

Empirical Analysis of Object-Oriented Design Metrics for Predicting Unit Testing Effort of Classes

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ABSTRACT

In this paper, we investigate empirically the relationship between object-oriented design metrics and testability of classes. We address testability from the point of view of unit testing effort. We collected data from three open source Java software systems for which JUnit test cases exist. To capture the testing effort of classes, we used metrics to quantify the corresponding JUnit test cases. Classes were classified, according to the required unit testing effort, in two categories: high and low. In order to evaluate the relationship between object-oriented design metrics and unit testing effort of classes, we used logistic regression methods. We used the univariate logistic regression analysis to evaluate the individual effect of each metric on the unit testing effort of classes. The multivariate logistic regression analysis was used to explore the combined effect of the metrics. The performance of the prediction models was evaluated using Receiver Operating Characteristic analysis. The results indicate that: 1) complexity, size, cohesion and (to some extent) coupling were found significant predictors of the unit testing effort of classes and 2) multivariate regression models based on object-oriented design metrics are able to accurately predict the unit testing effort of classes.

Keywords: Software Testability; Unit Testing; Testing Effort; Metrics; Relationship; Prediction and Empirical Analysis

1. Introduction

Software testability is an important software quality attribute. IEEE [1] defines testability as the degree to which a system or component facilitates the establishment of test criteria and the performance of tests to determine whether those criteria have been met. ISO [2] defines testability (characteristic of maintainability) as attributes of software that bear on the effort needed to validate the software product.

Software testability is, in fact, a complex notion. Indeed, software testability is not an intrinsic property of a software artifact and cannot be measured simply such as size, complexity or coupling. According to Baudry *et al.* [3,4], software testability is influenced by many factors including controllability, observability and the global test cost. Yeh *et al.* [5] argue also that diverse factors such as control flow, data flow, complexity and size contribute to testability. Zhao [6] states that testability is an elusive concept, and it is difficult to get a clear view on all the potential factors that can affect it. Dealing with software testability raises several questions such as [7,8]: Why is one class easier to test than another? What makes a class hard to test? What contributes to the testability of a class? How can we quantify this notion? In addition, according

to Baudry *et al.* testability becomes crucial in the case of object-oriented (OO) software systems where control flows are generally not hierarchical, but diffuse and distributed over whole architecture [3,4].

Software metrics can be useful in assessing software quality attributes and supporting various software engineering activities [9-12]. In particular, metrics can be used to assess (predict) software testability and better manage the testing effort. Having quantitative data on the testability of a software can, in fact, be used to guide the decision-making of software development managers seeking to produce high-quality software. Particularly, it can help software managers, developers and testers to [7, 8]: plan and monitor testing activities, determine the critical parts of the code on which they have to focus to ensure software quality, and in some cases use this data to review the code. One effective way to deal with this important issue is to develop prediction models based on metrics that can be used to identify critical parts of software requiring a (relative) high testing effort. There is a real need in this area.

A large number of OO metrics were proposed in literature [13]. Some of these metrics related to different OO software attributes (such as size, complexity, coupl-

ing, cohesion and inheritance) were already used in recent years to assess (predict) testability of OO software systems [7,8,14-20]. Software testability has been addressed from different point of views. According to Gupta *et al.* [8], none of the OO metrics is alone sufficient to give an overall reflection of software testability. Software testability is, indeed, affected by many different factors as pointed out by several researchers [3-6,21,22]. Moreover, even if there is a common belief (and empirical evidence) that several of these metrics (attributes) have an impact on testability of classes, few empirical studies have been conducted to examine their combined effect (impact), particularly when taking into account different levels of testing effort. As far as we know, this issue has not been empirically investigated.

The aim of this paper is to investigate empirically the relationship between OO design metrics, specifically, the Chidamber and Kemerer (CK) metrics suite [23,24] and testability of classes taking into account different levels of testing effort. We also include the well-known (size related) LOC (Lines of Code) metric as a “baseline”. The question we attempt to answer is how accurately do the OO metrics (separately and when used together) predict (high) testing effort. We addressed testability of classes from the perspective of unit testing effort. We performed an empirical analysis using data collected from three open source Java software systems for which JUnit test cases exist. To capture the testing effort of classes, we used the suite of test case metrics introduced by Bruntink *et al.* [7,17] to quantify the corresponding JUnit test cases. These metrics were used, in fact, to classify the classes (in terms of required testing effort) in two categories: high and low.

In order to evaluate the relationship between OO design metrics and unit testing effort of classes, we used logistic regression methods. We used the univariate logistic regression method to evaluate the individual effect of each metric on the unit testing effort of classes. The multivariate logistic regression method was used to investigate the potential of the combined effect of the metrics. The performance of the prediction models was evaluated using Receiver Operating Characteristic (ROC) analysis. In summary, the results indicate that complexity, size, cohesion and (to some extent) coupling were found significant predictors of the unit testing effort of classes. Moreover, the results show that multivariate regression models based on OO metrics are able to accurately predict the unit testing effort of classes. In addition, we explored the applicability of the prediction models by examining to what extent a prediction model built using data from one system can be used to predict the testing effort of classes of another system.

The rest of this paper is organized as follows: A brief summary of related work on software testability is given

in Section 2. Section 3 introduces the OO design metrics investigated in the study. Section 4 presents the selected systems, describes the data collection, introduces the test case metrics we used to quantify the JUnit test cases and presents the empirical study we performed to investigate the relationship between OO design metrics and unit testing effort of classes. Finally, Section 5 concludes the paper and outlines directions for future work.

