

# Cross-Version Defect Prediction: Does Excessive Train-Test Similarity Affect the Reliability of Evaluation?

Zsuzsanna Oneț-Marian<sup>a</sup> and Diana-Lucia (Miholca) Hotea<sup>b</sup>

*Faculty of Mathematics and Computer Science,  
Babeș-Bolyai University, 400084, Cluj-Napoca, Romania  
{zsuzsanna.onet, diana.miholca}@ubbcluj.ro*

**Keywords:** Cross-Version Defect Prediction, Machine Learning, Train-Test Similarity, Performance Evaluation.

**Abstract:** Software Defect Prediction is defined as the automated identification of defective components within a software system. Its significance and applicability are extensive. The most realistic way of performing defect prediction is in the cross-version scenario. However, although emerging, this scenario is still relatively understudied. The prevalent approach in the cross-version defect prediction literature is to consider two successive software versions as the train-test pair, expecting them to be similar to each other. Some approaches even propose to increase this similarity by augmenting or, on the contrary, filtering the training set derived from historical data. In this paper, we analyze in detail the similarity between the instances in 28 pairs of successive software versions and perform a comparative supervised machine learning study to assess its impact on the reliability of cross-version defect prediction evaluation. We employ three ensemble learning models, Random Forest, AdaBoost and XGBoost, and evaluate them in different scenarios. The experimental results indicate that the soundness of the evaluation is questionable, since excessive train-test similarity, in terms of identical or highly similar instances, inflates the measured performance.

## 1 INTRODUCTION

Software Defect Prediction (SDP) consists in automatically identifying defective components in a software system.


Relatively recently, SDP has become one of the most active subdomains in Software Engineering (Zhang et al., 2021), which is not surprising given its broad applicability in the context of increasing software complexity. SDP helps to increase the cost effectiveness of software quality assurance. By identifying defect-prone software components in new versions of a software system, it allows to prioritize the allocation of testing and fixing efforts for those components (Xu et al., 2018b).


Depending on where the training and testing data come from, SDP approaches can be categorized into two primary groups: Cross-Project Defect Prediction (CPDP) and Within-Project Defect Prediction (WPDP) (Cohen et al., 2022). CPDP involves transfer learning by using data from one software project to train a model which is then used to conduct SDP on another project. In contrast to this, WPDP aims to find

software defects in a given project using data from the same project. In turn, WPDP divides into two subcategories: Within-Version Defect Prediction (WVDP) and Cross-Version Defect Prediction (CVDP). Under WVDP, data from the same software version is split into training data and testing data. Unlike this, CVDP uses historical versions of data for training, while testing the predictor on the upcoming version.

When comparing CVDP to its within-project alternative, that is WVDP, although in the within-version scenario the data is typically more uniform, it is also typically scarce (Xu et al., 2018b) and, very important, the within-version scenario is less realistic (Cohen et al., 2022) since it is unlikely that a part of the instances for a new software version are already labeled according to their defectiveness so as to be usable for training. In the case of projects with multiple versions, CVDP is by far a more practical scenario (Zhao et al., 2022b) as labeled data is usually available due to defect reporting (Lu et al., 2014).

A current software version usually inherits and updates some components from the previous version (or more previous versions), which results in a more comparable distribution of defect data across versions than across projects (Zhang et al., 2021). The minimal

<sup>a</sup>  <https://orcid.org/0000-0001-9006-0389>

<sup>b</sup>  <https://orcid.org/0000-0002-3832-7848>

change in the distribution of defects is also expected due to the fact that the project team is usually fixed and there is a correlation between the developer's programming habits and the business code (Wang et al., 2022). As a consequence, CVDP is also more realistic than CPDP, being more reasonable to expect similarity between different versions than between different projects (Kabir et al., 2021).

Due to its realistic nature, CVDP has emerged in recent years, but there are still relatively few studies under this SDP category (Zhang et al., 2021), prevalent being the studies on WVPD or CPDP (Zhao et al., 2022b).

While there are proposals in the CVDP literature for further increasing the similarity between the training and testing data (Lu et al., 2014; Xu et al., 2018b; Amasaki, 2017; Xu et al., 2018a; Xu et al., 2019), the opposite problem is highly understudied: what happens when the training data and the testing data are too similar? A basic principle of evaluating any prediction model is that the model should be evaluated on data that was not used during training. This is why train-test splits or cross-validation are used. However, when consecutive versions of a software system are considered, we expect them to be similar to each other. Considering an object-oriented software system, it is very likely that many classes with the same name exist in consecutive versions, and even if the code in some classes can change from a prior version to the next one, we expect many classes to remain unchanged (Zhang et al., 2020; Wang et al., 2022). These unchanged classes will probably have identical feature vectors (except for the case when the value of a software metric used in the representation of the class changes, even if the source code of the class itself does not change, for example, for the *number of children* metric). Identical feature vectors can cause problems in the case of a CVDP scenario, because training data can contain instances that are also part of the testing data, introducing bias in the evaluation of the result and making the measured performance unrealistic, overestimating it due to the non-empty intersection of training and testing data sets.

On the other hand, the source code in some classes changes and, consequently, the class label for some classes may also change. Classes that are defective in one version may be fixed for the next version, and classes that are not defective in one version might suffer defect-inducing modifications for the next one. A good CVDP approach should be capable of identifying those classes for which the class label changed from one version to another, since a model that predicts the same label as in the previous version is only moderately useful in practice (it might still have good

performance in predicting the defectiveness of newly introduced classes). Identifying the correct class label might be complicated by the presence of classes for which the feature vector is almost the same in two consecutive versions (especially if they have different labels), since many Machine Learning (ML) models are based on the idea that instances that are close to each other should have the same label.

The issue of having common instances in consecutive versions with identical feature vectors was mentioned by (Zhang et al., 2020) as a motivation for their approach, but they did not fully analyze the extent of the phenomenon and did not evaluate its consequences. The purpose of this paper is to investigate the presence of identical and very similar data in training and testing data sets and to evaluate how they influence the performance of CVDP models. Thus, we have defined the following research questions:

- **RQ1:** How prevalent is the occurrence of identical and very similar instances across two consecutive versions of a software system?
- **RQ2:** How does the presence of identical and very similar instances influence the performance of CVDP models?

In order to answer the first above-formulated research question, we perform a detailed analysis on the similarity between 28 pairs of consecutive versions of the most frequently studied software projects in the CVDP literature.

We address the second research question through a comparative empirical study carried out from a supervised ML perspective. We employ three different ensemble learning models, Random Forest, AdaBoost and XGBoost, and evaluate them in five different scenarios.

