

The Art of Testing Less without Sacrificing Quality

Kim Herzigⁱ
kimh@microsoft.com

Michaela Greilerⁱⁱ
mgreiler@microsoft.com

Jacek Czerwotkaⁱⁱ
jacekcz@microsoft.com

Brendan Murphyⁱ
bmurphy@microsoft.com

ⁱ Microsoft Research, United Kingdom

ⁱⁱ Microsoft Corporation, Redmond, United States

Abstract—Testing is a key element of software development processes for the management and assessment of product quality. In most development environments, the software engineers are responsible for ensuring the functional correctness of code. However, for large complex software products, there is an additional need to check that changes do not negatively impact other parts of the software and they comply with system constraints such as backward compatibility, performance, security etc. Ensuring these system constraints may require complex verification infrastructure and test procedures. Although such tests are time consuming and expensive and rarely find defects they act as an insurance process to ensure the software is compliant. However, long lasting tests increasingly conflict with strategic aims to shorten release cycles. To decrease production costs and to improve development agility, we created a generic test selection strategy called *THEO* that accelerates test processes without sacrificing product quality. *THEO* is based on a cost model, which dynamically skips tests when the expected cost of running the test exceeds the expected cost of removing it. We replayed past development periods of three major Microsoft products resulting in a reduction of 50% of test executions, saving millions of dollars per year, while maintaining product quality.

Index Terms—measurement, cost estimation, test improvement.

I. INTRODUCTION

Software testing is a key element of software development processes. The purpose of testing is to ensure that code changes applied to a software product do not compromise product quality. Often, testing is associated with checking for functional correctness. However, for large complex software systems, it is also important to verify system constraints such as backward compatibility, performance, security etc. Complex systems like Microsoft Windows and Office are developed by thousands of engineers that simultaneously apply code changes, which may interfere with each other. In such environments, testing may be seen as an insurance process verifying that the software product complies with all necessary system constraints at all times. By nature, system and compliance tests are complex and time-consuming although they rarely find a defect. Large complex software products tend to run on millions of configuration in the field and emulating these configurations requires multiple test infrastructures and procedures that are expensive to run in terms of cost and time. Making tests faster is desirable but usually requires enormous development efforts. Simply removing tests increases the risk of expensive bugs being shipped as part of the final product. This is a generic issue for developing large

complex software systems [1]. At the same time, long running test processes increasingly conflict with the need to deliver software products in shorter periods of time while maintaining or increasing product quality and reliability. Increasing productivity through running less tests is desirable but threatens product quality, as code defects may remain undetected.

The goal of this work is to develop a cost based test selection strategy (called *THEO*¹) to improve development processes. *THEO* is a dynamic, self-adaptive test selection strategy, which does not sacrifice product quality. *THEO* automatically skips test executions when the expected cost of running a test exceeds the expected cost of not running it. We designed *THEO* to ensure that all tests will execute on all code changes at least once before shipping the software product. Executing all tests at least once ensures that we eventually find all code defects. Thus, *THEO* does not sacrifice product quality but may delay defect detection to later development phases. *THEO* and its underlying cost model are based on historic test measurements to estimate future test execution costs and causes no test runtime overhead. Additional dynamic or static test analysis data, such as coverage or dependency graphs are not required.

We evaluated the effects of *THEO* by simulating historic development processes for three major Microsoft products: Windows, Office, and Dynamics. Combined, our simulation results cover more than 26 month of industrial product development and more than 37 million test executions.

We make the following contributions in this paper:

- We develop a cost model for test executions based on historic test execution results that causes no test execution runtime overhead, and is capable of readjusting its cost estimations based on execution contexts (e.g., configurations of the test environment).
- We develop *THEO*, a self-adapting test selection strategy to accelerate test processes without sacrificing code quality.
- We evaluate *THEO* by simulating its impact on historic Windows, Office, and Dynamics developments.
- We briefly discuss expected secondary improvements such as developer satisfaction.

In Section II, we provide background information about development and verification processes to explain the context of this work, motivation and methodology are described in Section III. We define the historic data feeds in Section IV.

¹ Theo stands for: Test Effectiveness Optimization using Historic data.

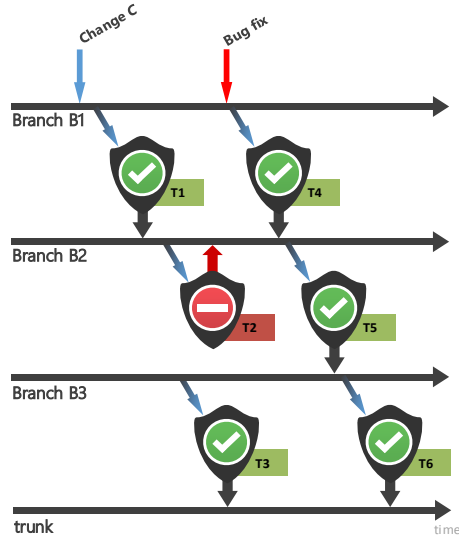


Fig. 1. Integration path example. The integration path of change C applied to branch B1 lists the branches B1, B2, B3, and trunk including the timestamps of the corresponding successful merge operations.

Based on this input, we derive failure probability functions (Section V) used in our cost model (Section VI). Section VII contains a description on simulating THEO on past development processes. Sections VIII and IX discuss simulation measurements and results. Secondary improvements are briefly discussed in Section X. We close the paper with threats to validity (Section XI), related work (Section XII) and a conclusion (Section XIII).

II. DEVELOPMENT AND VERIFICATION PROCESSES

In this section, we provide a brief overview of the complex subject of software development methodologies. The process for developing large software products is predominantly through developing a single component across multiple code branches (e.g. Microsoft Windows) or through developing independent components (e.g. Microsoft Office) which form the product.

When developing code across multiple code branches, a *code branch* is a forked version of the code base that allows parallel modifications without interference (for more details we refer to Bird and Zimmermann [2] and Murphy et al. [3]). The alternative is to design the product into multiple independent components. Each component can be developed independently on a single code branch [4].

Independent from the development methodology, development teams are often responsible for verifying functional correctness of any code change. Where system constraints exist on the product, additional test infrastructure is required to ensure all code meets those constraints. Since product constraints are system properties, they often need to be verified at system level. The complexity of the verification requirements is dependent upon system size and the number of system constraints. For example, Windows uses multiple development branches that integrate into a single trunk branch (see Fig. 1.). Developer commit their code changes to development branches (Branch B1 in Fig. 1.) and integrate these code changes through multiple

integration branches (B2 and B3 in Fig. 1.) into the trunk branch, which contains the current stable version of the next Windows release. Each integration path between any two branches is guarded by so-called *quality gates* checking for various constraints, e.g. backward compatibility requirements, both in terms of the hardware it runs on and in terms of supported applications. To verify that Windows meets these constraints requires the emulation of millions of different execution setups at each branch level. The lower the level of branches a quality gate fails, the higher the number of affected engineers and the more expensive a defect becomes.

