Abstract

Objectives: Development of an efficient test suite minimization approach in order to reduce the size of a previously acquired test suite and produce a new representative suite which will guarantee the same requirement coverage that was achieved before minimization for an effective and efficient regression testing. Method: Test suite minimization techniques try to reduce the size and redundancy of test suite by removing certain test cases since requirement covered by them are already covered by other test cases. But, it has been found that the acquired test cases after minimization severely lacks ability to achieve the desirable code coverage because the minimization was done based on a single test adequacy criteria. In this paper, we propose an efficient heuristic based test suite minimization algorithm which will reduce the size of the test suites with respective to multiple test adequacy criterions in order to preserve the fault detection effectiveness and code coverage characteristics of the final test suite. Findings: Our experimental results indicate that a significant percentage of reduction in the test suite size is achieved when the minimization is performed with respect to multiple test adequacy criterions. Our approach is unique compared to the existing approaches in the sense that, we carried out minimization based on multiple test adequacy criterions while most of the existing approaches usually take one or two criterions into consideration. The proposed approach is evaluated based on two well known software testing metrics; one indicate the percentage of reduction in test suite size and the second one indicate the percentage of code coverage achieved by the minimized test suite. Our experimental results indicate that a significant percentage of reduction in the size as well as significant code coverage characteristics is achieved when the minimization is done according to the proposed approach.

Improvements: The important contribution of this study is that, it presents a novel and efficient test suite minimization technique that optimizes the test suite size based on multiple adequacy criterions.

Keywords: Regression Testing, Software Testing, Test Data Generation, Test Suite Minimization, Test Suite Selection and Data Clustering

1. Introduction

Software engineering is a well-defined approach to the analysis, design, implementation, testing, maintenance and re-engineering of a product. In software engineering, testing is an important activity used to identify the defects and problems associated with the product being developed. The testing process is usually expensive and may represent 50% of the software development budget. The key factor responsible is the size of test suite as it takes a very long time to execute the whole generated test suite. The test suite size goes on increasing when software undergoes maintenance, because new test cases are needed to test the exiting code and the code that is newly added. Thus changes to existing program lead to the expansion in size of the test suite. Therefore test suite management becomes an important research issue and in literature it is termed as test suite minimization or test suite reduction. The aim of test suite minimization is to reduce the size of a previously acquired test suite and produce a new representative suite which will guarantee the same requirement coverage that was achieved before minimization.

The other related issue during software maintenance is regression test case selection. Regression testing is used to validate the modified software to detect whether
new faults are introduced into a previously tested code. Regression selection techniques are also used to reduce the cost by selecting and running a subset of test cases from the previous test suite. Test suite minimization and test case selection techniques are similar because both of them try to acquire a subset from the previously existing test suite, but can be differentiated based on the criteria imposed. For the test suite minimization, the criteria are whether the minimized test set cover all the test requirements whereas as selection process focus on the modified parts of the system under test. A test case is called redundant when it covers the requirement that has already been covered by another test case.

2. Test Suite Minimization and the Intuition Behind our Approach

Test suite minimization is an optimization problem and its goal is to, select a minimized subset of test cases from an existing test suite that exercises the same set of requirements as exercised by the initial test suite. The definition according to 3 is:

2.1 Definition
Given T (a test suite), R (a set of test requirements r1, r2, r3 ..., ri) that must be satisfied to get the desired coverage of the program.

2.2 Problem
Find a subset T' of T that satisfies all ri.

Trying to find a representative set T' that will cover the same requirements as covered by the initial test suite is the NP complete problem5. Due to NP completeness, test suite minimization encourages the use of heuristic approaches and in literature, many such approaches have been developed to produce a minimum hitting set5,8. In9, proposes the usage of simple greedy heuristic in which each candidate set has a cost associated with it and chooses test cases which cover almost all requirements about to be covered, until are accomplished. But, a potential weakness of the approach is that the early selection made can eventually be rendered redundant by the test cases subsequently selected. Another greedy heuristic approach developed by authors in9 chooses a minimal subset which covers the same set of requirements as covered by un-minimized test suite. The optimal test suite generated using the proposal of9 is equally good or better than computed by7. The ping pong procedure developed by10, declared that the technique presented in9 is more expensive than their proposed approach. Another study proposed by11 which is also known as double delayed greedy heuristic tried to overtake the weakness of the previous heuristic approaches by developing a concept lattice. The approach by11 works in three phases: (1) apply reduction by removing test cases test cases whose test requirement are subsumed by other test cases; (2) remove test requirements that are not present in the minimal requirement set; (3) generate test suite using greedy method12 from the remaining test cases. The empirical results showed that the minimized test suite minimized using double delayed greedy approach11 were smaller or even smaller than minimized by traditional greedy approaches13.