The main contributions of this empirical study are:

- First, we analyze in detail the similarities between instances in 28 pairs of versions, belonging to 11 software systems. The authors of (Zhang et al., 2020) performed a related study in which they have shown that the distribution of defective instances is different across versions, that this difference affects the CVDP performance and that there are instances in consecutive versions with the same name for which the distance between their feature vectors is very low. They did not study in detail the distribution of these instances and the effect of their presence on the predictive performance of ML-based CVDP models.
- Second, we show that the most frequently used scenario to evaluate CVDP approaches does not provide a realistic view of the practical usefulness

of the model. To the best of our knowledge, this issue was not yet presented in the literature.

The rest of the paper is structured as follows. Section 2 reviews the literature on CVDP. Section 3 details the methodology of our empirical study, the results of which are presented and discussed in Section 4. Possible threats to the validity of our research together with our strategy to mitigate them are presented in Section 5. In Section 6 we draw conclusions and outline directions for future work.

## 2 LITERATURE REVIEW

In the following, we summarize the existing literature on CVDP, while focusing on the methodology for selecting the training data.

We have identified three main directions for the training data set selection when it comes to CVDP:

1. Considering exclusively and entirely the previous version (Yang and Wen, 2018; Shukla et al., 2016; Wang et al., 2022; Li et al., 2018; Wang et al., 2016; Zhao et al., 2022a; Bennin et al., 2016; Cohen et al., 2022; Zhang et al., 2021; Huo and Li, 2019; Yu et al., 2024; Ouellet and Badri, 2023; Fan et al., 2019);
2. Merging all previous versions to build the training set (Chen and Ma, 2015; Chen et al., 2019);
3. Applying a methodology for finding a suitable training set from historical data (Xu et al., 2018a; Xu et al., 2018b; Zhang et al., 2020; Amasaki, 2017; Lu et al., 2014; Wang et al., 2022; Amasaki, 2018; Amasaki, 2020; Xu et al., 2019; Kabir et al., 2020; Kabir et al., 2023; Zhao et al., 2022b; Harman et al., 2014).

We note that a large proportion of approaches simply consider the immediately previous version, as it is, to train the CVDP model. The articles either do not explicitly motivate this choice or attribute it to the expectation that two successive versions share more identical characteristics (Shukla et al., 2016; Zhao et al., 2022a).

On the other side, of those concerned with selecting the right training set (in the third category), a significant proportion (Harman et al., 2014; Amasaki, 2018; Amasaki, 2020; Kabir et al., 2020; Zhao et al., 2022b; Kabir et al., 2023) choose from the previous version, all previous versions, or some previous versions on the criterion of increasing train-test similarity. Therefore, these approaches eventually boil down to one of the first two directions or an intermediate alternative where several, but not all, earlier versions are chosen. As in the case of the approaches that lie

in one of the first categories, these approaches do not filter out the instances of previous versions but just possibly merge them.

However, there are also some approaches that alter the content of the data sets afferent to previous versions.

For instance, others in the third category (Lu et al., 2014; Xu et al., 2018b) employ Active Learning in CVDP by enriching the training data consisting of the instances of the previous version(s) with some labeled instances selected from the current version under test. In such an approach, testing is performed on the remaining unlabeled instances of the current version. Lu et al. (Lu et al., 2014) were the first to introduce active learning into CVDP to identify the most valuable components from the current version for labeling by querying domain experts and then merged them into the prior version to construct a hybrid training set. The authors motivate their approach by stating that supplementing the defect information from previous versions with limited information about the defects from the current version detected early offers intuitive benefits, accommodating changing defect dynamics between successive software versions. Their work is extended by Xu et al. (Xu et al., 2018b) who argue that the components selected from the current version in the initial active learning based approach are merely informative but not representative. In the extended approach, Hybrid Active Learning is employed, as an improvement over the approach introduced in (Lu et al., 2014), for selecting a subset of both informative and representative components of the current version to be labeled and subsequently merged into the labeled components of the prior version to form an enhanced training set. These approaches come at the cost of affecting the realistic nature of CVDP in addition to the additional cost brought by the manual labeling phase.

The third category also includes approaches (Amasaki, 2017; Xu et al., 2018a; Xu et al., 2019) that propose selecting a subset of the historical data, from the previous version or multiple previous versions, for training the CVDP model. The selection criterion is to increase the similarity between the training and test sets using Dissimilarity-based Sparse Subset Selection (Xu et al., 2018a), Nearest Neighbor filter (Amasaki, 2017) or Sparse Modeling Representative Selection in conjunction with Dissimilarity-based Sparse Subset Selection (Xu et al., 2019).

Only the two remaining approaches circumscribed to the third category, (Zhang et al., 2020) and (Wang et al., 2022), have been found to consider instance overlapping between a current version under test and previous versions.

Zhang et al. (Zhang et al., 2020) observed that two versions usually contain a large number of files with the same name whose feature vectors are very similar or even identical, but can have different labels and proposed an approach based on splitting the test instances into classes which exist in previous versions and newly introduced classes and treating them differently. For existing instances, clustering has been used to find similar instances from the previous versions. The objective function of the clustering is based on four ideas: instances with similar features should have the same label; the label of an instance in the previous versions is important; more relevant previous versions should have higher weights; previous versions with less noise should have higher weights. For new instances, Weighted Sampling Model has been employed to sample a suitable training set for them. Subsequently, the training instances have been fed into a Random Forest.

Wang et al. (Wang et al., 2022) have also proposed a differential treatment for the software components that suffered changes from the prior version to the current one, but in the sense that they performed method-level CVDP exclusively on the changed modules of a current version to reduce the scope of SDP.

In conclusion, while the literature on CVDP is emerging, it is still relatively limited when compared to the literature on inner-version or cross-project SDP alternatives. Most CVDP studies consider one single version, the immediately previous one, for training a SDP model to be applied on a current version. The prior version is selected either by default (most commonly) or as the (most common) result of a comparative evaluation that also takes into account, as alternatives, all or some of the historical versions. The main argument remains the high similarity between two consecutive software versions. Increasing this similarity between training and testing CVDP data is also the rationale behind the approaches that supplement the training data taken from previous versions with instances from the current version under test (Lu et al., 2014; Xu et al., 2018b), as well as behind those that filter out the historical data (Amasaki, 2017; Xu et al., 2018a; Xu et al., 2019). So, there is a lot of focus on the similarity between the training and testing data sets for CVDP, which is desirable, while the possible negative impact of too much similarity is less considered. While (Zhang et al., 2020) counted instances with the same name in two not necessarily consecutive versions, showed that their number is not negligible and that they have very similar feature vectors but in many cases conflicting labels, they did not analyze the impact of this phenomenon on the soundness of the prediction performance.

### 3 METHODOLOGY

This section presents the experimental methodology followed to address the two research questions introduced in Section 1. We start by formally defining, in Section 3.1, the concepts used later. Then, we describe the experimental data sets in Section 3.2. Finally, in Sections 3.3 and 3.4, the analyses performed to answer the two research questions are presented.