At the same time, any complex test infrastructure evolves over time. New test are added, older tests might get less important or even deprecated. Maintaining tests and preventing test infrastructures from decay can be an enormous effort. For older products, there may be a lack of ownership for some of the older tests. These tests can affect development speed as the more tests are executed and the longer the runtime of tests, the longer the verification process and the slower the development speed, e.g. the time required to integrate code changes into the trunk branch. Additionally, verification time depends on the number of test failures. Most test failures require human effort to inspect and to fix the underlying issue. Note that test failures may be due to code defects or due to test reliability issues and that running and analyzing these failures is a time consuming task, especially at system and integration level. System tests can run for minutes or hours as they often require entire systems to be set-up and tore-down. At the same time, developing large complex software systems usually implies large development teams developing code changes in parallel that need to be tested also in parallel.

Consequently, increasing the effectiveness and efficiency of test processes has an immediate effect on product development. Running less tests might help to improve test performance. However, reducing testing imposes the risk of elapsing defects to later development stages and unnecessary involving or affecting more developers.

III. MOTIVATION & METHODOLOGY

The goal of this work is to decrease development costs and to increase productivity without sacrificing product quality. As we discussed in Section II, achieving this goal requires a careful balance between conservative test strategies to minimize the number of defects elapsing into later development stages, and reducing test time to allow faster integration processes and higher productivity. Any test optimization strategies should not compromise the quality of the code shipped to customers. It may be acceptable to find defects later than possible, but it remains unacceptable to weaken overall product quality. Our optimization strategy ensures that all test scenarios are executed at least once for each code change before integrating the code change into the main product code base, e.g. the trunk branch. From the example shown in Fig. 1., it is acceptable to skip a test scenario on branch B2 if and only if the very same test scenario will be executed on branch B3 for the very same code change.

The basic assumption behind this work and most other test optimization and test selection approaches is that for given scenarios, not all tests are equally well suited. Some tests are

more effective than others are. However, deciding the effectiveness of tests and when to execute them is not trivial.

The approach presented in this paper uses historic test execution data and development process cost factors to perform test selection. Each test execution is considered an investment and the expected test result considered as return of investment. Using a cost model, our goal is to create a dynamic, self-adaptive test selection strategy, which readjusts its cost estimations based on test execution context. To provide an actionable solution that fits into the Microsoft development processes, we considered only solutions that cause no runtime overhead and that required no additional data collection. THEO only uses historic test data collected by standard testing frameworks and excludes code coverage data as collecting code coverage can increase the runtime overhead. Later, we will show that THEO ensures all tests are executed at least once for each code change. Therefore, it does not affect the overall code coverage of the test process.

IV. HISTORIC TEST PERFORMANCE DATA FEEDS

The process collects the results of prior test executions; this data is already collected by most test execution frameworks. The individual data sources we use to select test cases are depict in TABLE I. . The main data collection categories are:

A. General Test Execution Information

The name of the executed test (*TestName*) and the unique identifier of the test execution instance (*TestExecID*) are collected. This data allows us to bind and group test execution results to the according test case.

B. Test Runtime

We use the time taken for the test to run, i.e. the test execution time (*TestExecDuration*) for each test execution as recorded by the test framework.

C. Test Results

Further, we collect the results of all tests being run within the development process. A test failure is where the expected result of a test could not be produced (i.e., assertion failed), or the whole test execution terminated with an error. Usually, we assume that a failing test indicates a code defect, caused by introducing a defect (e.g. through side effects) when merging multiple parallel-developed code changes. However, it might also be that the test case reporting the test failure is not reliable. We call test failures due to test reliability issues *false alarms*.

Categorizing the test result as *passing* or *failing* is implicitly given by the testing framework. However, it is also important to further distinguish test failures into *code defects* and *false alarms*. To do so, we need additional information. Using links between test failures and bug reports, we can distinguish test failures due to *code defects* from *false alarms* [5]. If the failure led to a bug report that was later fixed by applying a code change we mark it as a *code defect*. Otherwise, the failed test execution is marked as a *false alarm*. To identify their cause, test failures always need to be manually inspected to either fix the problem or identify the test failure as *false alarm*. Due to resource restrictions, not all test failures can be investigated. Therefore,

TABLE I. TEST EXECUTION DATA USED FOR TEST SELECTION.

Data point	Description
General test execution information	
TestName	Unique name of test case executed.
TestExecID	Unique identifier of test case execution.
Test runtime information	
TestExecDuration	Number of seconds the recorded test case execution lasted.
Test result information	
TestExecResult	The result of the test execution. Possible value: <i>passed</i> , <i>code defect</i> , <i>false alarm</i> , <i>undecided</i> . Requires interpretation as described in Section IV.C
Execution context information	
BuildType	The build type of the binaries on which the test was executed. Possible value: <i>debug</i> , <i>release</i> .
Architecture	Architecture information of the binaries under test. Possible values: <i>x86</i> , <i>x64</i> , <i>arm</i> .
Language	Language information of the binaries under test, e.g. <i>en-us</i> . Especially media and GUI tests depend on it.
Branch	Unique identifier of the source code branch on which the test execution was performed.

test failures that were not manually investigated are marked as *undecided* and ignored, as their cause is indeterminable.

D. Execution Context

Modern software systems tend to be multi-platform applications running on different processor architectures, e.g. *x64* and *arm*, different machines, and different configurations. We define an execution context as a set of properties used to distinguish between different test environments. In this paper, we use the execution context properties *BuildType*, *Architecture*, *Language*, *Branch* (see TABLE I. for detailed description). However, the concept of execution contexts is variable. Adding or removing properties will influence the number of different execution contexts but requires no modification of the general approach. This is a crucial point as a test may show different execution behaviors for different execution contexts. For example, a test might find more issues on code of one branch than another depending on the type of changes performed on that branch. For example, tests cases testing core functionality might find more defects on a branch containing kernel changes than on a branch managing media changes. Thus, our approach will not only differentiate between test cases, but also bind historic defect detection capabilities of a test to its execution context.