The previous studies5,9–11 at one end focus alone on single standard minimization problems and have achieved high test suite reduction, but, at the other end have neglected the other important dimensions like fault detection effectiveness and code coverage characteristics of the minimized test suite. In a study reported in16, it was observed that test suites achieving over 80% size reduction during minimization by different techniques suffer with less fault detection loss (around 50% loss on average). In another study proposed in15 in which it was observed that only 7% to 16% fault detection effectiveness loss happened to a test suite which undergoes 82% to 94% size reduction on average. Authors in14 carried an empirical investigation to deal with the limitations of single criterion minimization approaches by taking two testing demands (requirements) into account instead of one. The results reported in14 showed that fault detection effectiveness was better preserved by returning the larger test suite compared to the test suite returned by single criteria version of the HGS heuristic13.

Despite encouraging results by many studies like14–16 however, there is still definitely much room for improving the existing techniques and developing new techniques for an effective and efficient testing.

3. The Proposed Test Suite Minimization Approach

To find a representative set that satisfies all the
requirements initially satisfied before reduction or minimization is a NP complete problem. Therefore, we are unaware of any approximate solution, hence a heuristic based approach is proposed as shown in Figure 1, which will find a representative set of test cases with minimum cardinality from the initial test suite based on different code coverage matrices. The different steps of the proposed test suite minimization approach are shown in Figure 1. The important characteristics of our proposed approach is that we have used a filter in the form of an array (step 2 to step 4) to throw away redundant test cases from the test suite according to different code coverage criteria’s. A test case is redundant if the requirements satisfied by it have been previously satisfied by any other test case present in the test suite.

4. The Application of the Proposed Approach

The proposed approach is initially implemented on a test suite of a single sample program shown in Figure 2 and then extended to a large suite of sample programs. To test the program, a suite of test cases are generated and with an automated test data generation tool known as generatedata.com\textsuperscript{19}. The Initially generated test suite is

\begin{verbatim}
input: TS[i][j] .... all test cases present in the test suite
CM1.txt, CM2.txt and CM3.txt, Comma Separated Coverage Information in text format representing statement, branch and independent path coverage of each test case. 1 for covered and 0 for uncovered
output: RS: a reduced set of test cases from the test Initial Test Suite.
declare:
CM1 [m][s], CM2 [m][b] and CM3 [m][ip]: Matrices used to hold the data from CM1.txt, CM2.txt and CM3.txt files.
m[],m1[],m2[]: Index of test cases returned after Minimization Process.
r[],r1[],r2[]: array[1..n], Initially Empty, representing the requirements Covered by minimized test cases in m[],m1[],m2[].

algorithm TestSuiteMinimization
begin

STEP 1: Initialize each CM1 [m][s], CM2 [m][b] and CM3 [m][ip] Matrices by reading each text files using Java.io.BufferedReader Class.

STEP 2: for-each CM1[i][j] do
Minimization with Respect to Statement Coverage Perspective
if r[i] == 0 and CM1[i][j] equals to “1” then
r[i]=CM1[i][j];
m[i]=i+1;
endfor

STEP 3: for-each CM2[i][j] do
Minimization with Respect to Branch Coverage Perspective
if r1[j] == 0 and CM2[i][j] equals to “1” then
r1[j]=CM2[i][j];
m1[i]=i+1;
endfor

STEP 4: for-each CM3[i][j] do
Minimization from Independent Path Coverage Perspective
if r2[j] == 0 and CM3[i][j] equals to “1” then
r2[i]=CM3[i][j];
m2[i]=i+1;
endfor

STEP 5: RS := \{ m \} \cup \{ ml \} \cup \{ m2 \}; To further Remove the Redundant Test Cases
return RS;
end TestSuiteMinimization

Figure 1. The proposed approach.
\end{verbatim}
An Efficient Heuristic Based Test Suite Minimization Approach

presented in Figure 3. To remove the inconsistency of not generating fault revealing test cases, an efficient approach to test data generation is followed using our previous study\(^\text{17}\). Through the previous study reported in\(^\text{17}\), few combination of test cases that are added to the initially generated test suite are (10,10,10), (0,0,0), (1,2,2), (2,2,1), (1,2,1), (-1,-2,-3) and many others. The tool generates a large volume of test cases and is not an effective choice for an initial and regression testing due to many reasons like, its size is huge, and it is redundant and hence will take time to execute.