#### 3.1 Formal Definitions

In the following experiments we will consider that an object-oriented software system  $\mathcal{S}$  has  $v$  consecutive versions:  $\mathcal{S} = \{S_1, S_2, \dots, S_v\}$  and each version  $S_k$  is made of a set of  $n_k$  instances (classes):  $S_k = \{e_1^k, e_2^k, \dots, e_{n_k}^k\}$ .

We will also consider that we have a set of  $\ell$  features, that are usually software metrics,  $\mathcal{SF} = \{sf_1, sf_2, \dots, sf_\ell\}$ . Therefore, a software component  $e_i^k$  is represented as an  $\ell$ -dimensional vector,  $e_i^k = (e_{i1}^k, e_{i2}^k, \dots, e_{i\ell}^k)$ , where  $e_{ij}^k$  expresses the value of the software metric  $sf_j$  computed for the software component  $e_i^k$ .

Every software instance  $e_i^k$  in the  $k$ th version of the system  $\mathcal{S}$  also has an associated label:  $c_i^k$ , where  $c_i^k = 0$  if  $e_i^k$  is non-defective and  $c_i^k = 1$  otherwise. Additionally, for every  $e_i^k$  there is a text feature, called  $name_i^k$  which represents the name of component  $e_i^k$ .

Considering two consecutive versions of a software system  $\mathcal{S}$ , denoted by  $S_{v1}$  and  $S_{v2}$ , we can define the following subsets of  $S_{v2}$ :

$$S_{v1 \rightarrow v2}common = \{e_i^{v2} | e_i^{v2} \in S_{v2} \text{ and } \exists k, s. t. name_i^{v2} = name_k^{v1}, 1 \leq i \leq n_{v2}, 1 \leq k \leq n_{v1}\} \quad (1)$$

$$S_{v1 \rightarrow v2}new = \{e_i^{v2} | e_i^{v2} \in S_{v2} \text{ and } \nexists k, s. t. name_i^{v2} = name_k^{v1}, 1 \leq i \leq n_{v2}, 1 \leq k \leq n_{v1}\} \quad (2)$$

Naturally,  $S_{v2} = S_{v1 \rightarrow v2}common \cup S_{v1 \rightarrow v2}new$ . The set  $S_{v1 \rightarrow v2}common$  can further be divided into the following subsets, based on the labels of the instances:

$$S_{v1 \rightarrow v2}stayedDef = \{e_i^{v2} | e_i^{v2} \in S_{v2} \text{ and } \exists k, s. t. name_i^{v2} = name_k^{v1}, 1 \leq i \leq n_{v2}, 1 \leq k \leq n_{v1} \text{ and } c_k^{v1} = c_i^{v2} = 1\} \quad (3)$$

$$S_{v1 \rightarrow v2}stayedNonDef = \{e_i^{v2} | e_i^{v2} \in S_{v2} \text{ and } \exists k, s. t. name_i^{v2} = name_k^{v1}, 1 \leq i \leq n_{v2}, 1 \leq k \leq n_{v1} \text{ and } c_k^{v1} = c_i^{v2} = 0\} \quad (4)$$



$$S_{v1 \rightarrow v2} \text{becameDef} = \{e_i^{v2} | e_i^{v2} \in S_{v2} \text{ and} \\ \exists k, s. t. name_i^{v2} = name_k^{v1}, 1 \leq i \leq n_{v2}, \\ 1 \leq k \leq n_{v1} \text{ and } c_k^{v1} \neq c_i^{v2} \text{ and } c_i^{v2} = 1\} \quad (5)$$

$$S_{v1 \rightarrow v2} \text{becameNonDef} = \{e_i^{v2} | e_i^{v2} \in S_{v2} \text{ and} \\ \exists k, s. t. name_i^{v2} = name_k^{v1}, 1 \leq i \leq n_{v2}, \\ 1 \leq k \leq n_{v1} \text{ and } c_k^{v1} \neq c_i^{v2} \text{ and } c_i^{v2} = 0\} \quad (6)$$

We define the following two additional sets, based on the previous ones:

$$S_{v1 \rightarrow v2} \text{sameLabel} = S_{v1 \rightarrow v2} \text{stayedDef} \cup S_{v1 \rightarrow v2} \text{stayedNonDef} \quad (7)$$

$$S_{v1 \rightarrow v2} \text{changedLabel} = S_{v1 \rightarrow v2} \text{becameDef} \cup S_{v1 \rightarrow v2} \text{becameNonDef} \quad (8)$$

### 3.2 Data Sets

As case studies, we have decided to use all data sets from the *seacraft* repository (sea, 2017) which are related to SDP and where there are at least two versions for the same system, to unlock the CVDP scenario and where class names are part of the feature list. These systems are the prevalently used data sets to evaluate CVDP approaches, some or all of them being used in (Chen and Ma, 2015; Chen et al., 2019; Yang and Wen, 2018; Xu et al., 2018a; Shukla et al., 2016; Xu et al., 2018b; Zhang et al., 2020; Amasaki, 2017; Wang et al., 2022; Amasaki, 2018; Kabir et al., 2021; Amasaki, 2020; Li et al., 2018; Wang et al., 2016; Zhao et al., 2022a; Xu et al., 2019; Cohen et al., 2022; Kabir et al., 2020; Zhang et al., 2021; Huo and Li, 2019; Zhao et al., 2022b; Yu et al., 2024; Ouellet and Badri, 2023; Sun, 2024; Fan et al., 2019).

Table 1 details these data sets. For every data set it provides the name of the software system (column *Syst.*), the version (column *Vers.*), the number of instances (column *Inst.*), as well as the number and percentage of defective instances (columns *Nr. def.* and *Percent def.*, respectively).

To approach SDP from a cross-version perspective in the scenario in which for training the prediction model to be applied to a version  $S_{v2}$  the data from the immediately prior version of the same system  $S_{v1}$ , is used, we consider every possible pair of consecutive versions of the same project. This leads to 28 train-test pairs. To simplify plotting the results, we assign a number to every pair, in the order in which

Table 1: Details of the considered data sets.

Syst.	Vers.	Inst.	Nr. def.	Percent def.
camel	1.0	339	13	3.83
camel	1.2	608	216	35.53
camel	1.4	872	145	16.63
camel	1.6	965	188	19.48
jedit	3.2	272	90	33.09
jedit	4.0	306	75	24.51
jedit	4.1	312	79	25.32
jedit	4.2	367	48	13.08
jedit	4.3	492	11	2.24
forest	0.6	6	1	16.67
forest	0.7	29	5	19.24
forest	0.8	32	2	6.25
ivy	1.1	111	63	56.76
ivy	1.4	241	16	6.64
ivy	2.0	352	40	11.36
log4j	1.0	135	34	25.19
log4j	1.1	109	37	33.95
log4j	1.2	205	189	92.20
lucene	2.0	195	91	46.67
lucene	2.2	247	144	58.30
lucene	2.4	340	230	67.65
poi	1.5	237	141	59.49
poi	2.0	314	37	11.78
poi	2.5	385	248	64.42
poi	3.0	442	281	63.58
synapse	1.0	157	16	10.19
synapse	1.1	222	60	27.08
synapse	1.2	256	86	33.59
velocity	1.4	196	147	75
velocity	1.5	214	142	66.36
velocity	1.6	229	78	34.06
xalan	2.4	723	110	15.21
xalan	2.5	803	387	48.19
xalan	2.6	885	411	46.44
xalan	2.7	909	898	98.79
xerces	init	162	77	47.53
xerces	1.2	440	71	16.14
xerces	1.3	453	69	15.23
xerces	1.4	588	437	74.32

they can be read from Table 1, starting from 1 (assigned to the pair *camel 1.0 - camel 1.2*) and ending with 28 (assigned to the pair *xerces 1.3 - xerces 1.4*).