V. TEST FAILURE PROBABILITIES

Given a planned test execution and given the corresponding execution context, we can use past test executions of the same test in the same execution context and derive the number of reported defects and the number of false test alarm that the test reported. From these past observations, we can derive two failure probabilities: P_{TP} as the probability that the combination of test and execution context will detect a defect (true positive) and P_{FP} as the probability that the combination of test and execution context will report a *false alarm* (false positive). These probabilities are defined as:

$$P_{TP}(t, c) = \frac{\#detected\ defects(t, c)}{\#executions(t, c)}$$

$$P_{FP}(t, c) = \frac{\#false\ alarms(t, c)}{\#executions(t, c)}$$

where the tuple (t, c) is a combination of test t and execution context c , where $\#detected\ defects(t, c)$ represents the number of defects reported by t when executed in c , $\#executions(t, c)$ represents the number of times t has been executed in c , and where $\#false\ alarms(t, c)$ represents the number of false test alarms caused by t when executed in c . For example, consider a test t executed 100 times in an execution context c , e.g. on build type *release*, architecture *x64*, branch b , and language *en-us*, which reported 4 false alarms and 7 defects, then $P_{FP}(t, c) = 0.04$ and $P_{TP}(t, c) = 0.07$. Both probability measurements consider the entire history from the beginning of monitoring until the moment the test is about to be executed. Consequently, probability measures get more stable and more reliable the more historic information we gathered for the corresponding test.

Note that test failure probabilities enclose code coverage like information. For tests not covering a changed code area and for test covering the code area but not checking any execution results, the defect detection probability P_{TP} will be zero.

VI. COST MODELLING THEORY

The decision of when to execute or skip a test case in a given execution context is solely based on cost. The idea is to estimate the cost of executing or not executing a test in a given execution context beforehand and to choose the less expensive option.

A cost model was developed to deliver the cost factors for the test selection strategy, using the data feeds and test failure probabilities discussed in Section IV. It is sensitive to the history of a test case as it considers past test executions in the same context to assess the expected cost values. For each scheduled test execution, the cost model considers two different scenarios: executing the scheduled test and not executing it. For both scenarios and the given execution context, we estimate the corresponding expected costs and decide for the scenario which is expected to be less expensive. Thus, if the estimated cost of not executing the test ($Cost_{skip}$) is lower than the cost executing it ($Cost_{exec}$), THEO will skip the test execution—not selecting the test to be executed.

For both execution scenarios, the contributing cost factors must be considered. Executing a test raises both the computational cost (Section VI.A) and the cost of inspecting the test result (Section VI.B), if necessary. Executing tests that fail without detecting a real code defect will trigger unnecessary failure inspections performed by engineers. On the other hand, not executing a test might lead to undetected defects that will escape to later development stages and therefore impact more engineers than necessary (Section IV.C)

In this paper, cost factors, which are described with positive values, express the expected cost to be paid. We could also have described cost saving values with negative amounts and cost increasing values with positive amounts, but we explicitly wanted to avoid any up-front judgment on these figures.

A. Base Cost of Test Executions

A major cost factor is the time-shared cost of infrastructure necessary to execute a test on all required execution contexts.

The constant $Cost_{machine}$ is a constant representing the per minute infrastructure cost. Multiplied with the execution time per test, we get the total infrastructure cost of running a test. For the Microsoft development environment we computed $Cost_{machine}$ to have a value of 0.03 \$/min. The cost factor corresponds roughly to the cost of a memory intense Azure Windows virtual machine² and includes power and hardware consumption, as well as maintenance.

For example, consider we executed a test 100 times in a given execution context and that each execution took 10 minutes. The total machine cost required to run the test in that context accumulates to $100 * 10 * 0.03 \text{ \$/min} = \30 .

B. Cost of Test Inspections

All test failures require human inspection effort, but inspecting failing tests due to anything other than code defects is unnecessary and should be avoided. The cost of a test inspection equals the amount of time required to conduct the inspection times the salary of the engineer conducting the inspection. The cost constant $Cost_{inspect}$ represents the average cost rate of test failure inspections at Microsoft. It considers the size of the test inspection teams, the number of inspections performed and the average salary of engineers on the team. The average cost per test inspection is \$9.60. Although this cost may vary from case to case, for simplicity reasons, we use the average cost of a test inspection in our model. Note that this cost reflects only the time spent by inspecting engineers. Additional cost factors such as waiting time or the need to run extra tests is not included.

C. Cost of Escaped Defects

Code defects escaping a test run can be expensive. The longer a defect remains hidden the more people can potentially be affected and the more expensive the escaped defect become. Defects closer to release dates tend to be more expensive [6] and increased time from defect introduction to its detection increases cost due to aggravated root cause analysis (more changes have been applied since then). Understanding and fixing an older change is more difficult. Additionally, the greater the number of engineers affected by a defect, the more expensive disruptions will be while fixing the defect. Defects usually imply some sort of development freeze, e.g. no check-ins until issue resolved.

The constant $Cost_{escaped}$ represents the average cost of an escaped defect. This cost depends on the number of people that will be affected by the escaped defect and the time duration the defect remains undetected. We used a value of \$4.20 per developer and hour of delay for $Cost_{escaped}$. This value represents the average cost of a bug elapsing within Microsoft. Depending on the time the defect remains undetected and the number of additional engineers affected, elapsing a defect from a development branch into the main trunk branch in Windows can cost tens of thousands of dollars.

We do not model defect severity explicitly. There are two main reasons for this. First, the severity of a defect cannot be determined prior to its occurrence—we would need to predict defect severity, which will not be reliable or actionable. Second,

² Price for Azure A7 high memory VM as of Feb. 2014: \$1.6 per hour

all defects breaking a system and integration test and causing development activity to freeze on the corresponding branch must be considered severe. Vice versa, system constraints and properties whose violations are not considered severe will not be tested during system and integration testing. Such defects are caught by pre-check-in verification processes or dog-food and manual testing procedures. For example, breaking look and feel properties may not cause a development freeze. The impact of the defect on the overall system is too low to cause a severe disruption of the overall development process.

D. Final Cost Function

Finally, we combine the individual cost components into two cost functions: the expected cost of executing a test ($Cost_{exec}$) and the expected cost for not executing a test ($Cost_{skip}$).

$Cost_{exec}$ represents the expected cost if we decide to execute the test which depends on the machine cost ($Cost_{machine}$), the probability that the executed test will fail due to any other reason as a defect (P_{FP}), and the cost of conducting an unnecessary test failure inspecting ($Cost_{inspect}$):

$$Cost_{exec} = Cost_{machine} + (P_{FP} * Cost_{inspect})$$

$Cost_{skip}$ represents the expected cost of not executing the test which depends on the cost of escaped defects ($Cost_{escaped}$) and the number of additionally affected engineers ($\#Engineers$) and the time the defect remains undetected ($Time_{delay}$):

$$Cost_{skip} = P_{TP} * Cost_{escaped} * Time_{delay} * \#Engineers$$

The number of engineers ($\#Engineers$) is a static property of the engineering system and can be determined by counting the number of engineers whose code changes passed the current code branch. The $Time_{delay}$ is the average time span required to fix historic defects on the corresponding code branch. Both properties are easy to measure and reliable (we verified these values with the corresponding product teams).