2. Software Testability

Software testability has been addressed in literature from different point of views. Fenton *et al.* [10] define software testability as an external attribute. Freedman introduces testability measures for software components based on two factors: observability and controllability [25]. Voas defines testability as the probability that a test case will fail if a program has a fault [26]. Voas and Miller [27] propose a testability metric based on inputs and outputs domains of a software component, and the PIE (Propagation, Infection and Execution) technique to analyze software testability [28]. Binder [29] defines testability as the relative ease and expense of revealing software faults. He argues that software testability is based on six factors: representation, implementation, built-in text, test suite, test support environment and software process capability. Khoshgoftaar *et al.* investigate the relationship between static software product measures and testability [30,31]. Software testability is considered as a probability predicting whether tests will detect a fault. McGregor *et al.* [32] investigate testability of OO software systems and introduce the visibility component measure (VC). Bertolino *et al.* [33] investigate testability and its use in dependability assessment. They adopt a definition of testability as a conditional probability, different from the one proposed by Voas *et al.* [26], and derive the probability of program correctness using a Bayesian inference procedure. Le Traon *et al.* [34-36] propose testability measures for data flow designs. Petrenko *et al.* [37] and Karoui *et al.* [38] address testability in the context of communication software. Sheppard *et al.* [22] focus on formal foundation of testability metrics. Jungmayr [39] investigates testability measurement based on static dependencies within OO systems. He takes an integration testing point of view.

Gao *et al.* [40,41] consider testability from the perspective of component-based software construction. The definition of component testability is based on five factors: understandability, observability, controllability, traceability and testing support capability. According to Gao *et al.* [41], software testability is related to testing effort reduction and software quality. Nguyen *et al.* [42] focus on testability analysis based on data flow designs in the context of embedded software. Baudry *et al.* [3,4,21]

address testability measurement (and improvement) of OO designs. They focus on design patterns as coherent subsets in the architecture. Chowdhary [43] focuses on why it is so difficult to practice testability in the real world. He discusses the impact of testability on design and lay down guidelines to ensure testability consideration during software development. Khan *et al.* [44] focus on testability of classes at the design level. They developed a model to predict testability of classes from UML class diagrams. Kout *et al.* [45] adapted this model to the code level (Java programs) and evaluated it on two case studies. Briand *et al.* [46] propose an approach where instrumented contracts are used to increase testability. A case study showed that contract assertions detect a large percentage of failures depending on the level of precision of the contract definitions.

Bruntink *et al.* [7,17] investigate factors of testability of OO software systems. Testability is investigated from the perspective of unit testing. Gupta *et al.* [8] use fuzzy techniques to combine some OO metrics values into a single overall value called testability index. The proposed approach has been evaluated on simple examples of Java classes. Singh *et al.* [18] used OO metrics and neural networks to predict testing effort. The testing effort is measured in terms of lines of code added or changed during the life cycle of a defect. In [19], Singh *et al.* attempt to predict testability of Eclipse at the package level. Badri *et al.* [14] performed a similar study to that conducted by Bruntink *et al.* [7] using two open source Java software systems in order to explore the relationship between lack of cohesion metrics and testability of classes. In [15], Badri *et al.* investigated the capability of lack of cohesion metrics to predict testability using logistic regression methods. More recently, Badri *et al.* [16,47] investigate the effect of control flow of the unit testing effort of classes.

3. Object-Oriented Design Metrics

We present, in this section, the summary of the OO design metrics we selected for the empirical study. These metrics have been selected for study because they have received considerable attention from researchers and are also being increasingly adopted by practitioners. Furthermore, these metrics have been incorporated into several development tools. We selected in total seven metrics. Six of these metrics (CBO, LCOM, DIT, NOC, WMC and RFC) were proposed by Chidamber and Kemerer in [23,24]. We also include in our study the well-known LOC metric. We give in what follows a brief definition of each metric.

Coupling between Objects: The CBO metric counts for a class the number of other classes to which it is coupled (and vice versa).

Lack of Cohesion in Methods: The LCOM metric measures the dissimilarity of methods in a class. It is defined as follows: $LCOM = |P| - |Q|$, if $|P| > |Q|$, where P is the number of pairs of methods that do not share a common attribute and Q the number of pairs of methods sharing a common attribute. If the difference is negative, LCOM is set to 0.

Depth of Inheritance Tree: The DIT metric of a class is given by the length of the (longest) inheritance path from the root of the inheritance hierarchy to the class on which it is measured (number of ancestor classes).

Number of Children: The NOC metric measures the number of immediate subclasses of the class in a hierarchy.

Weighted Methods per Class: The WMC metric gives the sum of complexities of the methods of a given class, where each method is weighted by its cyclomatic complexity. Only methods specified in the class are considered.

Response for Class: The RFC metric for a class is defined as the set of methods that can be executed in response to a message received by an object of the class.

Lines of Code per class: The LOC metric counts for a class its number of lines of code.

4. Empirical Analysis

This study aims at investigating empirically the relationship between OO design metrics and testability of classes in terms of required unit testing effort. We considered in each of the used systems only the classes for which JUnit test cases exist. We noticed that developers usually name the JUnit test case classes by adding the prefix (or suffix) “Test” or “TestCase” into the name of the classes (and in few cases interfaces) for which JUnit test cases were developed. Only classes that have such name matching mechanism with the test case class name are included in the analysis. This approach has already been adopted in other studies [48].

JUnit is a simple Framework for writing and running automated unit tests for Java classes. A typical usage of JUnit is to test each class C_s of the program by means of a dedicated test case class C_t . However, by analyzing the JUnit test case classes of the subject systems, we noticed that in some cases there is no one-to-one relationship between JUnit classes and tested classes. This has also been noted in other previous studies [49,50]. In these cases, several JUnit test cases correspond in fact to a same tested class.

For each selected software class C_s , we calculated the values of OO metrics. We also used the suite of test case metrics (Section 4.3) to quantify the corresponding JUnit test case (cases) C_t . The OO metrics and the test case metrics have been computed using the Borland Together

tool¹. The selected classes of the subject systems have been categorized according to the required testing effort. We used the test case metrics to quantify the JUnit test cases and identify the classes which required a (relative) high testing effort. In order to simplify the process of testing effort categorization, we provide only two categorizations: classes which required a high testing effort and classes which required a (relatively) low testing effort.