Each component  $e_i^k$  of each considered system, in version  $k$ , is represented by a feature vector of 20 well-known object-oriented software metrics whose complete description can be found in (Jureczko and Madeyski, 2010). Therefore,  $e_i^k = (e_{i1}^k, e_{i2}^k, \dots, e_{i20}^k)$ , where  $e_{ij}^k$  expresses the value of the  $j$ th software metric computed for the software component  $e_i^k$ . Each instance has a numerical class label as well, denoting its

number of defects. As a pre-processing step, we have transformed the number of defects into 0 for non-defective and 1 for defective instances (having one or more defects). This is in line with the vast majority of the existing SDP approaches. As a consequence, SDP can be formulated as a binary classification problem approachable through supervised learning, the target function to be learned being the mapping that assigns to each software entity  $e_i^k$  a class  $t(e_i^k) \in \{0, 1\}$ .

In addition to the input features and the class label, each component is identified in its version by a fully qualified class name. This will be used to identify the common instances between two versions (more details are presented in Section 3.3).

Since all the necessary information is available, we can define the sets introduced in Section 3.1 for all the pairs of consecutive versions derived from the experimental data described in Table 1.

### 3.3 RQ1: Prevalence of Identical and Very Similar Instances

In order to analyze the prevalence of closely related instances, we study the data sets presented in Section 3.2. For every software system  $S$ , we consider every pair of consecutive versions, denoted by  $S_{v1}$ ,  $S_{v2}$ , and compute for them five sets that have been defined in Section 3.1:  $S_{v1 \rightarrow v2}common$ ,  $S_{v1 \rightarrow v2}stayedDef$ ,  $S_{v1 \rightarrow v2}stayedNonDef$ ,  $S_{v1 \rightarrow v2}becameDef$  and  $S_{v1 \rightarrow v2}becameNonDef$ .

First, we compute how many elements of  $S_{v2}$  appear in  $S_{v1 \rightarrow v2}common$ , to see how many common classes are in two consecutive versions. This information could confirm whether there really are many classes with the same name in two consecutive versions of a software system.

In order to determine whether an instance of  $S_{v2}$  appears in  $S_{v1}$ , we compare their *name* attribute values which are the fully qualified names of the classes. Although this simple approach might lead to false negatives, since it is possible that a class was renamed or moved to a different package from one version to the next, the number of impacted classes is not significant. The only exception is the *ivy* software system, where the entire package structure changed after version 1.4 (the package names changed completely and the number of packages doubled). Consequently, for the *ivy* system, we consider the unqualified (short) class names of the instances for comparison.

Next, we analyze the distribution of the elements from  $S_{v1 \rightarrow v2}common$  in its four subsets:  $S_{v1 \rightarrow v2}stayedDef$ ,  $S_{v1 \rightarrow v2}stayedNonDef$ ,  $S_{v1 \rightarrow v2}becameDef$  and  $S_{v1 \rightarrow v2}becameNonDef$ . We consider this important since, as presented in Section

1, we believe that a good CVDP approach should be able to identify the instances with changed labels and the analysis will show whether there are many such instances in our case studies.

The fact that the same class name appears in two consecutive versions in itself is not a problem, since class names are not used as an input feature for the SDP models. However, if their feature vector is the same, or highly similar, there might be a problem. In order to investigate this, we first count how many elements of  $S_{v1 \rightarrow v2}common$  have exactly the same feature vector in both versions. After this, we look at the distances between feature vectors in two ways:

1. We compute the distance between the feature vectors in the two consecutive versions for the instances from  $S_{v1 \rightarrow v2}common$ , to see how close they are to each other.
2. For every instance from  $S_{v1 \rightarrow v2}common$ , we find its nearest neighbor from  $S_{v1}$  and check if the nearest neighbor found has the same name.

This information is relevant, given that many machine learning models are based on the precondition that similar instances should have the same label.

We opted to compute the Cosine distance between the feature vectors, due to its scale-invariance. Assuming that the two feature vectors are  $v_1$  and  $v_2$ , each having  $\ell$  features, denoted by  $v_{11}, v_{12}, \dots, v_{1\ell}$  respectively  $v_{21}, v_{22}, \dots, v_{2\ell}$  the definition of the Cosine distance is given in Equation 9.

$$\cos(v_1, v_2) = 1 - \frac{\sum_{i=1}^{\ell} v_{1i} * v_{2i}}{\sqrt{\sum_{i=1}^{\ell} v_{1i}^2} * \sqrt{\sum_{i=1}^{\ell} v_{2i}^2}} \quad (9)$$

### 3.4 RQ2: Influence of Identical and Similar Train-Test Instances on the Performance of CVDP Models

In order to answer RQ2, we analyze how the presence of identical and similar train-test instances influences the measures evaluating the performance of CVDP models. For this, we train three different ML models in a CVDP scenario in which we use as training data an entire version  $v1$  of a software system, while considering the following testing sets:

1. The training data,  $v1$  - this is not a recommended evaluation scenario, but we use the training data for testing too in order to see how well the model learned the training data.
2. All instances of the next version,  $v2$  - this is the prevalent CVDP evaluation scenario, considered in a large proportion of papers from the literature.

3. All instances from  $\mathcal{S}_{v1 \rightarrow v2} \text{changedLabel}$  - these are the common instances for which the label changed from one version to the next. As already stated in Section 1, it is crucial that a good CVDP model classifies these instances correctly.
4. All instance from  $\mathcal{S}_{v1 \rightarrow v2} \text{sameLabel}$  - to compare the results with those for the changed labels.
5. All instances from  $\mathcal{S}_{v1 \rightarrow v2} \text{new}$  - these are the instances newly introduced in version  $v2$ .

We have opted to run the above-mentioned train-test scenarios considering three different ensemble learning models: Random Forest (RF), AdaBoost and Gradient Boosting (XGBoost), motivated by their suitability for imbalanced problems (Zhao et al., 2022a) like SDP (and, as can be seen in Table 1, the experimental SDP data sets are indeed imbalanced).