For tests that found no defects in the given execution context, P_{TP} and $Cost_{skip}$ is zero and the test is skipped. The same test for a different execution context (e.g. different branch) is likely to have a different P_{TP} value and thus might remain enabled. Note, that we skip tests only if we know that the code change will be tested by the same execution context later again, e.g. on a lower branch level as shown in Fig. 1.

VII. IMPROVEMENT STRATEGY SIMULATION

Applying THEO to a live development environment without a period of thorough evaluation is too risky as it can directly impact product quality. The result presented are based on simulations of THEO on past development periods. This section discusses the process of simulating the execution of the tests and also simulating the impact of any failures that would propagate as tests are removed. Simulating the test selection process also allows us to compare our results with actual test and code quality behavior.

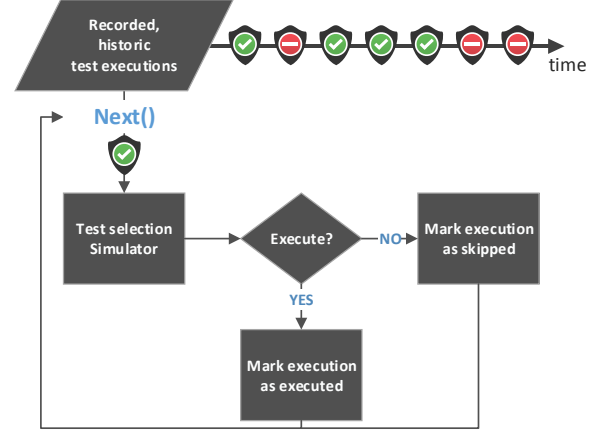


Fig. 2. Flow chart illustrating the test execution simulation process. For each test execution and execution context, ordered by time, we decide which tests should be executed.

A. Simulating Test Case Executions

To simulate the behavior and impact of our test selection strategy, we replayed test executions as they occurred in past development periods. Tests executions and their test results (failed or passed) are recorded in databases by the test execution frameworks at Microsoft. Using these databases, we know the test suite and test case executions, the execution contexts these tests were executed, and the order in which these tests run. This information is sufficient for the simulation. Our simulation process follows the following basic steps, described in Fig. 2.

Step 1: Using the databases containing the test executions and their corresponding test execution results (failed or passed), we order these historic test executions by their execution timestamp. Thus, our test optimization strategy is fed with test executions in the order they were applied.

Step 2: Each historic test execution and the corresponding test execution context definition is fed into a simulation process running an implementation of our test selection strategy. The test selection process then returns a binary decision indicating whether the test case received as input is selected to be executed by the test selection strategy.

Step 3: Depending on the binary result, the originally executed test is marked as *skipped* or *executed* in a separate simulation table. Skipped test executions represent those test executions that would not be executed when using our test selection strategy.

Our simulation process does not execute test cases. It only makes decisions on whether a test case would have been executed, depending on the cost balance tightly influence by its defect finding capabilities. The result of this test case simulation is a simple list of test case executions that would have been prevented when using our test selection strategy. This list can be used to compare against the original set of executed tests.

B. Simulating Defect Detection

Removing test executions may impact code quality. Defects detected by test executions that have been removed by THEO

would remain undetected, at least for some time. Disabling test executions is likely to have impact on code changes and developer behavior, which cannot be simulated. Thus, we have to estimate how undetected defects would propagate through the development process and when they would be detected.

The heuristic estimating when and where escaped defects would have been recaptured requires more data about the actual project specific development process. This data is needed to gain further insight in how code changes, and thus defects, propagate through the development process. For this part of our simulator, we collect the following, project specific datasets and make some basic assumptions about code defects and test behavior.

Integration paths of code changes and defects

Assuming a base code branch, usually called *trunk*, the *integration path* of a code change is a sequence of branches and timestamps the corresponding code change was applied to before the code change was merged into trunk. For projects using a single development branch, e.g. Microsoft Office, the integration path of a code change is a single entry identifying the name of the single branch and the commit timestamp. For projects using multiple code branches, e.g. Microsoft Windows, the integration path usually contains multiple entries. For example, consider the example shown in Fig. 1. The integration path of change *C* lists the branches *B1*, *B2*, *B3*, and *trunk* including the timestamps of the corresponding merge operation that applied *C* to the code base in each branch.

For each change originally applied to the version control system, we compute their corresponding integration paths tracing code changes through the version control system [3]. For more details on that procedure, we refer to Murphy et al. [3].

Basic defect and test behavior assumptions

We make the following two assumptions with respect to code issues and test cases detecting these code issues:

1. A combination of test case and execution context³, that detected and reported a defect at time t_i will also detect and report the same defect at any time t_k if and only if $t_k \geq t_i$ and if t_k is executed on an integration path of the defect. This assumption disregards that (even though unlikely) the code defect might have been suppressed but not fixed by other code changes applied to the code base.
2. The code issue can be replicated by re-running the test in the corresponding execution context.

We discussed these assumptions with various Microsoft product teams who verified and confirmed their validity. Product teams also confirmed that in few cases, code defects escape their original branches and are re-captured on higher-level branches or later on the same branch.

C. Assigning defects to simulated test executions

The integration path of code changes is assumed to correspond to the propagation path of undetected defects, and

can be used to estimate which test execution would have re-captured an escaped defect. In the example shown in Fig. 1. a defect in change *C* is caught by test *T2* and the code does not progress past branch *B2*. A bug fix is created and verified by tests *T4*, *T5* and *T6*. If THEO skips test *T2* the defect is assumed to be immediately merged into branch *B3*. THEO assumes the defect is caught by test *T6* as it runs the same tests as *T2*. In this scenario the bug fix would be applied in branch *B1* after running test *T6* and THEO would assume that the cost of fixing the defect is now higher than its original cost.

While the original association between defect and test execution is stored in the test execution framework database, our simulator returns a modified version of the original associations reflecting simulation results. For each test that is executed during simulation, we assign all original code issues detected during test execution. Additionally, we assign all escaped defects to the test execution that would have been caught given the heuristics above. As a result, the number of defects associated with a test execution equals the number of defects during the actual execution of the test, plus an additional set of escaped defects.