4.1. Selected Systems

Three open source Java software systems from different domains were selected for the study: ANT, JFREECHART (JFC) and POI. **Table 1** summarizes some of their characteristics. It gives, for each system, the total number of software classes, the total number of attributes, the total number of methods, the total number of lines of code, the number of selected software classes (for which JUnit test cases were developed), and the total number of lines of code of selected software classes (for which JUnit test cases were developed). ANT (www.apache.org) is a Java library and command-line tool whose mission is to drive processes described in build files as targets and extension points dependent upon each other. This system consists of 713 classes that are comprised of 2491 attributes and 5365 methods, with a total of roughly 64,000 lines of code. JFC (<http://www.jfree.org/jfreechart>) is a free chart library for Java platform. This system consists of 496 classes that are comprised of 1550 attributes and

5763 methods, with a total of roughly 68,000 lines of code. The Apache POI (<http://poi.apache.org/>) project's mission is to create and maintain Java APIs for manipulating various file formats based upon the Office Open XML standards (OOXML) and Microsoft's OLE 2 Compound Document format (OLE2). This system consists of 1540 classes, that are comprised of 4463 attributes and 14,084 methods, with a total of roughly 136,000 lines of code. Moreover, we can also observe from **Table 1**, and this for each system, that JUnit test cases were not developed for all classes. The number of selected software classes for which JUnit test cases were developed varies from one system to another. In total, our experiments will be performed on 688 classes and corresponding JUnit test cases.

4.2. Descriptive Statistics

Table 2 shows the descriptive statistics for all the OO metrics considered in the study. We give, for illustration, only the descriptive statistics corresponding to system ANT. We give in fact two tables of descriptive statistics (labeled I and II). The table labeled (I) indicates the descriptive statistics for OO metrics and this for all classes of the system. The table labeled (II) indicates the descriptive statistics for OO metrics only for selected classes for which JUnit test cases were developed. Moreover, the metric LCOM is not computed for classes having no attributes. This is why the number of observations (**Table 2: ANT(I) and ANT(II)**) corresponding to the

Table 1. Some characteristics of the used systems.

	#Classes	#Att	#Meth	#LOC	#TClasses	#TLOC
ANT	713	2491	5365	64062	111	17609
JFC	496	1550	5763	68312	226	53115
POI	1540	4463	14084	136005	351	51734

Table 2. Descriptive statistics for OO metrics.

ANT I	Obs.	Min	Max	Mean	Sigma	ANT II	Obs.	Min	Max	Mean	Sigma
CBO	713	0	41	6.59	7.15	CBO	111	0	39	10.49	8.57
DIT	713	0	6	2.20	1.37	DIT	111	1	6	2.68	1.34
NOC	713	0	238	1.52	11.81	NOC	111	0	45	0.71	4.33
LCOM	506	0	3621	76.23	263.78	LCOM	98	0	3621	155.93	454.19
RFC	713	0	550	51.20	46.44	RFC	111	15	444	78.65	59.83
WMC	713	0	245	17.10	23.64	WMC	111	1	178	31.31	31.11
LOC	713	1	1252	89.85	130.07	LOC	111	5	846	158.64	154.20

¹<http://www.borland.com/>

metric LCOM is different from the number of observations corresponding to the other OO metrics.

From **Table 2** (ANT (I) and ANT (II)), we can see that classes for which JUnit test cases were developed are relatively large and complex classes. The mean values of the metrics LOC, RFC and WMC of **Table 2-ANT(II)** (respectively 158.64, 78.65 and 31.31), are all greater than the mean values of the same metrics in **Table 2-ANT(I)** (respectively 89.85, 51.20 and 17.10). This is a plausible finding. The testers actually focus on large and complex classes. We can also observe that mean value of coupling (CBO metric) in the case of selected classes for which JUnit test cases were developed (**Table 2-ANT(II)**: 10.49) is greater than the mean value of coupling of all classes of ANT (**Table 2-ANT(I)**: 6.59), suggesting that the coupling in the case of classes for which JUnit test cases were developed is relatively high. Descriptive statistics of JFC and POI follow exactly the same trend.

4.3. Test Case Metrics

In order to quantify a JUnit test class (C_t) corresponding to a software class (C_s), we used the following two metrics [7,17]: 1) TLoc: This metric gives the number of lines of code of a test class C_t . It is used to indicate the size of the test suite corresponding to a software class C_s ; 2) TAss: This metric gives the number of invocations of JUnit assert methods that occur in the code of a test class C_t . JUnit assert methods are, in fact, used by the testers to compare the expected behavior of the class under test to its current behavior. This metric is used to indicate another perspective of the size of a test suite. It is directly related to the construction of the test cases.

These metrics have been introduced by Bruntink *et al.* in [7,17] to indicate the size of a test suite. Bruntink *et al.* based, in fact, the definition of these metrics on the work of Binder [29]. They used, particularly, an adapted version of the *fish bone* diagram developed by Binder [29] to identify factors of testability. The used test case metrics reflect different source code factors [7,17]: factors that influence the *number of test cases* required to test the classes of a system, and factors that influence the *effort required* to develop each individual test case. These two categories have been referred as *test case generation* and *test case construction* factors. We assume that the effort necessary to write a test class C_t corresponding to a software class C_s is proportional to the characteristics measured by the test case (TC) metrics.

