
 607 on $oracle_{issues}$.

608 As a last step, we compute the set of bug-fixing commits for which none of
 609 the experimented SZZ variants was able to correctly identify the bug-inducing
 610 commit(s). Then, we qualitatively discuss these cases to understand (i) the
 611 weak points of the applied heuristics and (ii) if it is possible to refine these
 612 heuristics to cover particular cases.

613 *4.2. Study Results*

Table 5: Precision, recall, and F-measure calculated for all SZZ algorithms in the context
 of RQ₁. † means Java only files.

	Algorithm	$oracle_{all}$				$oracle_{issue}$			
		Recall	Precision	F1	N	Recall	Precision	F1	N
No issue date filter	B-SZZ	0.68	0.39	0.49	1258	0.69	0.37	0.48	119
	AG-SZZ	0.65	0.38	0.48	1258	0.67	0.38	0.48	119
	L-SZZ	0.45	0.52	0.49	1258	0.43	0.50	0.46	119
	R-SZZ	0.57	0.66	0.61	1258	0.55	0.63	0.59	119
	MA-SZZ	0.63	0.36	0.46	1258	0.66	0.35	0.46	119
	†RA-SZZ*	0.49	0.22	0.31	81	0.50	0.22	0.31	8
	SZZ@PYD	0.67	0.39	0.49	1258	0.69	0.39	0.50	119
	SZZ@UNL	0.67	0.09	0.15	1258	0.71	0.06	0.11	119
	†SZZ@OPN	0.20	0.33	0.25	81	0.12	0.50	0.20	8
With date filter	B-SZZ	0.68	0.42	0.52	1258	0.69	0.38	0.49	119
	AG-SZZ	0.62	0.40	0.49	1258	0.67	0.39	0.49	119
	L-SZZ	0.47	0.55	0.51	1258	0.45	0.51	0.48	119
	R-SZZ	0.62	0.73	0.67	1258	0.57	0.66	0.61	119
	MA-SZZ	0.63	0.39	0.49	1258	0.66	0.36	0.47	119
	†RA-SZZ*	0.49	0.26	0.34	81	0.50	0.22	0.31	8
	SZZ@PYD	0.67	0.42	0.52	1258	0.69	0.41	0.51	119
	SZZ@UNL	0.67	0.09	0.15	1258	0.71	0.06	0.11	119
	†SZZ@OPN	0.20	0.34	0.25	81	0.12	0.50	0.20	8

614 Table 5 reports the results achieved by the experimented SZZ variants
 615 and tools. The top part of the table shows the results when the issue date
 616 filter has not been applied, while the bottom part relates to the application
 617 of the date filter. With “issue date filter” we refer to the process through
 618 which we remove from the list of candidate bug-inducing commits returned
 619 by a given variant all those performed after the issue documenting the bug
 620 has been opened. Those are known to be false positives. For this reason, such
 621 a filter is expected to never decrease recall (since the discarded bug-inducing

622 commits should all be false positives) while increasing precision. The left
623 part of Table 5 shows the results achieved on $oracle_{all}$, while the right part
624 focuses on $oracle_{issue}$.

625 R-SZZ achieves the highest F-Measure (61%) when not using the issue
626 date filtering (top part). Our implementation of R-SZZ uses the annotation
627 graph, ignores cosmetic changes and meta-changes (as MA-SZZ), and only
628 considers as bug-inducing commits the latest change that impacted a line
629 changed to fix the bug. Thanks to that combination of heuristics, R-SZZ
630 also achieves the highest precision on both oracles, achieving a precision score
631 of 66% on $oracle_{all}$ and 63% on $oracle_{issue}$.

632 B-SZZ, the simplest SZZ version, exhibits the highest recall score of 68%
633 on $oracle_{all}$ and 69% on $oracle_{issue}$, followed by PyDriller and SZZ@UNL.
634 Nonetheless, B-SZZ pays in precision, making it the fourth algorithm to-
635 gether with the PyDriller implementation for $oracle_{all}$ and the sixth for
636 $oracle_{issue}$. Due to the similarity between B-SZZ and the PyDriller im-
637 plementation, also their performances are quite similar.

638 Despite the recall/precision tradeoff, R-SZZ and B-SZZ are not heavily
639 affected in terms of recall score compared to SZZ@UNL (SZZ Unleashed). It
640 achieves 66% of recall on $oracle_{all}$ and 67% on $oracle_{issue}$ datasets, with a very
641 low precision of 9% and 6%, respectively. We investigated the reasons behind
642 such a low precision, finding that it is mainly due to a set of outlier bug-fixing
643 commits for which SZZ@UNL identifies a high number of (false positive) bug-
644 inducing commits. For example, three bug-fixing commits are responsible for
645 72 identified bug-inducing commits, out of which only three are correct. We
646 analyzed the distribution of bug-inducing commits reported by SZZ@UNL for
647 the different bug-fixing commits. Cases for which more than 20 bug-inducing
648 commits are identified for a single bug-fix can be considered outliers. By
649 ignoring those cases, the recall and precision of SZZ@UNL are 66% and 17%,
650 respectively on $oracle_{all}$, and 71% and 16% on $oracle_{issue}$. By lowering the
651 outlier threshold to 10 bug-inducing, the precision grows in both datasets
652 to 22%. We believe that the low precision of SZZ@UNL may be due to
653 misbehavior of the tool in few isolated cases.

654 Two implementations (*i.e.*, RA-SZZ* and SZZ@OPN) only work with
655 Java files. In this case, we compute their recall and precision by only con-
656 sidering the bug-fixing commits impacting Java files. Both of them exhibit
657 limited recall and precision. While this is due in part to limitations of the
658 implementations, it is also worth noting that the number of Java-related
659 commits in our datasets is quite limited (*i.e.*, 81 in $oracle_{all}$ and only 8

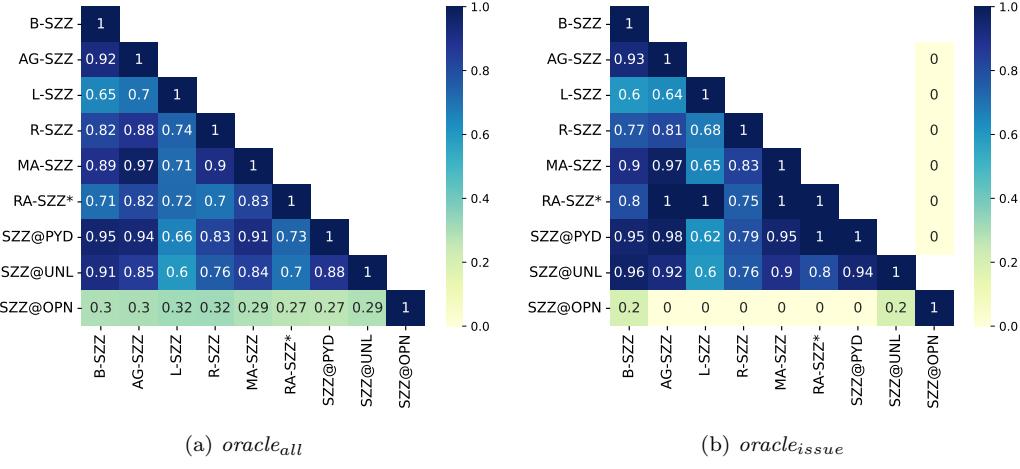


Figure 3: Overlap between SZZ variants, evaluated in RQ₁, when no issue date filter is applied.

in *oracle_{issue}*). Thus, failing on a few of those cases penalizes in terms of performance metrics.