The analyses for both research questions were implemented in Python, using *scikit-learn* (Pedregosa et al., 2011). An important parameter for all three methods is the number of trees to be considered. For our experiments, we used the minimum value between 100 (which is the default value for RF and XGBoost) and a quarter of the training instances. For the other hyperparameters, the default values were used. Since all these algorithms imply randomness, we have run the experiments 30 times and will report average values for these runs.

Since SDP is framed as a binary classification problem, the performance is measured based on the four values from the confusion matrix. There are many different performance measures used in the literature, but, due to lack of space, we select two of them: AUC and MCC. Both are recognized as particularly good evaluation measures in case of imbalanced data (Zhao et al., 2022a). MCC has the advantage of considering all 4 values in the confusion matrix. For both measures, higher values mean better performance. AUC has values between 0 and 1, where randomly guessing the label would mean an AUC of 0.5. MCC, being a correlation coefficient, takes values between -1 and 1, a value of 0 meaning that there is no correlation between the predicted and the actual labels.

## 4 RESULTS AND ANALYSIS

In this section we will present and interpret the results of the analyses described in Sections 3.3 and 3.4.

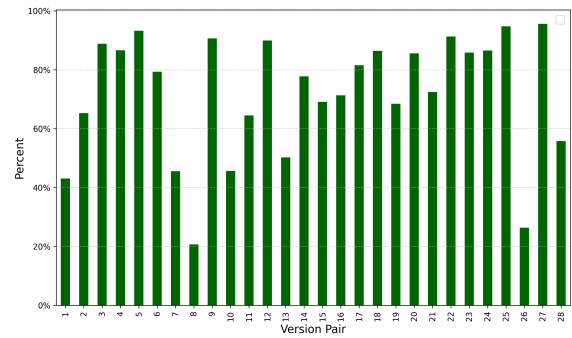


Figure 1: Percent of common files in the considered data sets.

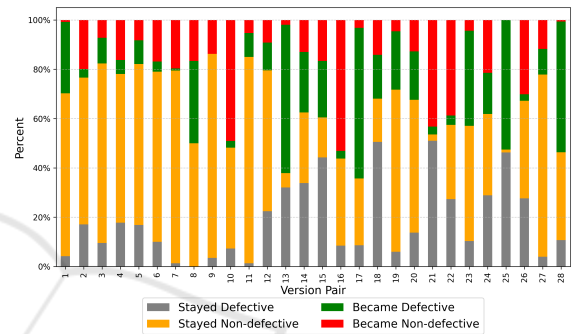


Figure 2: Percent of changed and unchanged labels in the considered data sets for the common instances.

### 4.1 RQ1: Prevalence of Identical and Similar Instances

For every pair of consecutive versions,  $v1$  and  $v2$ , from those presented in Section 3.2, Figure 1 depicts the percentage of instances from  $v2$  which appear in  $v1$ . We can see that these percentages are quite high, there being only two pairs (*forest* 0.6 - *forest* 0.7 and *xerces init* - *xerces* 1.2) where the value is below 40%. For 13 pairs, the percentages are above 80%. The average value is 72%, while the median is 79%. These significant percentages confirm our intuition that, in most cases, two consecutive versions of a software system share a lot of common classes.

Figure 2 presents how these common classes (elements of the set  $\mathcal{S}_{v1 \rightarrow v2} \text{common}$ ) are divided into the four possible subsets, depending on their labels. The gray and orange bars represent the instances for which the labels did not change, while the red and green ones represent the instances for which the labels changed. We can see that in general, most of the instances keep the same label (the mean is 65% and the median is 67%). However, there are a few pairs, where more classes changed their labels, 6 of them have values greater than or equal to 50%, the maximum being 64% for the *poi* 2.0 - *poi* 2.5 pair, closely followed by

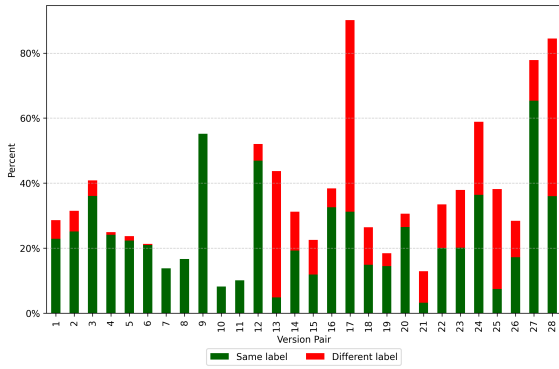


Figure 3: Percentage of identical instances and their division into same-label and different-label categories in the common instances of the considered data set.

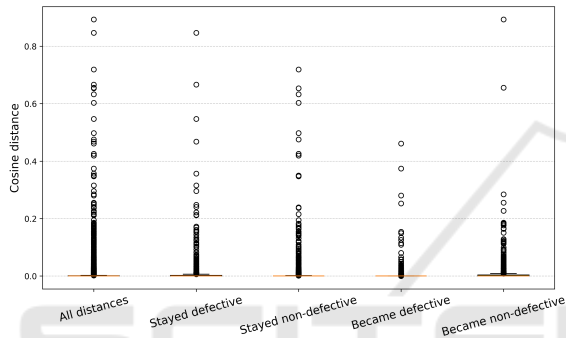


Figure 4: Cosine distance between common instances.

the *log4j 1.1 - log4j 1.2* pair with 62%. As we have already mentioned, these instances with changed labels are the ones which should be identified by a good CVDP approach.

While Figures 1 and 2 considered the classes with the same name (called common instances), on Figure 3 we can see the percentage of the common instances which have identical feature vectors. We can see that there are big differences in the values for different pairs, the mean value being 35% with a median of 31%. There are 3 pairs with a value around 80%:

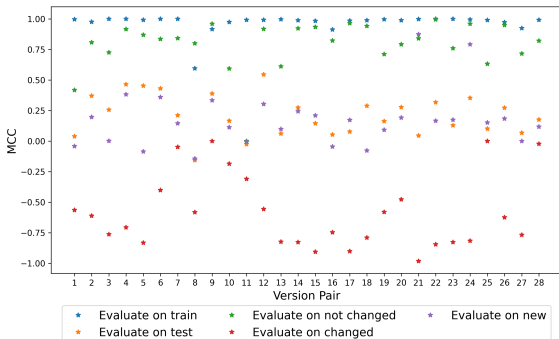


Figure 5: MCC values for the Random Forest models, for the considered data sets.

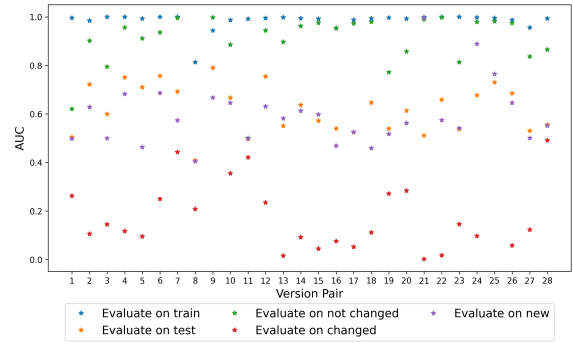


Figure 6: AUC values for the Random Forest models, for the considered data sets.