D. Executing all Test Cases At Least Once

The goal of this work is to optimize testing processes without sacrificing product quality. This implies that we ensure that all escaped defects are eventually caught, before releasing the product to customers. To satisfy this condition, we ensure all originally executed combinations of tests and execution contexts for all code changes applied to the code base are executed at least once. To ensure this happens we use two separate criteria, depending on the development process:

Option 1: For single branch development processes, e.g. Microsoft Office, we enforce each test to execute at least every third day⁴. Since all code changes are applied to the same branch, re-execution of each test for each execution context periodically ensures that each code change has to go through the same verification procedures as performed originally.

Option 2: For multi-branch development processes, e.g. Microsoft Windows, we enforce to execute a combination of test and execution context on the branch closest to trunk on which the test had been executed originally.

Thus, THEO can only skip test executions if the criteria described above allow a test to be skipped. Otherwise, THEO's decision to skip a test in a given execution context will be ignored by the simulator and the test will be executed.

E. Training Phase

As the underlying cost model depends on risk factors extracted from historic data, these risk factors will be unknown and unreliable in the early stages of the simulation process, in which no historic data is known. To compensate, each test and execution context combination has to go through a training

³ For defect propagation purposes, we ignore all branch specific execution context information as long as the change containing the defect was integrated into the branch.

⁴ This value is the result of a complex analysis we conducted with the Office product team and reflects the optimal solution for the system. Due to confidential reasons, we cannot share the details of this process.

phase of 50 executions before the simulator will allow THEO to disable the corresponding test in the given execution context.

VIII. SIMULATION EVALUATION

A. Test Execution Reduction

The first evaluation identifies the number of test executions that were skipped during the simulation of the test selection strategy. To retrieve this number, we count the number of originally recorded test executions and subtract the number of test executions that our test strategy would have executed during simulation. We report the *relative test reduction rate* as the number of skipped test execution divided by the total number of originally executed test execution during development. Considering the execution time of individual test executions, see Section IV.B, we can translate the relative test reduction rate into *relative test execution time improvements*—the total execution time of all skipped test executions divided by the total test execution time of all tests executed originally. We further show reduction rates over time. The number of skipped test executions and their summed execution duration determines how much machine cost $Cost_{machine}$ has been saved.

B. Test Result Inspection

As discussed in Section VI.B, test failures require human effort for inspection in order to decide what action to take. Skipping test cases that would have caused unnecessary test inspections (*false alarms*) is an improvement. Relating these suppressed *false alarms* with the corresponding cost factor for test failure inspections ($Cost_{inspect}$), identifies the relative improvement with respect to test inspection time and the associated development cost improvements.

C. Escaped Defects

While the reduction in test executions (Section VIII.A) and the reduction in test inspections (Section VIII.B) relate to productivity and cost improvements, the number of defects that escaped due to skipped test executions reflects the negative aspects of THEO and relates to development cost increases. We report the number of *escaped defects* relative to the number of all code defects reported by test executions. The simulator is pessimistic assuming defects can only be found by the same test cases that are ignored (comparing *TestName* and *TestExecID*), in reality they may be caught earlier by other test cases.

D. Cost Improvement

Skipping tests may save development time. At the same time it imposes risk of escaped defects temporarily compromising code quality, and thus to increase development cost—finding defects later in the development tends to be more expensive [6]. To validate if the estimated development cost improvements predominate the estimated development cost increases, we report the *total cost balance* as the balance of cost reductions. We add the cost reductions due to reduced test time and due to less test failure inspections and subtract the extra cost of escaped bugs. A positive balance reflects cases in which the improvements predominate. Negative balances refer to cases in which our optimization strategy THEO does not payoff and

TABLE II. EVALUATION SUBJECT DETAILS.

	Windows	Office	Dynamics
Simulated period	~11 months	~3 months	~12 months
#test executions	> 30 million	> 1.2 million	> 6.5 million
# branches	> 1	1	> 1

would have caused additional development costs rather than lowering them.

E. Evaluation Subject

We evaluated the effects of THEO on three major Microsoft products: Windows, Office, and Dynamics. Combined, our simulation results cover 26 months of product development, more than 37 million test executions. TABLE II. contains information about the duration of simulated development periods and the number of simulated test cases per project.

Results presented for Windows reflect the entire Windows 8.1 development period (~11 months). For Windows, we simulated more than 30 million test executions. Simulation results for Office cover development activities and test executions covering three months—a total of more than 1.2 million test executions. For Dynamics, we simulated a development period of 12 months with more than 6.5 million test executions. While Windows and Dynamics use multi-branch development setups, Office uses a single collaboration branch. Thus, for simulations for Windows and Dynamics, we enforce to execute a combination of test and execution context on the branch closest to trunk (Option 2 discussed in Section VII.D), while for Office we simulate using the time based test execution policy (Option 1 discussed in Section VII.D).

IX. SIMULATION RESULTS

In this section, we present and discuss the results of our simulation experiments as described in Section VII. We will restrict the discussion in this section to measurable improvements. Section X contains a discussion on secondary improvements that cannot be measured directly.

Similar to the cost model the overall cost improvement depends on the constant cost estimations as presented in Section VIII. The results are summarized in TABLE III.

A. Test Execution and Test Time Reduction

THEO would have skipped 40.6% of all Windows test executions across all branches. Considering the runtime of these tests and relating it to the total runtime of all executed tests, THEO would have saved 40.3% of the total test execution time. This is a significant improvement. In simulation, submitting a code change to a development branch in Windows could have been integrated into trunk in only 60% of the original integration time. Note that this measurement considers only test execution time, but does not consider other development or human factors. Thus, the test time improvement of 40% may not translate to a 40% increase in integration time, but it certainly lowers the lower bound of integration time. Multiplying the test time improvement with the cost factor for test execution ($Cost_{machine}$), we yield a cost improvement of over \$1.6 million. Note that the test time cost improvement figures

TABLE III. SIMULATION RESULTS FOR MICROSOFT WINDOWS, OFFICE, AND DYNAMICS.

Measurement	Windows		Office		Dynamics	
	Rel. improvement	Cost improvement	Rel. improvement	Cost improvement	Rel. improvement	Cost improvement
Test executions	40.58%	--	34.9%	--	50.36%	--
Test time	40.31%	\$1,567,607.76	40.1%	\$76,509.24	47.45%	\$19,979.03
Test result inspection	33.04%	\$61,532.80	21.1%	\$104,880.00	32.53%	\$2,337,926.40
Escaped defects	0.20%	\$11,970.56	8.7%	\$75,326.40	13.40%	\$310,159.42
Total cost balance		\$1,617,170.00		\$106,063.24		\$2,047,746.01

TABLE IV. DISTRIBUTION OF ESCAPED DEFECTS OVER NUMBER OF ESCAPED BRANCHES FOR WINDOWS AND DYNAMICS.