AG-SZZ, L-SZZ, and MA-SZZ exhibit, as compared to others, good performance for both recall and precision. These algorithms provide a good balance between recall and precision, as also shown by their F-Measure (~50%).

The bottom of Table 5 shows the results achieved by the same algorithms when using the issue data filter.

As expected, the recall remains, for the most of the cases, equal to the previous scenario with marginal improvements in precision (thanks to the removal of some false positives). While most of the algorithms improve their precision by 1%-4%, R-SZZ obtain substantial improvements in the *oracle_{all}* dataset R-SZZ (+6%). This boosts the latter to a very good 73% precision on *oracle_{all}*, and 66% on *oracle_{issue}* (+3%).

To summarize the achieved results: We found that R-SZZ is the most precise variant on our datasets, with a precision ~70% when the issue date filter is applied. Thus, we recommend it when precision is more important than recall (*e.g.*, when a set of bug-inducing commits must be mined for qualitative analysis). If the focus is on recall, the current recommendation is to rely on B-SZZ, using, for example, the implementation provided by PyDriller. Finally, looking at Table 5, it is clear that there are still margins of improvement for the accuracy of the SZZ algorithm.

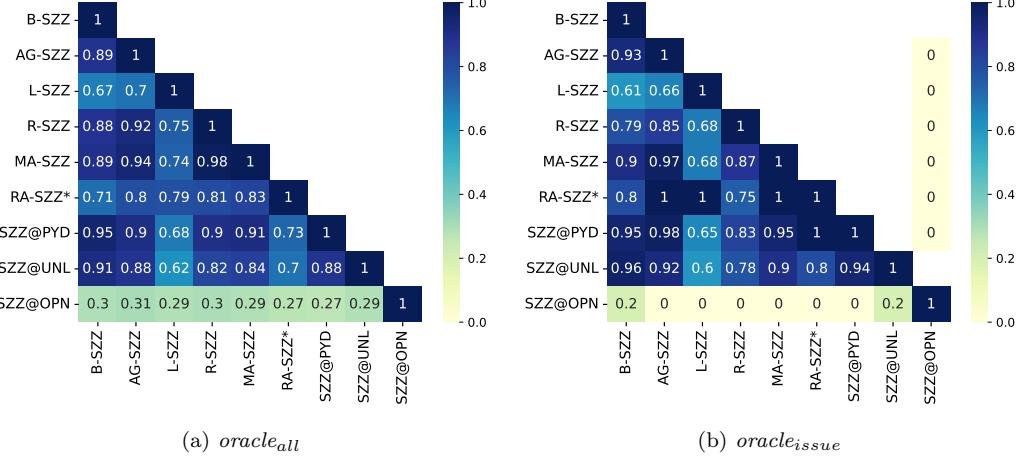


Figure 4: Overlap between SZZ variants, evaluated in RQ₁, when the issue date filter is applied.

Table 6 shows the $correct_{v_i \setminus (SZZ_{exp} \setminus v_i)}$ metric we computed for each SZZ variant v_i . This metric measures the correct bug-inducing commits identified only by variant v_i and missed by all the others.

Table 6: Bug inducing commits correctly identified exclusively by the v_i algorithm. † Java only files.

Algorithm	No date filter		With date filter	
	$oracle_{all}$	$oracle_{issue}$	$oracle_{all}$	$oracle_{issue}$
B-SZZ	1/898	0/86	1/898	0/86
AG-SZZ	0/898	0/86	0/898	0/86
L-SZZ	0/898	0/86	0/898	0/86
R-SZZ	0/898	0/86	0/898	0/86
MA-SZZ	0/898	0/86	0/898	0/86
†RA-SZZ*	0/56	0/5	0/56	0/5
SZZ@PYD	0/898	0/86	0/898	0/86
SZZ@UNL	19/898 (2%)	2/86 (2%)	19/898 (2%)	2/86 (2%)
†SZZ@OPN	0/56	0/5	0/56	0/5

Fig. 3a and Fig. 3b depict the $correct_{v_i \cap v_j}$ metric computed between each pair of SZZ variants when not filtering based on the issue date, while Fig. 4a and Fig. 4b show the same metric when the issue filter has been applied. Given the metric definition, the depicted heatmaps will be symmetric. To improve the readability, we keep only the lower triangular matrix (*i.e.*,

690 $\text{correct}_{v_i \cap v_j} = \text{correct}_{v_j \cap v_i}$). The only variant able to identify bug-inducing
691 commits missed by all others SZZ implementations is SZZ@UNL (19 on
692 oracle_{all} and 2 on oracle_{issue}) – Table 6. This is not surprising considering
693 the high SZZ@UNL recall and the high number of bug-inducing commits
694 it returns for certain bug-fixes. The main difference with the other evaluated
695 SZZ variants is the BIC identification method used (*i.e.*, Line-number
696 Mapping(Williams and Spacco, 2008a)). This can be the reason why none of
697 the other implementations identifies such bug-inducing commits: Given 898
698 as cardinality of the intersection of the true positives identified by all SZZ
699 variants, SZZ@UNL correctly retrieves 842 of them.

700 Looking at the overlap metrics in Fig. 3 and Fig. 4, two observations can
701 be made. First, the overlap in the identified true positives is substantial.
702 Excluding SZZ@OPN, 24 of the 28 comparisons have an overlap in the identified
703 true positives $\geq 70\%$ and the lower values are still in the range 60-70%.
704 The low overlap values observed for SZZ@OPN are instead due to its low
705 recall. Second, the complementarity between the different SZZ variants is
706 quite low, which indicates that there is a set of bug-fixing commits for which
707 all of the variants fail in identifying the correct bug-inducing commit(s).

708 4.2.1. Current Limitation of SZZ

709 We manually analyzed the cases in which *all* the variants we considered
710 failed to identify the correct BIC. We found that there are two possible
711 improvements that might help SZZ finding the correct BICs, which we discuss
712 below.