*poi 2.0 - poi 2.5*, *xerces 1.2 - xerces 1.3* and *xerces 1.3 - xerces 1.4*. On the other side, we have values around 10% for the two pairs considered for the *ivy* data set. What is particularly interesting on Figure 3 is the height of the red bars. They represent instances for which the feature vectors are identical, but the label changed. This situation can appear if the source code did change, but the considered features are not sensitive enough to detect the source code changes, or they can be due to labeling error. In order to determine the exact situation, a more detailed analysis on the exact source code is needed, but this is outside the scope of this paper.

While the red bars in Figure 3 represent instances that will very likely be classified incorrectly, the green bars represent those instances that are exactly the same in both versions, which means that they represent an overlap between the train and the test set of the ML-based CVDP models.

Next, for the common instances, we have computed the cosine distance between their feature vectors in the two versions. Figure 4 plots these distances, aggregated over all version pairs, but divided into categories based on whether the labels changed (and how) or not between them. We can see that the median of these values is actually very close to 0. More specifically, it is 0.0004 for instances which stayed defective, 2.220E-16 for instances which stayed non-defective, 2.22E-16 for instances which became defective and 0.0002 for instances which became non-defective. While there are obviously outliers and there are pairs with distance as big as 0.89, there are only 101 classes out of the total 8608 with a distance greater than 0.1. This shows that most common classes are not changed a lot (or the change is not reflected by the software metrics used as features). Also, it does not seem to be a pattern in the values depending on the label change.

We have looked at the average cosine distance for each version pair, considering the same 5 categories



as in case of Figure 4. The exact figure is omitted due to lack of space. As expected, the average values are very low, even the maximum is below 0.06. Similarly to Figure 4, there does not seem to be a pattern in the distances for different changes in the label. For 11 version pairs the maximum average distance is for instances which stayed defective, for 2 pairs it is for instances which stayed non-defective, for 5 pairs it is for instances which became defective and for the remaining 10 pairs it is for instances which became non-defective.

Finally, we have counted how many of the common instances have as nearest neighbor in  $v_1$  the instance with the same name. The median value for the 28 version pairs is 73%, with a minimum of 36% (for the pair *ivy 1.1 - ivy 1.4*) and a maximum is 1 (the pair *forrest 0.6 - forrest 0.7*).

In conclusion, we can answer RQ1 saying that on average, 72% of the classes from a version of a software system are in common with the previous version and on average 35% of them are actually identical, although they might have different labels. So when a ML model is trained on a version and tested on the next one, there will be instances in the test set which were part of the train set as well. Moreover, the instances which are not identical have, on average, a very small cosine distance between their feature vector in the two versions.

## 4.2 RQ2: Influence of Identical and Similar Instances

The results of the experiments presented in Section 3.4 can be visualized on Figures 5, 6 (for the RF models), 7, 8 (for the AdaBoost models) and 9, 10 (for the XGBoost models). We can observe that the patterns seem to be the same for both MCC and AUC, so in the following, due to lack of space, we will detail the results based on the MCC values.

In all figures we can observe that the evaluation on the train data (the blue asterisks) produces very good results: with the exception of the *forest 0.6 - forest 0.7* pair having an MCC of 0.6, the MCC is above 0.9 for RF. XGBoost also leads to MCC values above 0.9 (with the exception of the two pairs from *forest*) while AdaBoost has a slightly worse performance, with MCC around 0.6-0.7 for most version pairs (but with a minimum of 0.31). RF and XGBoost seem to have managed to learn the train data very well.

If we are looking at the orange asterisks, representing the use of the next version for testing, we can see that the performance is not as good as on the training data, but in most cases, still acceptable: MCC is

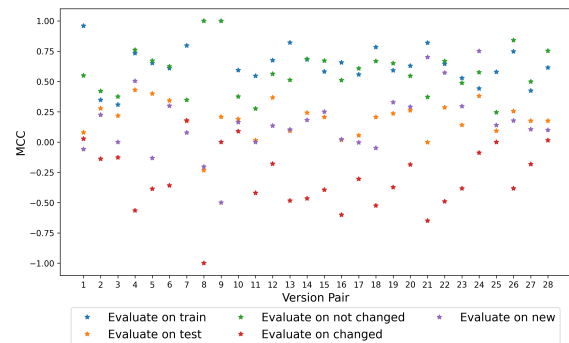


Figure 7: MCC values for the AdaBoost models for the considered data sets.

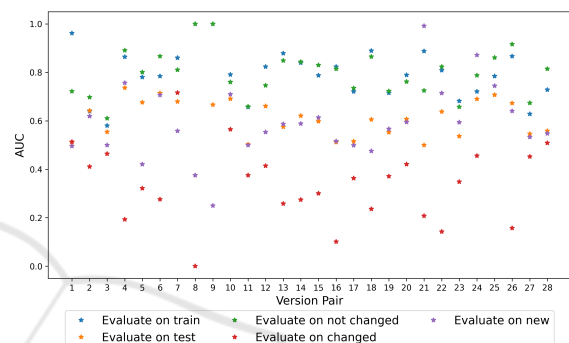


Figure 8: AUC values for the AdaBoost models for the considered data sets.

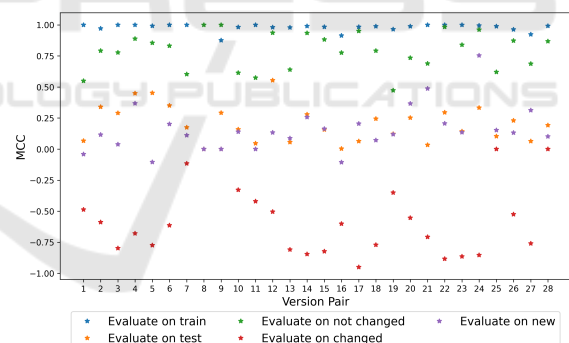


Figure 9: MCC values for the XGBoost models, for the considered data sets.

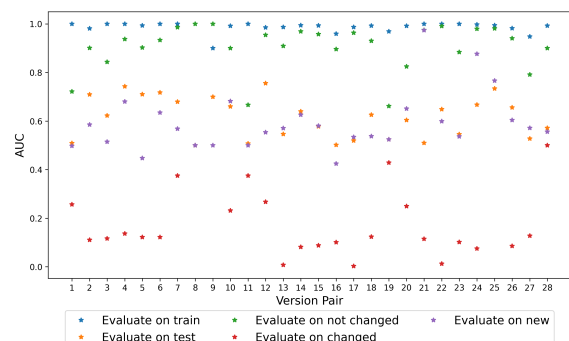


Figure 10: AUC values for the XGBoost models, for the considered data sets.

between -0.157 and 0.54 for RF, between -0.23 and 0.43 for AdaBoost and between 0 and 0.55 for XGBoost. The purple asterisks, representing the evaluation on the new instances, are pretty much overlapping with the orange ones, suggesting that the models had moderate performance in classifying new instances.