	Number of escaped branch levels		
	1	2	3
Windows	71%	21%	8%
Dynamics	97%	3%	0%

consider only the time of not executing the skipped tests. It does not include potential cost improvements due to skipping test setups, test teardowns, removing entire dedicated test machines from a branch, etc. Thus, the test time cost improvement must be seen as a lower bound of the actual cost improvement.

The average test execution reduction rate for Dynamics is above 50%. This means that THEO would have prevented more than half of the originally executed test executions and saved 47% of test execution time. In theory, code could have been moved nearly 50% faster into the trunk branch, a significant improvement. Although the test execution and test time reduction rate exceeds the values achieved for Windows, the test machine cost improvements that correlated with the reduced test time are two orders of magnitude lower than for Windows. This is due to the fact, that tests executed for Dynamics terminate much faster than Windows tests. Thus, the reduction rate is translating into less computational time and thus is less lucrative. The same is true for Office tests, which also execute much faster and therefore the savings on reduction of test execution time are lower than for Windows. The cost savings for Office are further less significant as we only simulate a three-month period and test executions on one branch. Nevertheless, THEO would have skipped a significant number of 34.9% of all performed test executions and saved 40.1% of the total test execution time

B. Test Result Inspection.

As discussed for the cost modelling theory (Section VI), THEO specifically targets unnecessary test inspections caused by test failures due to other reasons than code defects (false test alarms). Suppressing such test failures implies reduction of unnecessary test result inspections, which translates into cost savings. Row “Test result inspection” of TABLE III. contains the relative number of spared test inspections for all three products. For Windows and Dynamics, the reduction rate lies around 33%; one third of originally carried out test result inspections were unnecessary. For Office, THEO would suppress 21.1% of all false positives. Interestingly, the associated cost improvements for Windows (\$61k) and Office (\$104k) are again two orders of magnitudes lower when compared to Dynamics (\$2.3M). The reason for the difference is again the different absolute number of test failures suppressed.

C. Escaped Defects

While removed test executions and reduced test inspections determines a positive cost savings, the number of temporarily escaped defects increases development costs.

In our Windows simulation, 0.2% of all defects escaped at least one test execution. As shown in TABLE IV. 71% of these escaped defects escaped only one branch and were found in the corresponding next merge branch. 21% of escaped Windows defects escaped two branches and 8% escaped even 3 branches. Importantly, none of the defects escaped into the trunk branch. On Dynamics, THEO would have elapsed 13.4% of all defects, a much higher escape rate as for Windows. The vast majority (97%) of these escaped Dynamics defects were caught on the direct consecutive merge branch. The remaining 3% escaped two branch levels. For both Windows and Dynamics, the extra cost caused by escaped bugs is significant. However, in both cases, these new extra costs are orders of magnitudes lower than the highest cost savings achieved by removed test executions and inspections.

For Office, the results are a bit different. Whereby the percentage of bugs that escaped is 8.7%, which is comparable to Dynamics, the costs are \$75k higher in relation to the cost savings. This is due to an additional cost of manual testing work that we added as a penalty for Office in case the bugs was not found within 10 days. The rationale behind this lies in the way the Office test and development is performed. Nevertheless, approximately 40% of bugs escaped would have been found already in the next scheduled build and test.

D. Cost Improvement.

Looking at the overall cost balance, we see cost savings for all three evaluation subjects. For Windows, we estimate a total cost saving of \$1.6M, for Dynamics, a total cost saving of approximate \$2.0M and for Office a cost saving of approximate \$100k. These values may seem small considering the total development budgets of projects of their scale. However, this only identifies test savings. Considering the actual test execution reduction rates of 35% to 50% puts these numbers into perspective. The actual values are secondary, it is important that the achieved productivity increase though faster integrations.

E. Variable Performance over Time

Fig. 3. shows the relative test execution reduction over time (measured in development days) for Windows. The dark area corresponds to originally executed tests that were removed during simulation. As shown, THEO requires an initial training

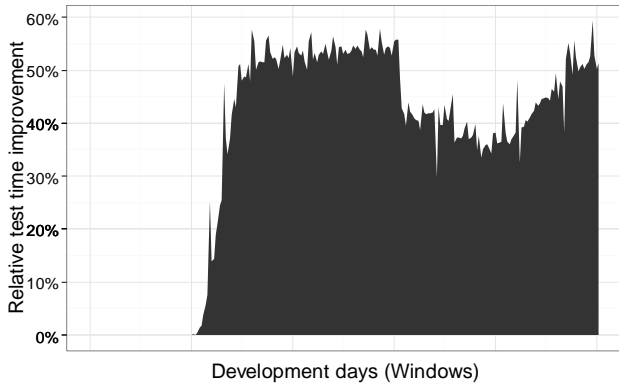


Fig. 3. Relative test execution reduction rate for Windows over time. The area shows the relative number of tests skipped by THEO.

phase (see Section VII) in which we observe the current testing process to estimate risk factors before applying any test selection. Once THEO starts skipping test executions, the ratio of removed executions converges to an almost stable state. The plot shows fluctuations in the relative number of reduced test executions, e.g. a sharp drop from nearly 55% to 40% midway through the plotted timespan. The reason for these fluctuations in test execution reduction rates are natural fluctuations in code quality. The quality of submitted code changes is not constant; a drop in overall code quality causes more test failures and directly influences risk factors. Changes in risk factors can cause previously skipped tests to be re-enabled. Reduction rates for Office and Dynamics look similar. Due to space reason, we abstain from showing these plots.

X. SECONDARY IMPROVEMENTS

The measurable improvements discussed in Section IX are likely to have further, secondary consequences. Although, these improvements are not directly measurable, they are an important part of the improvement of the development processes.

A. Code Velocity

Reducing the number of executions and consequently the overall required test time may have positive effects on code velocity. Executing fewer tests implies that code changes have to spend less time in verification and changes can be integrated faster, freeing up engineering time that may have been spent evaluating false positives. However, the immediate impact on code velocity is hard to measure. Code velocity is determined by many different aspects, including human behavior, which is not possible to simulate. Thus, it is hard to predict how THEO would affect actual development speed. It might well be that the bottleneck of current development processes is not only testing. Nevertheless, the number of executed tests represents a lower bound to code velocity, as the consecutive time necessary to pass all required tests is the minimal time required to integrate code changes. By lowering the number of executed tests, THEO lowers the lower bound for code velocity.