713 **The buggy line is not always impacted in the bug-fix.** In some
714 cases, fixing a bug introduced in line l may not result in changes performed to
715 l . An example in Java is the addition of an `if` guard statement checking for
716 `null` values before accessing a variable. In this case, while the bug has been
717 introduced with the code accessing the variable without checking whether
718 it is `null`, the bug-fixing commit does not impact such a line, it just adds
719 the needed `if` statement. An example from our dataset is the bug-fixing
720 commit from the `thcrap` repository⁸ in which line 289 is modified to fix a bug
721 introduced in commit `b67116d`, as pointed by the developer in the commit
722 message. However, the bug was introduced with changes performed on line
723 290. Thus, running git blame on line 289 of the fix commit will retrieve
724 a wrong bug-inducing commit. Defining approaches to identify the correct

⁸ <https://github.com/thpatch/thcrap/commit/29f1663>

725 bug-inducing commit in these cases is far from trivial. Also, in several bug-
726 fixing commits we inspected, the implemented changes included both added
727 and modified/deleted lines. SZZ implementations focus on the latter, since
728 there is no way to blame a newly added line. However, we found cases in
729 which the added lines were responsible for the bug-fixing, while the modi-
730 fied/deleted ones were unrelated. An example is commit `ca11949` from the
731 *snake* repository⁹, in which two lines are added and two deleted to fix a bug.
732 The deleted lines, while being the target of SZZ, are unrelated to the bug-
733 fix, as clear from the commit message pointing to commit `315a64b`¹⁰ as the
734 one responsible for the bug introduction. In the bug-inducing commit, the
735 developer refactored the code to simplify an `if` condition. While refactoring
736 the code, she introduced a bug (*i.e.*, she missed an `else` branch). The fixing
737 adds the `else` branch to the sequence of `if/else if` branches introduced
738 in the bug-inducing commit. In this case, by relying on static analysis, it
739 should be possible to link the added lines, representing the `else` branch, to
740 the set of `if/else if` statements preceding it. While the added lines cannot
741 be blamed, lines related to them (*e.g.*, acting on the same variable, being
742 part of the same “high-level construct” like in this case) could be blamed to
743 increase the chances of identifying the bug-inducing commit.

744 **SZZ is sensible to history rewriting.** Bird et al. (2009b) highlighted
745 some of the perils of mining git repositories, among which the possibility
746 for developers to rewrite the change history. This can be achieved through
747 rebasing, for example: using such a strategy can have an impact on mining
748 the change history (Kovalenko et al., 2018), and, therefore, on the perfor-
749 mance of the SZZ algorithm. Besides rebasing, git allows to partially rewrite
750 history by reverting changes introduced in one or more commits in the past.
751 This action is often performed by developers when a task they are working
752 on leads to a dead end. The revert command results in new commits in
753 the change history that turn back the indicated changes. Consequently, SZZ
754 can improperly show one of these commits as candidate bug-inducing. For
755 example, in the message of commit `5d8cee1` from the *xkb-switch* project¹¹,
756 the developer indicates that the bug she is fixing has been introduced in
757 commit `42abcc`. By performing a blame on the fix commit, git returns as a

⁹ <https://github.com/krmpotic/snake/commit/ca11949>

¹⁰ <https://github.com/krmpotic/snake/commit/315a64b>

¹¹ <https://github.com/grwlfxkb-switch/commit/5d8cee1>

758 bug-inducing commit 8b9cf29¹², which is a revert commit. By performing
759 an additional blame step, the correct bug-inducing commit pointed by the
760 developer can be retrieved¹³.

761 **5. New Heuristics for Improving SZZ**

762 Based on the discussed limitations, we propose two new heuristics aimed
763 at improving SZZ. In the first one, H_{DU} , we use data flow analysis to process
764 added lines in bug-fixing commits in order to identify unchanged lines that
765 might be the actual buggy lines on which the blame must be performed
766 to correctly retrieve the bug-inducing commits. In the second one, H_R , we
767 propose a heuristic that allows SZZ to be aware of reverted changes, *i.e.*,
768 changes that result in new commits that undo previous changes. While both
769 heuristics can be combined with any SZZ variant, we experiment them with
770 MA-SZZ and R-SZZ, providing four new variants that we implement in our
771 `pyszz` tool.

772 *5.1. H_{DU} : Handling Added Lines*

773 As outlined in Section 4.2, developers might add new lines to fix bugs,
774 but such lines are ignored by all SZZ variants. To overcome such a limitation,
775 it would be necessary to (i) identify the instructions functionally impacted
776 by the added lines and (ii) run the SZZ on those lines, assuming that some
777 of them induced the bug.

778 To achieve this goal, we define H_{DU} , a heuristic that relies on Definition-
779 Use Chains (DUCs) (Kennedy, 1978) to process added lines. We report below
780 the steps for running H_{DU} :

781 **Step 1: Building Definition-Use Chains.** A Definition-Use Chain
782 (DUC) is a data structure that links the definition of a variable to all its uses.
783 DUCs can be statically extracted from source code. To extract the DUCs
784 from a given file, we first identify all the declared functions or methods. Then,
785 for each of them, we parse each line and we assign the label def_v if it assigns
786 the variable v and the labels use_v if it uses variable v . For example, the line
787 `int a = b + c` is marked with the labels def_a , use_b , and use_c . Finally, for
788 each variable v , we link all the instruction that use v (marked with use_v) to
789 the nearest instruction that precedes and defines it (*i.e.*, marked with def_v).

¹² <https://github.com/grwlfxkb-switch/commit/8b9cf29>

¹³ <https://github.com/grwlfxkb-switch/commit/42abcc0>

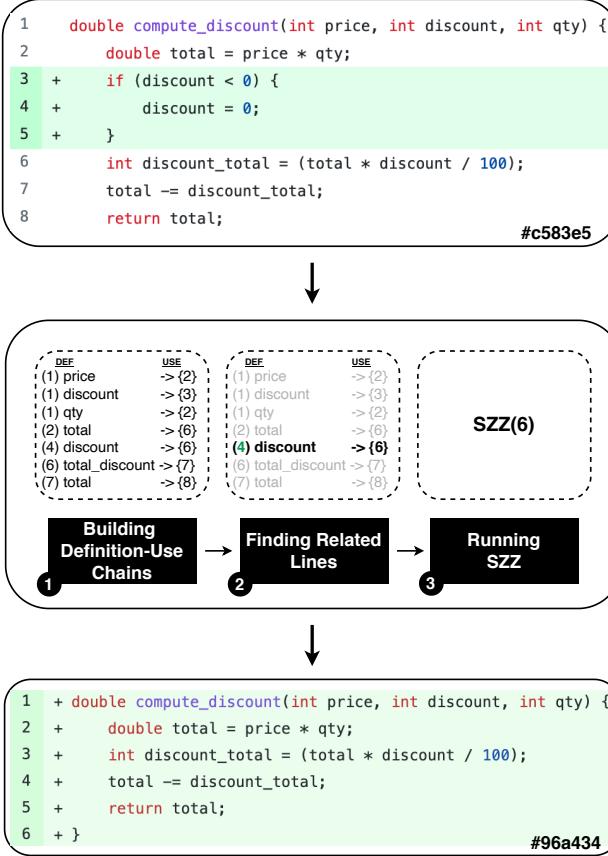


Figure 5: Example workflow of H_{DU} heuristic.