To determine the adequacy or efficiency of a test suite, test case requirements play an important role. Test case requirements in case of black box testing are derived from program specifications while in case of white box testing; they are derived from program components. For the present study, we are employing program component based test adequacy criterion like statements, branches, and path coverage to determine the adequacy of the reduced test data set\(^\text{18}\). A test data set is adequate when all the test requirements are covered otherwise more test cases are added to achieve the desired coverage\(^\text{18}\). The experiments are carried in Eclipse with control flow graph factory, JUnit and EclEmma as plug-ins for knowing the structural components, test case execution and code coverage measurements.

4.1 Minimization with Respect to a Single Adequacy Criterion

The initial test suite when minimized using the proposed approach based on single test adequacy criteria (Statement coverage criteria) will result in formation of a sub-optimal representative subset RS1 shown in Table 1.
Table 1. Sub-optimal test suite (only Statement Adequate)

<table>
<thead>
<tr>
<th>Test Case ID</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>t11</td>
<td>78</td>
<td>67</td>
<td>47</td>
</tr>
<tr>
<td>t2</td>
<td>99</td>
<td>110</td>
<td>73</td>
</tr>
<tr>
<td>t10</td>
<td>24</td>
<td>17</td>
<td>90</td>
</tr>
<tr>
<td>ts1</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>ts2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The minimized test suite or representative suite RS1 = {t11, t2, t10, ts1, ts2} when executed achieves around 94.1% statement code coverage and is shown in Figure 3.

The code coverage characteristic of other components of the subject program achieved by the RS1 is shown in Figure 4.

4.2 Minimization with Respect to Multiple Test Criterions

In order to enhance the code coverage efficiency and fault detection effectiveness of a test suite, minimization should always be carried out using multiple adequacy criterions.

With the proposed test suite minimization, the initial test suite is further minimized with respect to branch and path coverage perspective in order to improve the code coverage and fault detection effectiveness. The minimized branch coverage and independent path coverage test suite are depicted in Table 2 and Table 3.

Table 2. Branch Adequate Test suite (RS2)

<table>
<thead>
<tr>
<th>Test Case ID</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>t11</td>
<td>78</td>
<td>67</td>
<td>47</td>
</tr>
<tr>
<td>t2</td>
<td>99</td>
<td>110</td>
<td>73</td>
</tr>
<tr>
<td>t10</td>
<td>24</td>
<td>17</td>
<td>90</td>
</tr>
<tr>
<td>ts1</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>ts2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>t32</td>
<td>24</td>
<td>0</td>
<td>93</td>
</tr>
<tr>
<td>t52</td>
<td>67</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>ts4</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>ts5</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>T57</td>
<td>-1</td>
<td>-2</td>
<td>-3</td>
</tr>
<tr>
<td>T66</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

The final outcome of the proposed technique is the RS, a representative subset of TS formed by the union of RS1, RS2 and RS3. The purpose of taking union between RS1, RS2 and RS3 is to further minimize the size and redundancy among test cases.

\[ RS = [(RS1) U (RS2) U (RS3)] \]

\[ RS = \{t11, t2, t10, ts1, t32, t52, ts1, ts2, ts3, ts4, ts5, ts6, ts7\} \]

With the implementing of the proposed approach, a considerable amount of reduction in the number of test cases (from 110 to 11) is also achieved and is given as:
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% Reduction = \left(\frac{TS - RS}{110}\right) \times 100 = \frac{110 - 13}{110} \times 100 = 88\%.

The final representative suite $RS$ after execution as shown in Figure 5 and Figure 6 has achieved above 95% statement coverage, 100% branch coverage and around 90.90% path coverage.