B. Developer Satisfaction

A very important but also hard to measure factor of every development process is developer satisfaction. Reducing the

time for testing and the number of required test inspections is likely to increase developer satisfaction. It should help to increase the confidence in test results and decisions based on testing. Increasing the speed of the development process will itself also impact the developer experience. The ability to merge, integrate, and share code changes faster can reduce the number of merge conflicts and is likely to support collaboration.

XI. THREATS TO VALIDITY

Like most empirical studies, the presented study has threats to validity. We identified three main groups of threats.

A. Generalizability

We investigated test executions specific to three Microsoft products and their development processes. Even though some terminology might be unique to Microsoft, the execution of tests during software development and the impact of test execution time on development speed are generalizable.

The estimated costs presented in this paper are specific to Microsoft. The cost model considers several independent but development process specific aspects and cost factors are likely to vary across releases and projects (e.g. cost factors for machines and engineers). Replicating this study for different projects or releases requires detailed reviews and adjustments.

B. Construct Validity

The approach to estimate the impact of escaped defects and to identify those test cases that would eventually re-capture these defects is a heuristic and associated cost values must be considered approximations. However, our data was derived through investigations, discussions and fine-tuning with the corresponding product teams. We consider the approximations of these heuristics as fair and realistic. Cost factors used in this study are based on average Microsoft development figures and numbers (e.g. average salary and work hours per year). These numbers vary and might not consider all possible aspects.

Execution context information might be particularly important for system and integration tests while other tests, e.g. unit tests, might be more independent from them. However, the presented concept is generic. Reducing the number of execution contexts to one or further increasing the number of execution contexts does not threaten the validity of the overall approach.

C. Internal Threats to Validity

The simulator may contain defects. To conquer this threat, we implemented multiple test cases and performed manual inspections. Through validating with product teams, we are confident that the data collected and analyzed reflects the development processes accurately.

XII. RELATED WORK

In this section, we give an overview of related studies.

A. Test Selection, Prioritization, and Reduction

“Measuring the absolute effectiveness of testing is generally not possible, but comparison between effectiveness of tests is” [7]. Based on this concept, Basili and Selby [8] presented one of the first studies comparing the effectiveness and cost of testing

strategies showing that changing or choosing different test strategies might impact test effectiveness.

Many of the following research studies focused on the area of test case selection, prioritization, and reduction. In 2007, Yoo and Harman [9] presented a comprehensive survey of research studies showing that many techniques assume access either to code, execution traces or some sort of model to derive selection criteria (i.e., based on code coverage) [9, 10, 11]. In contrast, the strategy discussed in this paper, does not make any such assumption. We treat tests entirely as black boxes. Lately, Anderson et al. [12] used software repositories to measure historic test performances. This study was carried out in parallel to this work and does not provide any dynamic test selection solution, but rather assess the effectiveness of tests.

Schroeder and Korel [13] used input-output analysis to construct test input to reduce the number of required black box test executions without lowering test effectiveness. Contrary to their study, THEO measures test effectiveness based on a cost model and uses the context and frequency of executions to drive efficiency improvement. Altering inputs for tests would not be actionable at Microsoft. Goradia [14] used the fault exposing potential of a test as the selection criteria, whereby he relies on mutation analysis, i.e., modification of the original program to determine the probabilities of a test to reveal a fault. More generally, a number of empirical case studies and extensive literature reviews compared and identify test tools most likely to yield optimal test effectiveness [14, 15, 16, 17, 10, 18].

With respect to test executions costs, Vallespir and Herbert [19] used machine and inspection costs for individual unit tests to conclude that the number found defects is low compared to the relatively high cost of unit tests. However, the cost calculation presented in [19] are based on three samples and are rather vague and seem not applicable for development processes nor for system and integration tests at Microsoft.

B. Cost Aware Improvement Strategies

Using cost-aware test improvement strategies is not unique. Yoo and Harman [20] and Alspaugh et al. [21] used time-aware techniques selecting a subset of test cases that can be executed in a given time budget. Do et al. [22] assessed the effect of time constraints on the cost and benefits of prioritization techniques. Additionally, empirical studies exist that consider the impact of testing strategies on the cost-effectiveness in the wider context of the overall software lifecycle [10, 23]. Lately, Li and Boehm [24] proposed a value-based test prioritization strategy ranking tests by their risk exposure coverage and the relative cost of tests. Gustafson [25] applied cost factors to software flow graphs to define areas that require additional testing. The difference between these studies and THEO is that THEO is solely based on a dynamic, empirically derived cost model, which directly impacts the strategy decisions. Our model uses not only the cost and risk of executing or skipping a test but relates both values to each other. Empirical evaluations and application of testing techniques at industrial settings [26, 27, 28] remain limited [9].

All those studies focus on regression test suites. To the best of our knowledge, this study is the first that evaluates system and integration test effectiveness based on execution contexts such as branching structures and architectures.

C. Merge Conflicts and Awareness

Even though version control systems allow parallel development activities and avoid conflicts, several studies showed that merge conflicts occur frequently, whereby most of the studies focused on facilitating collaboration effectiveness. One of the first studies that showed how frequent merge conflicts occur has been performed by Zimmermann [29]. He showed that between 22% and 46% of integrations could not be automatically resolved and resulted in conflicts. In a recent study, Brun et al. [30] showed that merge conflicts are frequent and persistent. In summary, they showed that 33% of merges that were reported to contain no textual conflicts by the version control system, in fact contained higher-order conflicts, which manifested themselves as a build or a test failure. Also Perry et al. showed significant correlations between the degree of parallel work and the number of quality problems [31]. The effect of merge conflicts on quality has also been studied by Bird and Zimmermann [2]. Those studies aimed at quantifying the degree of merge conflicts, or at establishing collaborative awareness for merge conflicts, we focus on quantifying and improving the effectiveness and efficiency of tests.

XIII. CONCLUSION

We presented a novel cost based test selection strategy, THEO, which skips test executions where the expected cost of running the test exceeds the expected cost of not running it. Our strategy is dynamic and self-adaptive and only uses historical test data, which is already collected by most test frameworks. THEO was verified through simulating its impact on the Microsoft Windows, Office, and Dynamics developments. THEO would have reduced the number of test executions by up to 50% cutting down test time by up to 47%. At the same time, product quality was not sacrificed as the process ensures that all tests are ran at least once on all code changes. Removing tests would result in between 0.2% and 13% of defects being caught later in the development process, thus increasing the cost of fixing those defects. Nevertheless simulation shows that THEO produced an overall cost reduction of up to \$2 million per development year, per product. Through reducing the overall test time, THEO would also have other impacts on the product development process, such as increasing code velocity and productivity. These improvements are hard to quantify but are likely to increase the cost savings estimated in this paper.