790 It is worth noting that for each instruction we keep the line number in which
 791 it appears. Therefore, we transform the instructions into line numbers, and
 792 determine which lines are related by definition-use relationships. The output
 793 of this step is a map DUM that associates each def line with its respective
 794 use lines.

795 **Step 2: Finding Related Lines.** Given the list of added lines L_a in
 796 the bug-fixing commit, we aim at finding related lines in DUM . We find
 797 for all the line numbers L_a their reference in DUM , where we extract the
 798 DUCs containing L_a . From the selected DUCs, for each def , we select the
 799 use line at distance $k = 1$. As a result, we obtain a set of $def - use$ pairs,
 800 from which we extract the referenced line numbers. Pairs involving the lines
 801 added in the bug-fixing commits are ignored, since it would not be possible

802 to run SZZ on them due to the lack of a change history.

803 **Step 3: Running SZZ.** As a final step, we use SZZ on all the lines
804 identified in the previous step, as if they were modified in the commit. The
805 assumption is that the commit that introduced/modified such lines was prob-
806 ably responsible for the introduction of the bug.

807 Fig. 5 shows an example of our H_{DU} heuristic. We implemented a pro-
808 totype implementation of H_{DU} for the *C* programming language, given the
809 need to perform language-dependent static analysis. We choose *C* because
810 it is the programming language with the largest number of instances in our
811 dataset. It is worth noting, however, that our methodology can be adapted
812 to other languages. We used **SrcML**¹⁴ to parse the input files and convert
813 them in XML-like format to support the static analysis.

814 *5.2. H_R : Filtering Revert Commits*

815 The second heuristic that we introduce is a filter for reverting changes.
816 As we found in our first study, SZZ is sensible to history rewritings: Rebase
817 operations and revert commits might be erroneously selected as bug-inducing
818 commits.

819 When a rebase operation is performed, the change history is entirely
820 wiped up to a specific commit. In such cases, it is impossible to go back to
821 the previous version of the history. In other words, rebase operations can
822 not be treated. Revert commits, instead, are additional commits that apply
823 inverse changes up to a given point. Therefore, revert commit explicitly
824 appear in the revision history. Similarly to what done in MA-SZZ, we
825 filter the SZZ output to ignore revert commits and reduce the number of
826 false positives. Therefore, we implemented H_R , a heuristic that leverages
827 the commit message to identify reverted commits and ignore them. Such a
828 filter consists in a simple string match using two patterns. With the first
829 one, we skip commit that contain the sequence “*This reverts commit*” in
830 the message. With the second pattern, we skip commits that start with
831 the sequence “*Revert*”. We define these two pattern taking into account the
832 default reverting commit message provided by git. This means that H_R can
833 not identify reverting commits having a customized commit message.

¹⁴ https://www.srcml.org/doc/c_srcML.html

834 6. Study 2: Evaluating the Proposed SZZ Heuristics

835 In this section we report our second study, in which we evaluate the two
836 novel heuristics we introduced.

837 6.1. Study Design

838 The *goal* of this study is to evaluate whether the two new heuristics we
839 propose, H_{DU} and H_R , allow to improve the accuracy of the SZZ algorithm.
840 In particular, we aim to answer the following research questions:

- 841 • **RQ₂:** *Does H_{DU} improve the accuracy of SZZ?* With this research
842 question, we want to evaluate the effectiveness of the heuristic we de-
843 fined for handling added lines.
- 844 • **RQ₃:** *Does H_R improve the accuracy of SZZ?* In this research question,
845 we aim to experiment our heuristic that allows SZZ to be aware of
846 reverting commits.

847 6.1.1. Study Context

848 We rely on the previously described $oracle_{all}$ and $oracle_{issues}$ dataset.
849 Since the implementation of our H_{DU} heuristic performs data flow analysis
850 for functions written in C, we defined two additional datasets: $oracle_{all}^C$ (397
851 instances) and $oracle_{issues}^C$ (40 instances), obtained by considering only C-
852 related commits from the $oracle_{all}$ (1,258 instances) and $oracle_{issues}$ (119
853 instances), respectively. That means we selected all the bug-fix commits
854 impacting only .c and .h source files.

855 6.1.2. Experimental Procedure

856 To answer RQ₂, we perform an experiment to evaluate the effectiveness
857 of the SZZ variants using the heuristics to process also added lines (H_{DU} and
858 A-SZZ (Sahal and Tosun, 2018)). The *hypothesis* is that using heuristics for
859 the processing of added lines improves the effectiveness of SZZ in terms of
860 detected bug-inducing changes.

861 As reported in Section 2, Sahal and Tosun (2018) proposed a heuristic to
862 run SZZ on all the lines belonging to the same instruction block, including
863 also the added lines. We re-implemented that heuristic as described in their
864 original paper (Sahal and Tosun, 2018). Furthermore, we implemented a
865 version of H_{DU} which supports C source code. To understand if H_{DU} allows
866 improving the accuracy of SZZ, we combine it (and also the baseline heuristic)

867 with two SZZ variants: MA-SZZ (*i.e.*, the implementation adopting the
868 most complete set of filtering heuristics, excluding RA-SZZ that only works
869 for Java code), and R-SZZ (*i.e.*, the one that achieved the best results in
870 our first study).

871 In total, we define four new variants: MA-SZZ@DU, MA-SZZ@A, R-
872 SZZ@DU, and R-SZZ@A. Note that the variants starting with “DU-” are
873 those adopting our H_{DU} heuristic, while those starting with “A-” are those
874 using the approach defined by Sahal and Tosun (2018). We run such variants
875 on the $oracle_{all}^C$ and the $oracle_{issues}^C$ datasets. As a reference baseline, we also
876 run the original SZZ implementation on these datasets. Thus, the *factor* of
877 the experiment is the SZZ variant. Specifically, the treatments are both the
878 SZZ variants able to process also added lines (MA-SZZ@DU, MA-SZZ@A,
879 R-SZZ@DU, and R-SZZ@A) and the respective base variants that can only
880 process deleted lines (MA-SZZ and R-SZZ). The *dependent variables* are
881 *precision*, *recall*, and *F1-score*.

882 To answer RQ₃, similarly to RQ₂, we conduct an experiment having
883 as *hypothesis* that using heuristics to handle revert commits improves the
884 effectiveness of SZZ in terms of identified bug-inducing commits. To achieve
885 this, we combine H_R with MA-SZZ and R-SZZ obtaining two new variants,
886 namely MA-SZZ@REV and R-SZZ@REV. We have as *factor*, again, the
887 SZZ variant. The treatments are both the variants based on the heuristic
888 H_R (MA-SZZ@REV and R-SZZ@REV) and the basic variants without it
889 (MA-SZZ and R-SZZ). The *dependent variables* are *precision*, *recall*, and
890 *F1-score*. Since H_R is not language-dependent, we run it on $oracle_{all}$ and
891 $oracle_{issues}$. Again, as a reference, we compare the results with the ones
892 obtained by MA-SZZ, R-SZZ, and B-SZZ.