When considering the common instances for which the class labels did not change in the two versions (denoted by green asterisks), we can see the same excellent performance as seen in case of evaluating on the train data. This is most probably due to the fact that those exact instances were seen during the training phase of the models.

Finally, the performance on those instances that changed their label is indicated by the red asterisks. Correctly identifying them is extremely important. Yet, the MCC values for them are mostly negative, suggesting that there is a negative correlation between the predicted values and the actual ones: for RF there are only 2 MCC values of 0, the rest being negative, while the minimum value is -0.98. AdaBoost, since it did not learn the train data that well, has a few positive MCC values for the instances with changed labels, but the maximum is still only 0.17. Finally, XGBoost has MCC values between -0.95 and 0.

Furthermore, we have computed the Pearson correlations between the two performance measures of the three models tested on the entire test version v2 (which is the standard CVDP scenario) and the percentage of instances in different subsets of v2. The results are depicted in Figure 11. We can see that there is a positive correlation of around 0.5 between the performance values and the percentage of common instances (dark blue bars), meaning that the more common instances we have between v1 and v2, the higher the performance measures. There is an even stronger correlation between the performance values and the percentage of common instances with identical labels (light blue bars). Somehow surprisingly, the percentage of identical instances in the common ones (orange bars) and the percentage of identical instances with the same label (green bars) is less correlated with the performance than the previous two categories. Finally, as expected, the percentage of common instances with different labels (purple bars) is negatively correlated with the performance, the correlation value being around -0.5. This points out that the more common instances with changed labels, the worst the performance measure.

Another interesting observation is that the correlations for AdaBoost are in general lower than those of RF and XGBoost. This might be related to the fact that AdaBoost was the model where the performance

measures on the train data and on the common instances with the same label were lower than for the other two models. AdaBoost did not learn the train data so well, so it is less influenced by the occurrence of common instances.

From the above analysis, we can answer RQ2 by saying that the presence of identical and similar instances in two consecutive versions strongly influences the performance of CVDP approaches. Computing the performance for the entire version will hide the fact that the model performs poorly on the important instances whose labels changed from one version to another. The evaluation of the new instances does not seem to be influenced by this issue, as on them the classification performance is in line with that computed for the entire version v2.

## 5 THREATS TO VALIDITY

*Internal validity.* For our experiments, one internal validity aspect is the randomness in the considered ML algorithms. In order to mitigate this, we have repeated the experiments 30 times and considered average values for the performance measures.

*External validity.* A common external validity issue for applying ML models for software engineering problems is that the results might not generalize for other ML models and/or other data sets. We tried to mitigate this by considering all data sets from the *seacraft* repository that fit our requirements. These are also the data sets that appear most frequently in the related literature thus the presented insights affect a large proportion of the literature. Nevertheless, in the future we will repeat the experiments for other data sets with different feature spaces, for ex. semantic, syntactic or code change metrics.

*Construct validity.* In our case, construct validity refers to the selection of performance measures and baseline algorithms. We have considered two performance measures which are suitable and often used for imbalanced data sets (such as SDP data sets): AUC and MCC. Both show the same conclusions. For comparison, we have used only three relatively simple baseline methods, but our goal was not to assess their predictive performance, but to show how that performance changes for different parts of the test data. Another aspect of the validity of the construct is the reliance on the labels and the metric values of the considered data sets. As presented in Section 4.1, there are identical instances with changed labels, which could be the result of labeling errors. Since these data sets are used a lot for SDP (not just cross-version, but also cross-project and within-version),

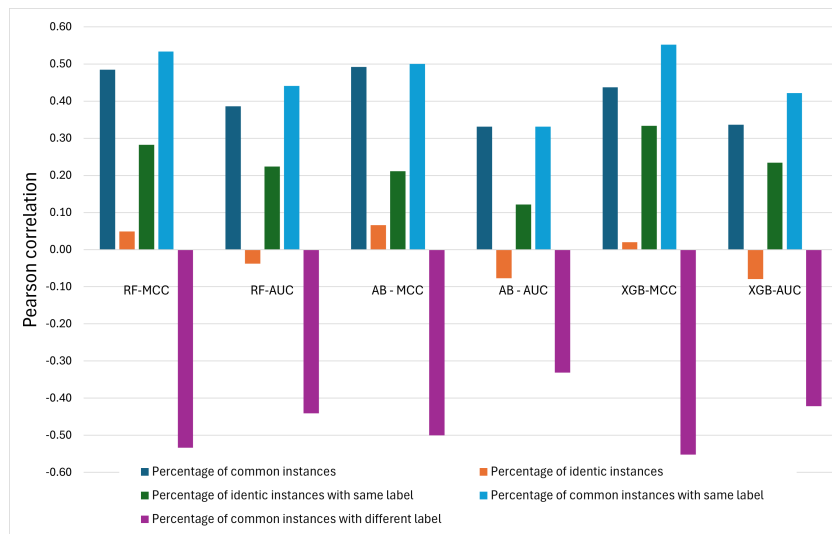


Figure 11: Pearson correlations between performance measures and percentage of common and identical instances. RF stands for Random Forest, AB for AdaBoosting and XGB stands for XGBoost.

we consider them trustworthy. In addition, the conclusions of our study apply to all data sets considered, not just those with a high number of such instances.

## 6 CONCLUSIONS

In this paper we have shown, through an empirical study, that the performance of CVDP approaches is influenced by train-test similarity. By analyzing 28 software version pairs, we have confirmed that identical and highly similar instances are frequent in successive software versions. By employing three ensemble learners, we have also shown that using the standard “train the model on version  $v_1$  and evaluate it on the next version  $v_2$ ” CVDP scenario leads to overly optimistic performance indicators due to these instances, which hides the extremely poor performance of the models in predicting the labels that changed from  $v_1$  to  $v_2$ . We seek to raise awareness to this issue and to work towards a better evaluation of CVDP approaches.

There are many directions in which we envision continuing this research. First, it would be worth investigating whether the presence of identical instances with different labels is the result of labeling errors or are due to not sufficiently sensitive software features. Besides this, we aim to replicate the study using different software representations based on semantic features automatically extracted from the source code or code change metrics, or embeddings, a really popular code representation nowadays. Extending the investigation by employing additional classifiers is another future direction taken into consider-

ation. Finally, we consider exploring how the evaluation of CVDP models could be improved, while giving enough attention to the performance on the instances whose labels changed. We will analyze why models fail on instances with changed labels and study how to build models with better generalization capabilities.