4.4. Correlation Analysis

In this section, we present the first step of the empirical study we performed to explore the relationship between OO metrics (m_s) and test case metrics (m_t). We per-

formed statistical tests using correlation. We used a non-parametric measure of correlation in order to test the correlation between m_s and m_t metrics. We used the Spearman's correlation coefficient. This technique, based on ranks of the observations, is widely used for measuring the degree of linear relationship between two variables (two sets of ranked data). It measures how tightly the ranked data clusters around a straight line. Spearman's correlation coefficient will take a value between -1 and $+1$. A positive correlation is one in which the ranks of both variables increase together. A negative correlation is one in which the ranks of one variable increase as the ranks of the other variable decrease. A correlation of $+1$ or -1 will arise if the relationship between the ranks is exactly linear. A correlation close to zero means that there is no linear relationship between the ranks. We used the XLSTAT² tool to perform the analysis.

For each selected class C_s and corresponding JUnit test case (s) C_t , we have a total of 14 pairs of metrics $\langle m_s, m_t \rangle$. We analyzed the collected data set by calculating the Spearman's correlation coefficient r_s for each pair of metrics. **Table 3** summarizes the results of the correlation analysis. It shows, for each of the selected systems and between each distinct pair of metrics $\langle m_s, m_t \rangle$, the obtained values for the Spearman's correlation coefficient. The obtained Spearman's correlation coefficients that are significant are set in boldface. The chosen significance level is $\alpha = 0.05$. This means that for the corresponding pairs of metrics there exist a correlation at the 95% confidence level. We discuss briefly, in what follows, the obtained results. The main purpose of this study is, in fact, to evaluate the ability of the selected OO metrics (separately and when used together) to predict (using logistic regression methods) the testing effort of classes.

The coupling metric CBO measures dependencies on

Table 3. Correlation values between OO and TC metrics.

	ANT		JFC		POI	
	TAss	TLoc	TAss	TLoc	TAss	TLoc
CBO	0.135	0.394	0.261	0.305	0.280	0.392
DIT	-0.203	0.006	0.069	0.166	-0.100	-0.327
NOC	0.034	0.048	0.224	0.106	0.011	0.025
LCOM	0.347	0.434	0.439	0.388	0.155	0.040
RFC	0.071	0.342	0.197	0.257	0.365	0.237
WMC	0.391	0.566	0.453	0.450	0.400	0.398
LOC	0.391	0.582	0.414	0.437	0.397	0.397

²<http://www.xlstat.com/>

external classes and methods. The fact that a class depends on other classes will probably influence its testing effort. From the obtained correlation values, between the CBO metric and the test case metrics, we can observe that the CBO metric is significantly correlated to the metric TLoc in the three subject systems. This metric is significantly correlated to the test case metric TAss in only two systems (JFC and POI). The observed correlation values between the metric CBO and the metric TLoc are higher than the correlation values (when significant) between the CBO metric and the test case metric TAss.

The cohesion metric LCOM is, in fact, a lack of cohesion metric (inverse cohesion measure). From the obtained correlation values, we can observe that the metric LCOM is significantly correlated to the two test case metrics for ANT and JFC. In the case of ANT and JFC, the metric LCOM is, overall, better correlated with the test case metrics than the metric CBO. The number of methods in a class influences its cohesion (lack of cohesion value) and the number of methods of the corresponding test class, which is related to the characteristics measured by the used test case metrics.

The inheritance metrics DIT and NOC are, overall, not as correlated to the used test case metrics as the metrics CBO and LCOM. The obtained correlations values are, overall, relatively low (when significant). Theoretically, if we consider that inherited methods have to be retested in any subclass, the depth of inheritance tree is likely to be correlated with at least TLoc metric. These results may, however, be affected by the testing strategies used by the developers (or the adopted style while writing test cases). The relative low use of inheritance in the case of the subject systems may also explain why the inheritance metrics are not as correlated to the test case metrics as the other OO metrics. Moreover, the used test case metrics are measured at the class level (unit testing). This may also affect the results. The inheritance metrics would probably have a significant influence on testability at other levels.

The complexity metric WMC is significantly correlated to the test case metrics in all the selected systems. Also, we can see from **Table 3** that the obtained correlation values for the metric WMC are, overall, higher than those obtained with the other OO metrics (except for the pair <LOC, TLoc> for ANT). The highest correlation value of the metric WMC is observed with the test case metric TLoc (for ANT), which is a plausible result knowing the strong relationship between size and complexity. The size metric LOC is significantly correlated to the test case metrics in the used systems (same trend as WMC). These results are, in fact, plausible. A large class, containing a large number of methods in particular, will require a high testing effort. The RFC metric is significantly correlated to the test case metrics in JFC and POI.

In ANT, it is significantly correlated to TLoc.

We also calculated the Spearman's correlation coefficient r_s for each pair of OO metrics $\langle m_s, m_s \rangle$ (**Table 4**) and for each pair of test case metrics $\langle m_t, m_t \rangle$ (**Table 5**). The correlation coefficients shown in bold are significant (at $\alpha = 0.05$ level). The global observation that we can make from **Table 4** is that the OO metrics are (at least for most) correlated between themselves, in particular, the metrics CBO, LCOM, LOC, RFC and WMC, which are related to the OO software attributes: coupling, cohesion, size and complexity. The inheritance metrics DIT and NOC are, in general, weakly correlated (when the correlation values are significant) to the other OO metrics. From **Table 5**, the global observation that we can

Table 4. Correlation values between OO metrics.