893 As the last step, we compute the set of bug-fixing commits for which
894 none of the experimented SZZ variants was able to identify the bug-inducing
895 commit(s) correctly. Then, we qualitatively discuss these cases to understand
896 (i) the weak points of the applied heuristics and (ii) if it is possible to refine
897 these heuristics further to cover corner cases we did not consider.

898 *6.2. Study Results*

899 In the following subsection, we report the results to answer our research
900 questions.

Table 7: Precision, recall, and F-measure calculated for the SZZ algorithms evaluated in the context of RQ₂.

	Algorithm	$oracle_{all}^C$				$oracle_{issue}^C$			
		Recall	Precision	F1	N	Recall	Precision	F1	N
No filter	R-SZZ@A	0.51	0.54	0.53	397	0.40	0.40	0.40	40
	R-SZZ@DU	0.55	0.64	0.59	397	0.50	0.57	0.53	40
	R-SZZ	0.54	0.63	0.58	397	0.50	0.57	0.53	40
	MA-SZZ@A	0.73	0.06	0.12	397	0.68	0.03	0.06	40
	MA-SZZ@DU	0.62	0.28	0.38	397	0.57	0.20	0.29	40
	MA-SZZ	0.60	0.35	0.44	397	0.57	0.25	0.35	40
Issue date filter	R-SZZ@A	0.68	0.73	0.70	397	0.42	0.42	0.42	40
	R-SZZ@DU	0.60	0.72	0.66	397	0.53	0.60	0.56	40
	R-SZZ	0.59	0.72	0.65	397	0.53	0.60	0.56	40
	MA-SZZ@A	0.73	0.07	0.12	397	0.68	0.03	0.06	40
	MA-SZZ@DU	0.62	0.33	0.43	397	0.57	0.23	0.32	40
	MA-SZZ	0.60	0.37	0.46	397	0.57	0.26	0.35	40

6.2.1. **RQ₂**: Does H_{DU} improve the accuracy of SZZ?

Table 7 reports the resulting metrics for the six variants we compare based on R-SZZ and MA-SZZ.

When no issue date filter is applied, R-SZZ@DU is the best performing on $oracle_{all}^C$, followed by R-SZZ. Considering $oracle_{issues}^C$, both R-SZZ@DU and R-SZZ achieve an F-measure score of 53%. The same is true for Precision. R-SZZ@A is the worst performing variant, with an F-measure of 53% on $oracle_{all}^C$, which goes down to 40% for $oracle_{issues}^C$. However, MA-SZZ remains the best compared to its two variants regarding Recall and F-measure score. MA-SZZ@A have the lowest F-measure and Precision, obtaining the highest Recall of 73% and 68% on the two datasets. This is a consequence of the selection heuristic used where the entire code block encapsulating the added lines is returned.

The observed differences are related to the underlying BIC selection heuristic behind R-SZZ. With R-SZZ@A, the resulting BICs are filtered, selecting, for each instance, only the most recent commit, thus effectively reducing the disadvantage it has with MA-SZZ in terms of Precision, which, instead, does not filter the BICs. The same is true for R-SZZ@DU and MA-SZZ@DU, where the BIC filtering procedure used in R-SZZ (most recent commit) gives the same advantage to R-SZZ@A. However, as H_{DU} is more conservative than the heuristic by Sahal and Tosun (2018), the impact on Precision is always acceptable. For example, considering $oracle_{all}^C$,

923 MA-SZZ identifies a total of 688 bug-inducing changes against the 883 of
 924 MA-SZZ@DU and 4575 of MA-SZZ@A.

925 When the issue date filter is applied, similarly to RQ₁, there is a gen-
 926 eral improvement in the Precision score due to the reduced number of false-
 927 positive BICs.

928 In general, combining SZZ with heuristics that can process added lines
 929 improves SZZ. Therefore, both the heuristics work well when combined with
 930 R-SZZ and less well when combined with MA-SZZ.

931 6.2.2. **RQ₃**: Does H_R improve the accuracy of SZZ?

Table 8: Precision, recall, and F-measure calculated for the SZZ algorithms evaluated in the context of RQ₃.

	Algorithm	<i>oracle_{all}</i>				<i>oracle_{issue}</i>			
		Recall	Precision	F1	N	Recall	Precision	F1	N
No filter	MA-SZZ	0.63	0.36	0.46	1258	0.66	0.35	0.46	119
	MA-SZZ@REV	0.64	0.36	0.46	1258	0.66	0.36	0.47	119
With filter	R-SZZ	0.57	0.66	0.61	1258	0.55	0.63	0.59	119
	R-SZZ@REV	0.58	0.66	0.62	1258	0.57	0.65	0.61	119
With filter	MA-SZZ	0.63	0.39	0.48	1258	0.66	0.36	0.47	119
	MA-SZZ@REV	0.64	0.39	0.49	1258	0.66	0.37	0.47	119
With filter	R-SZZ	0.62	0.73	0.67	1258	0.57	0.66	0.61	119
	R-SZZ@REV	0.63	0.74	0.68	1258	0.59	0.67	0.63	119

932 We report in Table 8 the resulting metrics of our experiment. Both MA-
 933 SZZ@REV and R-SZZ@REV perform similar to MA-SZZ and R-SZZ,
 934 achieving a small improvement (~ 1%) with and without the issue date filter.
 935 When the issue date filter is applied, there is a general improvement in terms
 936 of Precision, as seen for RQ₁.

937 We can conclude that H_R only has a positive effect when combined with
 938 R-SZZ, where the BIC selection heuristic picks only one commit as a BIC
 939 candidate. As a consequence, the effectiveness of the revert commit filter is
 940 concrete only for some SZZ variants. Another point to consider is that the
 941 effectiveness of the heuristic directly depends on the presence of cases where
 942 there are revert commits. However, our heuristic never reduced the efficacy
 943 of the baselines: This means that H_R can be safely used on top of any SZZ
 944 variant, and we found no drawbacks in including it.

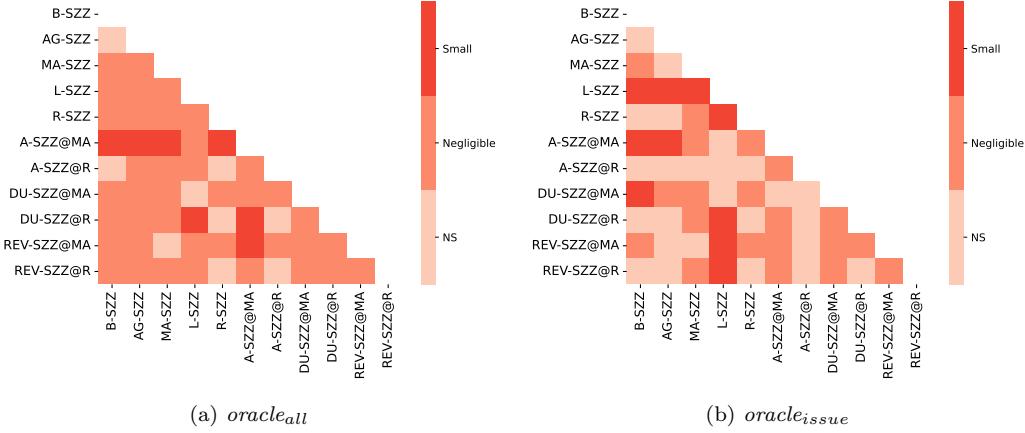


Figure 6: Cliff's delta magnitude computed between the correctness ratio values for pairs of SZZ variants, with no issue date filter applied