5. Application on Large Study

The proposed approach after its successful implementation on a single subject program is now carried on a suite of well known programs. The suite of programs and their corresponding test cases are listed in Table 4. The present study will evaluate the proposed approach with respect to the size and code coverage perspective. The other important parameter is the fault detection effectiveness measure. Fault detection effectiveness determines the fault detection ability of the reduced or minimized test suite. It is observed from some studies, one reported in [16] that test suite reduction can reduce the fault detection ability of the resulted minimized test suite significantly. But, on the other end, it is also reported in some studies like [20], that test reduction approaches achieve a substantial savings with little cost to fault detection effectiveness. In case of present study we assume that the fault detection ability of the minimized test suite is preserved due to the fact that the minimization is done with respect to multiple coverage criterions. In our previous studies [21], we have employed data clustering techniques for test suite minimization and have minimized test suite with respect single adequacy criteria, but this study presents an efficient heuristic based approach for the same reason with multiple test adequacy criterions.

Table 4. Suite of Test Programs and test data

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Subject Programs for Experiments.</th>
<th>Total Number of Test Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Triangle Classification</td>
<td>110 rows</td>
</tr>
<tr>
<td>P2</td>
<td>Roots of Quadratic Eq.</td>
<td>100 rows</td>
</tr>
<tr>
<td>P3</td>
<td>Largest of Three Numbers</td>
<td>110 rows</td>
</tr>
<tr>
<td>P4</td>
<td>Bubble Sort</td>
<td>100 rows</td>
</tr>
</tbody>
</table>

5.1 Evaluation with Respect to Size

The proposed approach is validated with respective to the size of the test suite and coverage of the structural components achieved for all programs. So, for an efficient testing and also for regression testing only a subset of test cases is required and this acquired subset should possess less number of test cases and should satisfy all the specified test requirements criterions.
The proposed approach after implementation achieved a considerable amount of reduction in the number of test cases for each program. The comparison of the size between initial test cases and the test cases acquired after implementation of proposed minimization approach is depicted in Figure 7.

![Figure 7](image_url)  
**Figure 7.** Comparison in terms of size between the original and minimized test cases.

The percentage of reduction in each test suite is also very effective and is calculated as:

\[
\% \text{ of reduction for } P1 = \frac{110 - 17}{110} \times 100 = 85\%
\]

\[
\% \text{ of reduction for } P2 = \frac{100 - 15}{100} \times 100 = 85\%
\]

\[
\% \text{ of reduction for } P3 = \frac{110 - 13}{110} \times 100 = 88\%
\]

\[
\% \text{ of reduction for } P4 = \frac{100 - 13}{100} \times 100 = 87\%
\]

### 5.2 Evaluation with Respect to Multiple Requirement Coverage Criteria
In this study, multiple requirement coverage criteria are used to determine the adequacy of each test suite. The proposed approach is also evaluated with respect to the following well-known adequacy criteria:

1. The number of Instructions covered,
2. The number of branches covered,
3. The number of statements or lines exercised and
4. The number of independent paths covered.

The specified requirement coverage resulted by the minimized test suite minimized using the proposed approach for each subject program P1, P2, P3, and P4 are given in Figure 8, Figure 9, Figure 10, and Figure 11. The Figure 8–11 represents the total number components, the number of components covered, and the number of components missed by the minimized test cases against experimental programs P1, P2, P3, and P4.

![Figure 8](image_url)  
**Figure 8.** Requirement coverage of the specified components of P1.

![Figure 9](image_url)  
**Figure 9.** Requirement coverage of the specified components of P2.

![Figure 10](image_url)  
**Figure 10.** Requirement coverage of the specified components of P3.

![Figure 11](image_url)  
**Figure 11.** Requirement coverage of the specified components of P4.
6. Conclusion

In this study, we propose an efficient test suite minimization approach for unit testing. The proposed approach is evaluated with respect to two well known test metrics such as test suite size and test adequacy criteria. It has been observed by our experimentation that the size of the initial test suite is reduced to a great extent without compromising the test suite code coverage characteristics and its fault detection effectiveness. Although we have not measured the fault detection effectiveness of the minimized test suite but it assumed that it is preserved because the reduction is performed with respect to multiple code coverage criteria’s. A test suite which is statement adequate, branch adequate and path adequate would also be effective in terms of fault detection effectiveness. The requirement coverage of the acquired test suites with our proposed technique is also very good. The future scope of this study would be to measure the fault detection effectiveness of each minimized test suite on a large study and its comparison with other proposed test suite minimization approaches.

7. References