	ANT	CBO	DIT	NOC	LCOM	RFC	WMC	LOC
CBO	1		0.185	0.029	0.652	0.832	0.818	0.873
DIT			1	-0.076	-0.029	0.494	0.115	0.113
NOC				1	0.310	0.066	0.140	0.078
LCOM					1	0.670	0.819	0.780
RFC						1	0.782	0.812
WMC							1	0.960
LOC								1
JFC	CBO	DIT	NOC	LCOM	RFC	WMC	LOC	
CBO	1	0.575	0.276	0.644	0.862	0.693	0.792	
DIT		1	0.071	0.349	0.762	0.291	0.376	
NOC			1	0.336	0.268	0.296	0.294	
LCOM				1	0.549	0.757	0.740	
RFC					1	0.640	0.742	
WMC						1	0.966	
LOC							1	
POI	CBO	DIT	NOC	LCOM	RFC	WMC	LOC	
CBO	1	-0.209	0.113	0.259	0.626	0.511	0.556	
DIT		1	-0.122	0.093	0.218	-0.114	-0.108	
NOC			1	0.092	0.069	0.060	0.081	
LCOM				1	0.518	0.543	0.534	
RFC					1	0.714	0.725	
WMC						1	0.923	
LOC							1	

Table 5. Correlation values between test case metrics.

	ANT		JFC		POI	
	TAss	TLoc	TAss	TLoc	TAss	TLoc
TAss	1	0.769	1	0.842	1	0.716
TLoc		1		1		1

make is that the test case metrics are also correlated between themselves.

4.5. Evaluating the Effect of OO Metrics on the Testing Effort Using Logistic Regression Analysis

We present, in this section, the empirical study we conducted in order to evaluate the individual and combined effect of OO metrics on testability of classes in terms of unit testing effort. We used both the univariate and multivariate logistic regression analysis. The univariate regression analysis is used to find the individual effect of each OO metric, identifying which metrics are significantly related to the testing effort of classes. The multivariate regression analysis is used to investigate the combined effect of OO metrics on testability, indicating which metrics may play a more dominant role in predicting the testing effort of classes

4.5.1. Dependent and Independent Variables

We used logistic regression to explore empirically the relationship between OO metrics (independent variables) and testability of classes in terms of unit testing effort (dependent variable). We used the test case metrics TLoc and TAss to identify the classes which required a (relative) high testing effort. In order to simplify the process of testing effort categorization, we provide only two categorizations: classes which required a high testing effort and classes which required a (relative) low testing effort.

Category 1: includes the JUnit test classes for which the two following conditions are satisfied: 1) large number of lines of code (corresponding TLoc \geq mean value of TLoc); and 2) large number of invocations of JUnit assert methods (corresponding TAss \geq mean value of TAss). We affect the value 1 to the corresponding classes.

Category 2: includes all the other JUnit test classes. We affect the value 0 to the corresponding classes.

Table 6 summarizes the distribution of classes according to the adopted categorization.

4.5.2. Hypotheses

The study tested seven hypotheses, which relate the selected metrics to the testing effort. For each source code

Table 6. Distribution of classes.

	1	0
ANT	38.74%	61.26%
JFC	37.17%	62.83%
POI	35.04%	64.96%

metric m_s , the hypothesis was:

A class with a high m_s value is more likely to require a high testing effort than a class with a low m_s value.

The null hypothesis was:

A class with a high m_s value is no more likely to require a high testing effort than a class with a low m_s value.

4.5.3. Logistic Regression Analysis: Research Methodology

Logistic Regression (LR) is a standard statistical modeling method in which the dependent variable can take on only one of two different values. It is suitable for building software quality classification models. It is used to predict the dependent variable from a set of independent variables to determine the percent of variance in the dependent variable explained by the independent variables [9,51,52]. This technique has been widely applied to the prediction of fault-prone classes [20,52-56]. LR is of two types: Univariate LR and Multivariate LR. A multivariate LR model is based on the following equation:

$$P(X_1, \dots, X_n) = \frac{e^{(a + \sum_{i=1}^n b_i X_i)}}{1 + e^{(a + \sum_{i=1}^n b_i X_i)}} \quad (1)$$

The X_i s are the independent variables and the (normalized) b_i s are the estimated regression coefficients (approximated contribution) corresponding to the independent variables X_i s. The larger the absolute value of the coefficient, the stronger the impact of the independent variable on the probability of detecting a high testing effort. P is the probability of detecting a class with a high testing effort. The univariate regression analysis is, in fact, a special case of the multivariate regression analysis, where there is only one independent variable (one OO metric). The p -value (related to the statistical hypothesis) is the probability of the coefficient being different from zero by chance and is also an indicator of the accuracy of the coefficient estimate. To decide whether a metric is a statistically significant predictor of testing effort, we use the $\alpha = 0.05$ significance level to assess the p -value. R^2 (Nagelkerke) is defined as the proportion of the total variance in the dependent variable that is explained by the model. The higher R^2 is, the higher the effect of the

independent variables, and the more accurate the model.

4.5.4. Model Evaluation

In order to evaluate the performance of the predicted models, we used the ROC (*Receiver Operating Characteristic*) analysis. Indeed, *precision* and *recall*, which are traditional evaluation criteria used to evaluate the prediction accuracy of logistic regression models are subject to change as the selected threshold changes. The ROC curve, which is defined as a plot of sensitivity on the y-coordinate versus its 1-specificity on the x-coordinate, is an effective method of evaluating the performance of prediction models [57]. The optimal choice of the cutoff point that maximizes both sensitivity and specificity can be selected from the ROC curve. This will allow avoiding an arbitrary selection of the cutoff. In order to evaluate the performance of the models, we used particularly the AUC (*Area Under the Curve*) measure. It is a combined measure of sensitivity and specificity. It allows appreciating the model without subjective selection of the cutoff value. The larger the AUC measure, the better the model is at classifying classes. A perfect model that correctly classifies all classes has an AUC measure of 1. An AUC value close to 0.5 corresponds to a poor model. An AUC value greater than 0.7 corresponds to a good model [58]. Furthermore, if a prediction model is built on one data set (used as training set) and evaluated on the same data set (used as testing set), then the accuracy of the model will be artificially inflated [59]. A common way to obtain a more realistic assessment of the predic-

tive ability of the models is to use cross validation (*k*-fold cross-validation), which is a procedure in which the data set is partitioned in *k* subsamples (groups of observations). The regression model is built using *k* - 1 groups and its prediction evaluated on the last group. This process is repeated *k* times. Each time, a different subsample is used to evaluate the model, and the remaining subsamples are used as training data to build the model. We performed, in our study, a 10-fold cross-validation.