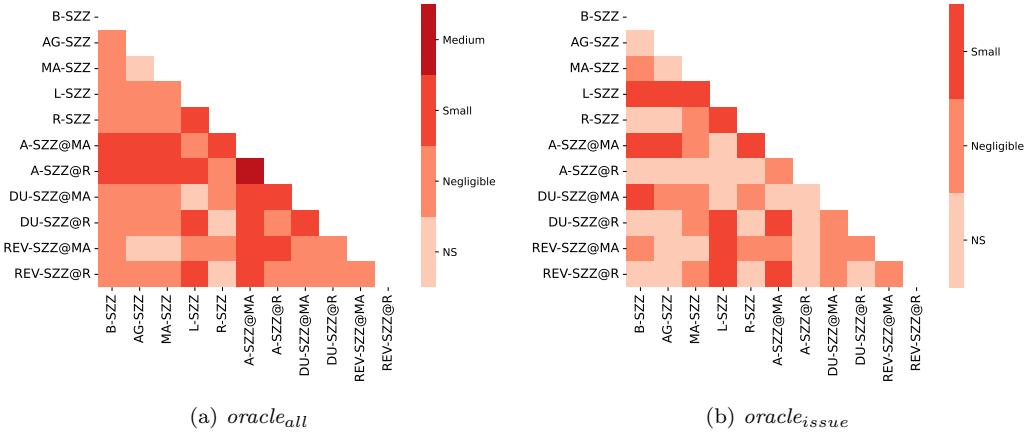


Figure 7: Cliff's delta magnitude computed between the correctness ratio values for pairs of SZZ variants, with issue date filter applied

Table 9: Correctness ratio computed among all evaluated SZZ approaches.

Algorithm	No issue date filter		With issue date filter	
	$oracle_{all}^C$	$oracle_{issues}^C$	$oracle_{all}^C$	$oracle_{issues}^C$
B-SZZ	32/397 (0.08)	6/40 (0.15)	19/397 (0.05)	5/40 (0.13)
AG-SZZ	4/397 (0.01)	0/40	0/397 (0.00)	0/40
MA-SZZ	1/397 (0.00)	0/40	0/397	0/40
L-SZZ	5/397 (0.01)	0/40	0/397	0/40
R-SZZ	2/397 (0.01)	20/40 (0.50)	1/397 (0.00)	21/40 (0.53)
MA-SZZ@A	10/397 (0.03)	2/40 (0.05)	3/397 (0.01)	2/40 (0.05)
R-SZZ@A	32/397 (0.08)	1/40 (0.03)	269/397 (0.68)	1/40 (0.03)
MA-SZZ@DU	0/397	0/40	0/397	0/40
R-SZZ@DU	218/397 (0.55)	0/40	12/397 (0.03)	0/40
MA-SZZ@REV	0/397	0/40	0/397	0/40
R-SZZ@REV	0/397	0/40	0/397	0/40

945 6.3. Evaluating Commit-Level Effectiveness of SZZ

946 In summary, our first and second studies show that (i) R-SZZ generally achieves the best results, and (ii) by considering added lines and revert commits, the accuracy of SZZ improves. Interestingly, we found such an advantage (mostly, the ones related to added lines) dependent on the context. 947 Some variants might work better in some cases, while some others in other 948 cases. Thus, we conduct an additional analysis where for each commit we 949 measure what is the best performing SZZ variant in terms of correctly 950 identified BICs. The *goal* of this analysis is to find out if the performance of the 951 SZZ variants are dependent on the context, *i.e.*, for each commit there is a 952 different variant which performs better than the others. To do this, for each 953 variant v_j and commit C_i , we compute the precision score for each bugfix 954 commit as follows:

$$F_{C_i}^{v_j} = \frac{|\text{identified}_{C_i}^{v_j} \cap \text{correct}_{C_i}|}{|\text{identified}_{C_i}^{v_j}|}$$

955 where $\text{identified}_{C_i}^{v_j}$ is the set of BICs returned by v_j for commit C_i , and 956 correct_{C_i} is the set of BICs correctly identified by v_j for the commit C_i . 957 The higher the score, the more the given variant is suitable for the commit. 958 For each commit C_i , we award a point to the SZZ variant(s), achieving the 959 highest score for C_i . Then, we sum such scores. In case there are more SZZ 960 implementations with the same score, we assign the point to the one that 961 also achieves the highest *F-measure* score on the entire dataset. We identify 962 the final resulting score as *correctness ratio*. This metric is comparable to the 963 964 965

966 *precision* score evaluated for all the SZZ variant for a single commit. Thus,
 967 it allows to measure which is the best variant of SZZ to use for each commit.
 968 In Table 9 we report the *correctness ratio* score. When the issue date filter
 969 is not applied, R-SZZ@DU achieves the highest score for $\text{oracle}_{\text{all}}^C$, while
 970 for $\text{oracle}_{\text{issues}}^C$ the best performing is R-SZZ. The SZZ variants that are less
 971 effective, without earning any points on both datasets, are MA-SZZ@DU,
 972 R-SZZ@REV, and MA-SZZ@REV. When the issue date filer is applied,
 973 R-SZZ@A achieves the highest *correctness ratio* score (68%) on $\text{oracle}_{\text{all}}^C$,
 974 while looking at $\text{oracle}_{\text{issues}}^C$ the top performer is still R-SZZ (53%). This
 975 confirms what we stated in RQ₂, that the best combination of line processing
 976 heuristic, BIC selection techniques and filters for SZZ depend on a specific
 977 bug-fixing context (*i.e.*, fix pattern). As the proposed heuristics give the best
 978 improvement to R-SZZ, we can also conclude that not all the SZZ heuristics
 979 are compatible, but some work better in combination with others. To verify
 980 this, for each commit, we pick only the best performing SZZ implementation
 981 to compare the resulting *F-measure* scores to the highest achieved in the
 982 context of RQ₂. Thus, we obtain an overall score of 0.71 (+0.12) for the
 983 dataset $\text{oracle}_{\text{all}}^C$ and 0.63 (+0.10) for $\text{oracle}_{\text{issues}}^C$, without applying the issue
 984 date filter. When the issue date filter is applied, we achieve 0.75 (+0.05)
 985 and 0.65 (+0.09), respectively. Surprisingly, both R-SZZ@REV and MA-
 986 SZZ@REV does not gain any points with and without filtering by issue date.
 987 This because the uniquely identified commits, looking at the results from
 988 RQ₃, do not impact C source files. Thus, the H_R does not give any advantage
 989 over the other SZZ implementations considering the C-only dataset. We also
 990 statistically compared the values of $F_{C_i}^{v_j}$ for each SZZ variant. In detail, we
 991 performed the Wilcoxon signed-rank test (Wilcoxon, 1945) between all pairs
 992 of SZZ variants to evaluate if there is a statistically significant difference
 993 between the resulting values. We applied the Benjamini-Hochberg *p-value*
 994 correction procedure (Benjamini and Hochberg, 1995) to account for multiple
 995 tests. For the SZZ pairs for which there is a statistically significant difference
 996 (*i.e.*, *p-value* < 0.05), we evaluated the effect size by computing the *Cliff's*
 997 *delta* (Cliff, 1993) between the two distributions. We report the results as
 998 heatmaps in Fig. 6 and Fig. 7 with and without the issue date filter applied,
 999 respectively. The values of the heatmaps are the effect size magnitude when
 1000 there is statistical significance, or *Not Significant (NS)* otherwise. In most
 1001 cases, there is a statistical significance with a *Negligible* effect size. The
 1002 detailed results can be found in our replication package (Rosa et al., 2023).