## ACKNOWLEDGEMENTS

The publication of this article was supported by the 2024 Development Fund of the UBB.

## REFERENCES

- (2017). The SEACRAFT repository of empirical software engineering data.
- Amasaki, S. (2017). On applicability of cross-project defect prediction method for multi-versions projects. In *Proceedings of the 13th International Conference on Predictive Models and Data Analytics in Software Engineering*, page 93–96. ACM.
- Amasaki, S. (2018). Cross-version defect prediction using cross-project defect prediction approaches: Does it work? In *Proceedings of the 14th International Conference on Predictive Models and Data Analytics in Software Engineering*, page 32–41. ACM.
- Amasaki, S. (2020). Cross-version defect prediction: use historical data, cross-project data, or both? *Empirical Software Engineering*, 25:1573 – 1595.
- Bennin, K. E., Toda, K., Kamei, Y., Keung, J., Monden, A., and Ubayashi, N. (2016). Empirical evaluation of cross-release effort-aware defect prediction models.

- In *2016 IEEE International Conference on Software Quality, Reliability and Security*, pages 214–221.
- Chen, M. and Ma, Y. (2015). An empirical study on predicting defect numbers. In *International Conference on Software Engineering and Knowledge Engineering*.
- Chen, X., Zhang, D., Zhao, Y., Cui, Z., and Ni, C. (2019). Software defect number prediction: Unsupervised vs supervised methods. *Information and Software Technology*, 106:161–181.
- Cohen, M., Rokach, L., and Puzis, R. (2022). Cross version defect prediction with class dependency embeddings. *ArXiv*, abs/2212.14404.
- Fan, G., Diao, X., Yu, H., Yang, K., Chen, L., and Vitiello, A. (2019). Software defect prediction via attention-based recurrent neural network. *Sci. Program.*, 2019.
- Harman, M., Islam, S., Jia, Y., Minku, L. L., Sarro, F., and Srivisut, K. (2014). Less is more: Temporal fault predictive performance over multiple hadoop releases. In Le Goues, C. and Yoo, S., editors, *Search-Based Software Engineering*, pages 240–246. Springer.
- Huo, X. and Li, M. (2019). On cost-effective software defect prediction: Classification or ranking? *Neurocomputing*, 363:339–350.
- Jureczko, M. and Madeyski, L. (2010). Towards identifying software project clusters with regard to defect prediction. In *Proceedings of the 6th international conference on predictive models in software engineering*, pages 1–10.
- Kabir, M. A., Keung, J., Turhan, B., and Bennin, K. E. (2021). Inter-release defect prediction with feature selection using temporal chunk-based learning: An empirical study. *Appl. Soft Comput.*, 113(PA).
- Kabir, M. A., Keung, J. W., Bennin, K. E., and Zhang, M. (2020). A drift propensity detection technique to improve the performance for cross-version software defect prediction. In *2020 IEEE 44th Annual Computers, Software, and Applications Conference (COMPSAC)*, pages 882–891.
- Kabir, M. A., Rehman, A. U., Islam, M. M. M., Ali, N., and Baptista, M. L. (2023). Cross-version software defect prediction considering concept drift and chronological splitting. *Symmetry*, 15(10).
- Li, Y., Su, J., and Yang, X. (2018). Multi-objective vs. single-objective approaches for software defect prediction. In *Proceedings of the 2nd International Conference on Management Engineering, Software Engineering and Service Sciences*, page 122–127. ACM.
- Lu, H., Kocaguneli, E., and Cukic, B. (2014). Defect prediction between software versions with active learning and dimensionality reduction. *2014 IEEE 25th International Symposium on Software Reliability Engineering*, pages 312–322.
- Ouellet, A. and Badri, M. (2023). Combining object-oriented metrics and centrality measures to predict faults in object-oriented software: An empirical validation. *Journal of Software: Evolution and Process*.
- Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D., Brucher, M., Perrot, M., and Duchesnay, E. (2011). Scikit-learn: Machine learning in Python. *Journal of Machine Learning Research*, 12:2825–2830.
- Shukla, S., Radhakrishnan, T., Kasinathan, M., and Neti, L. B. M. (2016). Multi-objective cross-version defect prediction. *Soft Computing*, 22:1959 – 1980.
- Sun, B. (2024). Bert-based cross-project and cross-version software defect prediction. *Applied and Computational Engineering*, 73:33–41.
- Wang, S., Liu, T., and Tan, L. (2016). Automatically learning semantic features for defect prediction. In *Proceedings of the 38th International Conference on Software Engineering*, page 297–308. ACM.
- Wang, Z., Tong, W., Li, P., Ye, G., Chen, H., Gong, X., and Tang, Z. (2022). BugPre: an intelligent software version-to-version bug prediction system using graph convolutional neural networks. *Complex & Intelligent Systems*, 9.
- Xu, Z., Li, S., Luo, X., Liu, J., Zhang, T., Tang, Y., Xu, J., Yuan, P., and Keung, J. (2019). TSTSS: A two-stage training subset selection framework for cross version defect prediction. *J. Syst. Softw.*, 154(C):59–78.
- Xu, Z., Li, S., Tang, Y., Luo, X., Zhang, T., Liu, J., and Xu, J. (2018a). Cross version defect prediction with representative data via sparse subset selection. In *Proceedings of the 26th Conference on Program Comprehension*, page 132–143. ACM.
- Xu, Z., Liu, J., Luo, X., and Zhang, T. (2018b). Cross-version defect prediction via hybrid active learning with kernel principal component analysis. In *IEEE 25th International Conference on Software Analysis, Evolution and Reengineering*, pages 209–220.
- Yang, X. and Wen, W. (2018). Ridge and lasso regression models for cross-version defect prediction. *IEEE Transactions on Reliability*, 67:885–896.
- Yu, X., Rao, J., Liu, L., Lin, G., Hu, W., Keung, J. W., Zhou, J., and Xiang, J. (2024). Improving effort-aware defect prediction by directly learning to rank software modules. *Information and Software Technology*, 165:107250.
- Zhang, J., Wu, J., Chen, C., Zheng, Z., and Lyu, M. R. (2020). CDS: A cross-version software defect prediction model with data selection. *IEEE Access*, 8:110059–110072.
- Zhang, N., Ying, S., Ding, W., Zhu, K., and Zhu, D. (2021). WGNCS: A robust hybrid cross-version defect model via multi-objective optimization and deep enhanced feature representation. *Inf. Sci.*, 570(C):545–576.
- Zhao, Y., Wang, Y., Zhang, D., and Gong, Y. (2022a). Eliminating the high false-positive rate in defect prediction through bayesnet with adjustable weight. *Expert Systems*, 39.
- Zhao, Y., Wang, Y., Zhang, Y., Zhang, D., Gong, Y., and Jin, D. (2022b). ST-TLF: Cross-version defect prediction framework based transfer learning. *Information and Software Technology*, 149:106939.