4.5.5. Univariate LR Analysis: Results and Discussion

In this section, we present the results obtained using the univariate LR analysis. The results, summarized in **Table 7**, show that: For system ANT, the *b*-coefficients of the metrics LCOM, WMC and LOC (respectively 0.946, 0.582 and 0.596) are significantly different from zero according to their p-values. The metrics LOC, WMC and LCOM have (respectively) the highest (and significant) R^2 values (respectively 0.2529, 0.2394 and 0.1455). The metrics NOC, DIT, RFC and CBO have (respectively) the lowest *b* and R^2 coefficients values. The metric CBO was, however, significant at 0.05 significance level. According to these results, the metrics LOC, WMC and LCOM are (more) significantly related to the testing effort compared to the other OO metrics. The AUC values (WMC: 0.798, LOC: 0.793 and LCOM: 0.73) confirm that univariate LR models based on the metrics WMC, LOC and LCOM are more predictive of testing effort than the other OO metrics. The metrics LOC and WMC have the highest R^2 (and AUC values), which shows that

Table 7. Results for univariate LR analysis.

		CBO	DIT	NOC	LCOM	RFC	WMC	LOC
ANT	R^2	8.67%	0.31%	0.20%	14.55%	3.86%	23.94%	25.29%
	2Log	0.007	0.617	0.686	0.001	0.074	<0.0001	<0.0001
	<i>b</i>	0.296	-0.054	-0.048	0.946	0.199	0.582	0.596
	<i>p</i> -value	0.009	0.618	0.707	0.015	0.091	<0.0001	<0.0001
	AUC	0.67	0.549	0.551	0.73	0.656	0.798	0.793
JFC		CBO	DIT	NOC	LCOM	RFC	WMC	LOC
	R^2	11.14%	0.46%	5.13%	13.49%	0.69%	26.96%	13.49%
	2Log	<0.0001	0.384	0.003	<0.0001	0.285	<0.0001	<0.0001
	<i>b</i>	0.341	0.066	0.344	1.156	0.081	0.870	1.156
	<i>p</i> -value	<0.0001	0.384	0.045	0.002	0.283	<0.0001	0.002
AUC	0.663	0.547	0.598	0.746	0.611	0.79	0.746	
POI		CBO	DIT	NOC	LCOM	RFC	WMC	LOC
	R^2	12.94%	11.23%	0.00%	4.82%	10.29%	15.26%	10.94%
	2Log	<0.0001	<0.0001	0.973	0.001	<0.0001	<0.0001	<0.0001
	<i>b</i>	0.420	-0.361	-0.002	0.343	0.409	0.552	0.414
	<i>p</i> -value	<0.0001	<0.0001	0.973	0.010	<0.0001	<0.0001	<0.0001
AUC	0.682	0.664	0.533	0.529	0.623	0.686	0.684	

these metrics are the best predictors of the testing effort. For system JFC, we can observe also the same trends. The metrics WMC, LOC and LCOM have (respectively) the highest (and significant) R^2 values (respectively 0.2696, 0.1349 and 0.1349). Here also, the AUC values (WMC: 0.79, LOC: 0.746 and LCOM: 0.746) confirm that univariate LR models based on the metrics WMC, LOC and LCOM are more predictive of testing effort than the metrics DIT, NOC, RFC and CBO. The WMC metric has the highest R^2 (and AUC value), which shows that it is (here also) the best predictor of testing effort. The LOC metric has the second highest R^2 (and AUC value). Moreover, in this case also the metric CBO was significant (at 0.01). The AUC value of the metric CBO is almost the same as that obtained for system ANT. For system POI, even if the results show that the b and R^2 coefficients values for the OO metrics (except NOC) are significant, the AUC values of the univariate models are all lower than 0.7. The metrics WMC, CBO and DIT have the highest (and significant) R^2 values (respectively 0.1526, 0.1294 and 0.1123). These results, based on the data set we used and particularly data collected from

ANT and JFC systems, suggest that the metrics WMC, LOC, LCOM and CBO (to some extent) are significant predictors of testing effort. Hence, we can reasonably support the hypothesis of each of these metrics. These metrics are related respectively to: complexity, size, cohesion and coupling.

4.5.6. Multivariate LR Analysis: Results and Discussion

We present, in this section, the results of the multivariate LR analysis. The main objective was to explore the potential of OO design metrics, when used in combination, to predict the unit testing effort of classes. Indeed, the multivariate LR analysis here is not intended to be used to build the best prediction model combining the OO source code metrics because, in this case, other metrics also have to be considered (for example, other coupling or size metrics). Such a model is out of the scope of this paper.

We performed, in this step, two different experiments. The first experiment includes all the selected metrics (**Table 8** MLR-I), in contrast to the second experiment

Table 8. Results for multivariate LR analysis.