1003 **7. Discussion**

1004 In this section we report some examples on unidentified bug-inducing
1005 changes, and we discuss some points about the differences between our oracle
1006 and past oracles.

1007 *7.1. Unidentified BICs*

1008 There are still bug-inducing changes that the improved SZZ implemen-
1009 tation can not identify. A first example is commit b0f795 from *libmesh*
1010 repository¹⁵, where the C file extension is used for a C++ source file and
1011 only added lines are present as fixing change. Our SZZ implementations can
1012 not correctly process such files as they only work for C source code. Another
1013 example is commit d6ef40 from the repository *gxt/QEMU*¹⁶. In that case,
1014 the bug and the fix impact different files (*cpu-all.h* and *main.c*, respec-
1015 tively). It is interesting to notice that, in such a case, the commit message
1016 of the bug-fixing commit contains a reference to the file involved in the bug-
1017 inducing commit: “...but we need to at least define the *reserved_va* global
1018 so that *cpu-all.h*’s *RESERVED_VA* macro will work correctly.”. A similar ob-
1019 servation can be done for commit aebda6 from *OpenChannelSSD/linux*¹⁷:
1020 To identify the bug-inducing change, SZZ has to process lines that are not
1021 related to those impacted by the fix (e.g., line 548). In this case, the commit
1022 message contains information about the method impacted by the fix: “...to
1023 fix the issue, as we have to do is make sure that our *start_config_issued*
1024 flag gets reset whenever we receive a *SetInterface* request.” This shows
1025 that it can be possible to use NLP-based techniques to extract information
1026 about code artifacts indirectly affected by a commit, using such a piece of
1027 information to improve the effectiveness of SZZ.

1028 *7.2. Differences with Past Oracles*

1029 Table 10 shows the recall and precision of the SZZ variants for studies
1030 in the literature also evaluating SZZ and its variants. We only focus on
1031 studies adopting our same evaluation metrics. All of them but Petrus et al.
1032 (2022) use oracles defined by researchers. Petrus et al. (2022) evaluate
1033 different SZZ variants using Mozilla’s benchmark dataset which is manually
1034 annotated by developers from Mozilla. This means that the oracle from

¹⁵ <https://github.com/libMesh/libmesh/commit/b0f7953>

¹⁶ <https://github.com/gxt/QEMU/commit/d6ef40b>

¹⁷ <https://github.com/OpenChannelSSD/linux/commit/aebda61>

Table 10: Summary table of the other studies from the literature using comparable evaluation metrics with our work. For each variant we report the values of *Precision* (P), *Recall* (R), the size of the dataset used for the evaluation (N).

Study	B-SZZ		AG-SZZ		MA-SZZ		L-SZZ		R-SZZ		N
	R	P	R	P	R	P	R	P	R	P	
Davies et al. (2014)	0.59	0.50	-	-	-	-	-	-	-	-	431
Wen et al. (2016)	-	0.64	0.69	-	-	-	-	-	-	-	357
Rodríguez-Pérez et al. (2020)	0.71	0.32	0.76	0.34	-	-	-	-	0.53	0.51	116
Bludau and Pretschner (2022)	0.62	0.34	0.21	0.26	0.26	0.19	0.19	0.32	0.17	0.29	300
Petrulio et al. (2022)	0.47	0.58	0.38	0.50	-	-	0.29	0.27	0.39	0.50	1,586
Our work (with date filter)	0.68	0.42	0.65	0.40	0.63	0.39	0.47	0.55	0.62	0.73	1,258

1035 Mozilla’s dataset is the most similar to our oracle, with the exception that it is
1036 manually annotated and not automatically generated. The studies of Petrulio
1037 et al. (2022) and Bludau and Pretschner (2022) conducted their evaluation
1038 using the first version of our `pyszz` tool, proposed in our previous work (Rosa
1039 et al., 2021) and extended in this paper. However, their results are lower
1040 compared to what we achieved on our dataset. According to Petrulio et al.
1041 (2022), this could be due to differences in the datasets, with our dataset
1042 not featuring ghost commits (Rezk et al., 2021), *i.e.*, BICs that can not be
1043 detected by SZZ since related to added lines, and extrinsic bugs (Rodríguez-
1044 Pérez et al., 2020), *i.e.*, changes from external dependencies not part of the
1045 repository. This directly affects the performance of SZZ, giving a boost when
1046 compared to Mozilla’s benchmark. As the authors explain, this could be due
1047 to the methodology we used to build the oracle. In fact, those cases seem to
1048 be present only if the bug was manually annotated by the developer when
1049 starting from a bug report.

1050 We can summarize the differences between the results in our study and
1051 those reported in previous oracles with the following points.

1052 **Recall and Precision.** SZZ obtains better performance (Table 5) when
1053 using our dataset, compared to the others existing in the literature (Table 10).
1054 This might be due to the fact that some particular cases, commonly present
1055 in bug-fix commits datasets, are absent in our dataset (Petrulio et al., 2022).

1056 **Scalability.** Although a manual effort is required in our case, it will be
1057 lower as compared to the manual effort spent to manually annotate datasets
1058 in the literature. We can reduce further the required manual effort by using
1059 only the H1 and H2 filters in our mining heuristics. This allows considering
1060 only those commits with explicit BIC reference, which are less prone to false

1061 positives.

1062 7.3. Implications

1063 Our work has various implications for both academia and industry. Con-
1064 cerning the former, we provide a high-quality dataset of bug-fixing and bug-
1065 inducing commits which, as documented in the literature, it is difficult and
1066 expensive to build (Herbold et al., 2022; Hosseini et al., 2017). In addition,
1067 we explored the benefits brought by SZZ heuristics considering the entire line
1068 of bug-fix by including both deleted and added lines (Hosseini et al., 2017),
1069 showing that the impact on the algorithm accuracy is limited.

1070 In industrial practice, there is evidence that SZZ is used in the evaluation
1071 of defect prediction tools (Bowes et al., 2017). Given the performance we
1072 obtained (*i.e.*, precision and recall values around 60-70%), the quality of
1073 the datasets used for defect prediction approaches (Fan et al., 2019; Herbold
1074 et al., 2022) might be lower than expected.

1075 *Generalizability of H_R .* Our heuristic can be extended to other types of
1076 changes that do not significantly alter commit history, such as *cherry-pick*.
1077 In the case of *squash* commits, most probably SZZ will simply go back in
1078 the history until the BIC is found, or it was part of the squashing, and the
1079 resulting commit containing all the squashed changes will be identified as
1080 BIC. In any case, further investigation is required for these particular cases.

1081 7.4. Limitations of our oracle.

1082 While it is true that we leverage information on the BIC related to specific
1083 bug fixing commits, we do not verify our oracle through a manual verification
1084 of the bug and the fix performed by the original developers. There is a chance
1085 that, in some cases, the commit reported as BIC is not the source of the
1086 bug, but a symptom. Also, the fix could be performed by more than one
1087 commit. However, we are interested in finding the association between a fix
1088 commit and its BIC, reported by the developer at that time (*i.e.*, with the
1089 intention of the performed change) assuming that the reported BIC comes
1090 from the knowledge that comes from the fact that he/she developed that
1091 system. Thus, if a developer performs several changes to fix a bug, he/she
1092 probably refers to the same BIC in the commit messages.

1093 8. Threats to Validity

1094 *Construct validity.* During the manual validation, the evaluators mainly
1095 relied on the commit message and the linked issue(s), when available, to con-

1096 firm that a mined commit was a bug-fixing commit. Misleading information
1097 in the commit message could result in the introduction of false positive instances
1098 in our dataset. However, all commits have been checked by at least
1099 two evaluators and doubtful cases have been excluded, privileging a conserva-
1100 tive approach. To build our dataset, we considered all the projects from
1101 GitHub, without explicitly defining criteria to select only projects that are
1102 invested in software quality. Our assumption is that the fact that developers
1103 take care of documenting the bug-introducing commit(s) is an indication that
1104 they care about software quality. To ensure that the commits in our dataset
1105 are from projects that take quality into account, we manually analyzed 123
1106 projects from our dataset, which allowed us to cover a significant sample of
1107 commits (286 out of 1,115, with $95\% \pm 5\%$ confidence level). For each of them,
1108 we checked if they contained elements that indicate a certain degree of at-
1109 tention to software quality, *i.e.*, (i) unit test cases, (ii) code reviews (through
1110 pull requests), (iii) and continuous integration pipelines. We found that in
1111 95% of the projects, developers (i) wrote unit test cases, and (ii) conducted
1112 code reviews through pull requests. Also, we found CI pipelines in 75% of
1113 the projects.

1114 *Internal validity.* There is a possible subjectiveness introduced of the
1115 manual analysis, which has been mitigated with multiple evaluators per bug-
1116 fix. Also, we reimplemented most of the experimented SZZ approaches, thus
1117 possibly introducing variations as compared to what proposed by the original
1118 authors. We followed the description of the approaches in the original papers,
1119 documented in Table 4 any difference between our implementations and the
1120 original proposals, and share our implementations (Rosa et al., 2023). Also,
1121 note that the differences documented in Table 4 always aim at improving
1122 the performance of the SZZ variants and, thus, should not be detrimental
1123 for their performance. Another point is that our new implementations of
1124 H_{DU} and A-SZZ can have critical point or exceptional cases actually not
1125 handled. For example, when construct Definition-Use chains only at method
1126 level, thus as discussed in Section 7 there are some cases where our heuristic
1127 can not identify the correct BIC. Also, for MA-SZZ@A and R-SZZ@A,
1128 currently we do not apply the BICs filter described in the paper, where they
1129 select at most 4 commits as BIC. This because we replaced that filter with
1130 the filtering heuristic of R-SZZ.

1131 *External validity.* While it is true that we mined millions of commits to
1132 build our dataset, we used very strict filtering criteria that resulted in 2,304
1133 instances for our oracle. Also, the SZZ implementations have been experi-

1134 mented on a smaller dataset of 1,258 instances that is, however, still larger
1135 than those used in previous works. Finally, our dataset represents a subset
1136 of the bug-fixes performed by developers. This is due to our design choice,
1137 where we used strict selection criteria when building our oracle to prefer qual-
1138 ity over quantity. It is possible that our dataset is biased towards a specific
1139 type of bug-fixing commits: there might be an inherent difference between
1140 the bug fixes for which developers document the bug-inducing commit(s)
1141 (*i.e.*, the only ones we considered) and other bug fixes.

1142 While, to date, this is the largest dataset to evaluate SZZ implemen-
1143 tations, additional mining and different filtering heuristics could help in im-
1144 proving the generalizability of our findings.

1145 In industrial settings, bugs are usually reported and then fixed using issue
1146 trackers (Zhang, 2020). This means that developers less probably annotate
1147 the BIC in the commit message, but they report the issue link to the fixed
1148 bug. Thus, the applicability of our methodology needs to be furtherly inves-
1149 tigated.

1150 9. Conclusion and Future Works

1151 Exploring new ways to improve the effectiveness of SZZ can be relevant
1152 for both industry and academia. In this paper, we proposed a developer-
1153 informed dataset for the evaluation of SZZ. We use that dataset to perform
1154 a thorough comparison of existing variants of the algorithm, including two
1155 new heuristics, namely H_{DU} and H_R . Based on our findings, the best per-
1156 forming SZZ variant is R-SZZ. The newly evaluated heuristics to enrich SZZ
1157 (H_{DU} and H_R), applied on the top of R-SZZ and MA-SZZ, provide a slight
1158 improvement in terms of *precision* and *recall* (*i.e.*, +1-2%) compared to the
1159 original versions. One possible future direction aimed at further improve per-
1160 formance could be the combination of different SZZ variants, trying to exploit
1161 their individual strengths and applying the most appropriate one based on
1162 the specific bug-fixing commit at hand.

1163 10. Data Availability

1164 The complete study material, data, and source code of our re-implementations
1165 are fully available in our replication package (Rosa et al., 2023).

1166 **CRediT authorship statement**

1167 **Giovanni Rosa:** Conceptualization, Data curation, Formal analysis, In-
1168 vestigation, Methodology, Software, Validation, Visualization, Writing. **Luca**
1169 **Pacarella:** Conceptualization, Data curation, Formal analysis, Investiga-
1170 tion, Methodology, Software, Validation, Visualization, Writing. **Simone**
1171 **Scalabrino:** Conceptualization, Methodology, Formal analysis, Visualiza-
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1173 tion, Writing. **Gabriele Bavota:** Conceptualization, Funding acquisition,
1174 Methodology, Supervision, Writing. **Michele Lanza:** Conceptualization,
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1176 Conceptualization, Funding acquisition, Methodology, Supervision, Writing.

1177 **Declaration of competing interest**

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