MLR-I	ANT		JFC		POI	
R^2	34.73%		38.23%		27.31%	
$2\log$	0.000		<0.0001		<0.0001	
	b	p -value	b	p -value	b	p -value
CBO	-0.382	0.206	0.218	0.311	0.191	0.217
DIT	0.271	0.145	0.162	0.198	-0.307	0.000
NOC	-0.065	0.704	0.095	0.46	0.052	0.465
LCOM	0.545	0.296	-1.109	0.000	-0.305	0.105
RFC	-0.962	0.066	-0.617	0.003	0.151	0.513
WMC	-0.226	0.723	2.333	0.000	0.392	0.180
LOC	1.663	0.022	-0.698	0.156	0.081	0.746
AUC	0.848		0.834		0.773	
MLR-II	ANT		JFC		POI	
R^2	25.69%		37.32%		27.27%	
$2\log$	0.002		<0.0001		<0.0001	
	b	p -value	b	p -value	b	p -value
CBO	-0.209	0.432	0.152	0.459	0.196	0.203
DIT	0.068	0.677	0.188	0.129	-0.304	0.000
NOC	-0.108	0.591	0.123	0.335	-0.307	0.109
LCOM	0.105	0.798	-1.036	0.000	0.051	0.472
RFC	0.923	0.008	-0.682	0.001	0.155	0.501
WMC	-0.351	0.389	1.633	<0.0001	0.466	0.013
AUC	0.78		0.832		0.772	

which excludes the metric LOC (**Table 8** MLR-II). This will allow us to compare the performance of the prediction model MLR-II which is based on the CK metrics only, with the performance of the prediction model MLR-I which is based on all the considered metrics. Moreover, as mentioned in Section 4.2 (descriptive statistics), the metric LCOM is not computed for all classes. The classes for which LCOM is not computed and the corresponding JUnit test cases have been excluded from our measurements (multivariate LR). So, the models MLR-I and MLR-II were built using data collected from only classes (and the corresponding JUnit test cases) for which LCOM is computed. The number of considered classes differ from one system to another (ANT: 98, JFC: 219 and POI: 313).

In the first experiment, we used all the OO metrics to build the multivariate regression model. **Table 8** MLR-I summarizes the results of the multivariate analysis. From **Table 8** MLR-I, it can be seen that for ANT the AUC value is 0.848, which is higher than the AUC values obtained with the univariate LR analysis. It is also the highest value of AUC obtained in this experiment. Moreover, the R^2 value increases (34.73%). This shows that the combined effect of the metrics is higher. The results also show that the metric LOC has the highest (and significant) contribution (impact of the metric on the probability of detecting a high testing effort). For JFC, we can see that the AUC value is 0.834, which is higher (here also) than the AUC values obtained with the univariate LR analysis. Moreover, the R^2 value, as in the case of ANT, increases (38.23%). The results show that the metrics WMC, LCOM and RFC have the highest (and significant) contributions. For POI, we can see that the AUC value is 0.773, which is higher (here also) than the AUC values obtained with the univariate LR analysis. Moreover, the results (combined effect of the metrics) are significant in contrast to the results of the univariate analysis (individual effect of the metrics). The R^2 value, as in the case of ANT and JFC, increases (27.31%). The R^2 value in this case is relatively high than all the R^2 values obtained in the case of univariate analysis. This shows once again that the combined effect of the metrics is more significant than when the metrics are considered individually.

In the second experiment, we used only the CK metrics to build the multivariate regression model. **Table 8** MLR-II summarizes the results of the multivariate analysis. From **Table 8** MLR-II, we can observe that the results have (overall) the same trend as those obtained during the first experiment. The results are significant for the three systems ANT, JFC and POI. From **Table 8** MLR-II, it can be seen that for ANT the AUC value is 0.780, which is slightly less than the AUC values of the univariate models based on the metrics WMC and LOC

(respectively 0.798 and 0.793), and greater than the AUC values of the univariate models based on the metrics CBO, DIT, NOC, LCOM and RFC. Moreover, the R^2 value (25.69%) increased slightly compared to the R^2 value of the univariate model based on the metric LOC (25.29%, which was the highest R^2 value obtained in the univariate analysis for ANT). The results also show that the metric RFC has the highest (and significant) contribution (impact of the metric on the probability of detecting a high testing effort). For JFC, we can see that the AUC value is 0.832, which is higher than the AUC values obtained with the univariate LR analysis. Moreover, the R^2 value increases (37.32%). The results show that the metrics WMC, LCOM and RFC have the highest (and significant) contributions. For POI, we can see that the AUC value is 0.772, which is higher (here also) than the AUC values obtained with the univariate LR analysis. Moreover, the results (combined effect of the metrics) are significant in contrast to the results of the univariate analysis (individual effect of the metrics). The R^2 value, as in the case of ANT and JFC, increases (27.27%). The R^2 value in this case also is relatively high than all the R^2 values obtained in the case of univariate LR analysis. This shows once again that the combined effect of the metrics is more significant than when the metrics are considered individually. In the case of POI, the results show that the metrics WMC and DIT have the highest (and significant) contributions (as for MLR-I).

The accuracies of the models MLR-I and MLR-II are, overall, comparable. Indeed, as we can see from **Table 8**, the AUC values of the models are almost identical in the two systems JFC and POI. This is true also for the R^2 values. This can be explained by the fact that size is (indirectly) captured by most of the considered metrics (WMC, RFC, LCOM and CBO), which may also be observed from the correlation values between these metrics in **Table 4**. The correlation values between, in particular, the metrics WMC and LOC are almost perfect (in the three systems). This explains also why the contributions of these two metrics, in **Table 8** MLR-I, vary from one system to another. In the case of system ANT, the performance of the multivariate model MLR-I is, however, better than the performance of the multivariate model MLR-II. The AUC and R^2 values of the model MLR-I (respectively 0.848 and 34.73) are greater than the AUC and R^2 values of the model MLR-II (respectively 0.780 and 25.69). In summary, the multivariate analysis shows that the combined effect of the metrics is more significant than when the metrics are considered individually. Moreover, it shows also, when the results are significant, that, overall, the metrics WMC, RFC, LCOM and LOC have the highest contributions. These metrics are respectively related to: complexity, coupling, cohesion and size. This confirms somewhere the results of the univariate

analysis. Furthermore, in order to obtain a more realistic assessment of the predictive abilities of the models, we performed in our study a 10-fold cross-validation (MLR models). We used the R^3 tool.

4.5.7. Applicability of the Prediction Models

In addition, we explored to what extent a prediction model built using data from one of the three used systems can be used to predict the testing effort of classes of the two other systems. Indeed, the practical purpose of building software prediction models (reliability, fault-proneness, testing effort, etc.) is to apply them to software systems. Knowing that we have collected data sets from three different systems, we evaluated each model M_i , constructed using data from a system S_i , on data from another system S_j ($i \neq j$). As mentioned previously, the three used systems are from different domains and have different characteristics. Moreover, they have been developed by different teams. We used, in fact, the data from a system as the training data set and the data from another system as the testing data set. Usually, the data set with the largest number of observations is designated as the training data set and the remaining system data sets as the testing sets [59]. So, in our study, we performed the following tests: 1) we applied the prediction model built using the data set of POI (referenced as M_{POI}) for predicting the testing effort of classes of JFC and ANT; and 2) we applied the prediction model built using the data set of JFC (referenced as M_{JFC}) to predict the testing effort of classes of ANT.

The results of a prediction model depend on the chosen value of the threshold. Indeed, if the predicted testing effort of a class is above the chosen value, the class is classified as requiring a high testing effort. Moreover, the value of the threshold may vary from one system to another because of differences between systems. To avoid an arbitrary selection of the cutoff, and as a first attempt to assess the applicability of the prediction models, we explored in each test different values of threshold. We used here also the ROC analysis to evaluate the performance of the models. The obtained AUC values are 0.69, 0.67 and 0.71 respectively for applying M_{POI} for predicting the testing effort of classes of JFC and ANT and for applying M_{JFC} to predict the testing effort of classes of ANT. The models do not show, in fact, a strong difference. Their prediction performance is, overall, acceptable. The results indicate that the LR prediction models built using the OO metrics seem viable. They show, at least, that the metrics when combined offer a promising potential for predicting the testing effort of classes. Further investigations are, however, needed to

make more general conclusions.

4.6. Threats to Validity

The achieved results are based on the data set we collected from the analyzed systems. We analyzed a total of 688 classes and corresponding JUnit test cases. Even if we believe that the analyzed set of data is large enough to allow obtaining significant results, we do not claim that our results can be generalized to all systems. The study should be, indeed, replicated on a large number of OO software systems to increase the generality of our findings. In fact, there are a number of limitations that may affect the results of the study or limit their interpretation and generalization.

First, the JUnit test cases used in our study were developed for large and complex classes. This is true for the three subject systems. It would be interesting to replicate this study using systems for which JUnit test cases have been developed for a maximum number of classes. This will allow observing the performance of the metrics (individually and used in combination) for different types of classes (small, medium and large). Second, it is also possible that facts such as the development style used by the developers for writing test cases may affect the results or produce different results for specific applications. We observed, for example, that in some cases the developed JUnit classes do not cover all the methods of the corresponding software classes. As the OO metrics are source code metrics and are computed using the complete code of the classes, this may bias the results. Finally, another important threat to validity is from the identification of the relationship between the JUnit test cases and tested classes. We noticed, in fact, by analyzing the code of the JUnit test cases of the investigated systems that, in some cases, there is no one-to-one relationship between JUnit test cases and tested classes. In these cases, several JUnit test cases have been related to a same tested class. Even if we followed a systematic approach for associating the JUnit test cases to the corresponding tested classes, unfortunately we have not been able to do that for all classes. This may also affect the results of our study, or produce different results from one system to another.

5. Conclusions and Future Work

The paper investigated empirically the relationship between OO metrics and testability of classes in terms of required testing effort. Testability has been investigated from the perspective of unit testing. We performed an empirical analysis using data collected from three Java software systems for which JUnit test cases exist. To capture testability of classes, we used different metrics to quantify the corresponding JUnit test cases. The metrics

³<http://www.r-project.org/>

related to the JUnit test cases were used, in fact, to classify the classes in two categories in terms of required testing effort: high and low.

In order to evaluate the relationship between OO metrics and unit testing effort of classes, we performed statistical analysis using correlation and logistic regression methods. We used the univariate logistic regression analysis to evaluate the individual effect of the selected metrics on the testing effort of classes. We used the multivariate logistic regression analysis to evaluate their combined effect. The performance of the predicted models was evaluated using Receiver Operating Characteristic analysis. We also included in our study the well-known LOC metric as a “baseline”. Univariate regression analysis, based on the data set we used, suggests that univariate LR models based on the metrics WMC, LOC, LCOM and CBO (also to some extent) are significant predictors of unit testing effort. Moreover, the results show that multivariate regression models based on OO metrics are able to accurately predict the unit testing effort of classes. The multivariate analysis shows that, overall, the metrics WMC, RFC, LCOM and LOC have the highest effect on the testing effort. In summary, the metrics that were found significant predictors of the testing effort (in the univariate analysis and in the multivariate analysis as having a relatively high effect) are related to the important OO attributes: size, complexity, cohesion and coupling.

In addition, we explored the applicability of the prediction models by examining to what extent a prediction model built using data from one system can be used to predict the testing effort of classes of another system. The results clearly show that the prediction models were able to achieve acceptable levels of performance in the classification of classes according to the predicted testing effort. We hope these findings will help to a better understanding of what contributes to testability of classes in OO systems, and particularly the relationship between OO attributes (metrics) and testability of classes. The performed study should be replicated using many other OO software systems in order to draw more general conclusions. The findings in this paper should be viewed as exploratory and indicative rather than conclusive. Moreover, knowing that software testability is affected by many different factors, it would be interesting to extend the used suite of test case metrics to better reflect the testing effort.

As future work, we plan to: extend the used test case metrics to better reflect the testing effort, use other OO metrics to improve the performance of the prediction models, use other methods (such as machine learning methods) to explore the individual and combined effect of the metrics on testability of classes, explore other approaches for testing effort rating (ranking) and finally

replicate the study on other OO software systems to be able to give generalized results.

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