The technique and results described in this paper have convinced an increasing number of product teams, within Microsoft, to provide dedicate resources to explore ways to integrate THEO into their actual live production test environments.

ACKNOWLEDGMENT

We thank the Windows, Office, and Dynamics development teams for their help and feedback. This work is based on data extracted from various development repositories by the CodeMine process managed by Microsoft's Tools for Software Engineers group. Our special thanks go to Jason Means, Blerim Kuliqi, Alex Gorischek, Alain Zariffa, Wayne Roseberry, Adrian Marius Marin, Craig Campbell, and Alan Back.

REFERENCES

- [1] M. Vakilian, R. Sauciu, J. D. Morgenthaler and V. Mirrokni, "Automated Decomposition of Build Targets," 2014.
- [2] C. Bird and T. Zimmermann, "Assessing the Value of Branches with What-if Analysis," in *Proceedings of the ACM SIGSOFT 20th International Symposium on the Foundations of Software Engineering*, Cary, North Carolina, 2012.
- [3] B. Murphy, J. Czerwona and L. Williams, "Branching Taxonomy," Microsoft Research, Cambridge, 2014.
- [4] D. Sprott, "Enterprise Resource Planning: Componentizing the Enterprise Application Packages," *Commun. ACM*, vol. 43, pp. 63–69, apr 2000.
- [5] K. Herzig and N. Nagappan, "The Impact of Test Ownership and Team Structure on the Reliability and Effectiveness of Quality Test Runs," in *Accepted for 8th International Symposium on Empirical Software Engineering and Measurement (ESEM)*, Torino, 2014.
- [6] F. Shull, V. Basili, B. Boehm, A. Brown, P. Costa, M. Lindvall, D. Port, I. Rus, R. Tesoriero and M. Zelkowitz, "What we have learned about fighting defects," in *Software Metrics, 2002. Proceedings. Eighth IEEE Symposium on*, 2002.
- [7] E. Weyuker, "Can we measure software testing effectiveness?," in *Software Metrics Symposium, 1993. Proceedings., First International*, 1993.
- [8] V. R. Basili and R. W. Selby, "Comparing the Effectiveness of Software Testing Strategies," *IEEE Trans. Softw. Eng.*, vol. 13, no. 12, pp. 1278–1296, December 1987.
- [9] S. Yoo and M. Harman, "Regression testing minimization, selection and prioritization: a survey," *Softw. Test. Verif. Reliab.*, vol. 22, no. 2, pp. 67–120, March 2012.
- [10] S. Elbaum, A. G. Malishevsky and G. Rothermel, "Test Case Prioritization: A Family of Empirical Studies," *IEEE Trans. Softw. Eng.*, vol. 28, no. 2, pp. 159–182, February 2002.
- [11] J. A. Jones and M. J. Harrold, "Test-Suite Reduction and Prioritization for Modified Condition/Decision Coverage," in *Proceedings of the IEEE International Conference on Software Maintenance (ICSM'01)*, 2001.
- [12] J. Anderson, S. Salem and H. Do, "Improving the Effectiveness of Test Suite Through Mining Historical Data," in *Proceedings of the 11th Working Conference on Mining Software Repositories*, 2014.
- [13] P. J. Schroeder and B. Korel, "Black-box test reduction using input-output analysis," in *Proceedings of the 2000 ACM SIGSOFT international symposium on Software testing and analysis*, Portland, Oregon, USA, 2000.
- [14] T. Goradia, "Dynamic impact analysis: a cost-effective technique to enforce error-propagation," in *Proceedings of the 1993 ACM SIGSOFT international symposium on Software testing and analysis*, Cambridge, Massachusetts, USA, 1993.
- [15] Y. Zhang, X. Zhao, X. Zhang and T. Zhang, "Test effectiveness index: Integrating product metrics with process metrics," in *Cyber Technology in Automation, Control, and Intelligent Systems (CYBER)*, 2012 IEEE International Conference on, 2012.
- [16] G. Whyte and D. L. Mulder, "Mitigating the Impact of Software Test Constraints on Software Testing Effectiveness," *Electronic Journal of Information Systems Evaluation*, vol. 14, pp. 254 – 270, 2011.
- [17] G. Rothermel, R. Untch, C. Chu and M. Harrold, "Test case prioritization: an empirical study," in *Software Maintenance, 1999. (ICSM '99) Proceedings. IEEE International Conference on*, 1999.
- [18] P. Braione, G. Denaro, A. Mattavelli, M. Vivanti and A. Muhammad, "An industrial case study of the effectiveness of test generators," in *Automation of Software Test, 2012 7th International Workshop on*, 2012.
- [19] D. Vallespir and J. Herbert, "Effectiveness and Cost of Verification Techniques: Preliminary Conclusions on Five Techniques," in *Computer Science (ENC), 2009 Mexican International Conference on*, 2009.
- [20] S. Yoo and M. Harman, "Pareto efficient multi-objective test case selection," in *Proceedings of the 2007 international symposium on Software testing and analysis*, London, United Kingdom, 2007.
- [21] S. Alspaugh, K. R. Walcott, M. Belanich, G. M. Kapfhammer and M. L. Soffa, "Efficient time-aware prioritization with knapsack solvers," in *Proceedings of the 1st ACM international workshop on Empirical assessment of software engineering languages and technologies: held in conjunction with the 22nd IEEE/ACM International Conference on Automated Software Engineering (ASE) 2007*, Atlanta, Georgia, 2007.
- [22] H. Do, S. Mirarab, L. Tahvildari and G. Rothermel, "An empirical study of the effect of time constraints on the cost-benefits of regression testing," in *Proceedings of the 16th ACM SIGSOFT International Symposium on Foundations of software engineering*, Atlanta, Georgia, 2008.
- [23] G. Rothermel, S. Elbaum, A. G. Malishevsky, P. Kallakuri and X. Qiu, "On test suite composition and cost-effective regression testing," *ACM Trans. Softw. Eng. Methodol.*, vol. 13, no. 3, pp. 277–331, july 2004.
- [24] Q. Li and B. Boehm, "Improving scenario testing process by adding value-based prioritization: an industrial case study," in *Proceedings of the 2013 International Conference on Software and System Process*, San Francisco, CA, USA, 2013.
- [25] D. A. Gustafson, "Guidance for Test Selection Based on the Cost of Errors," in *Proceedings of the July 9-12, 1984, National Computer Conference and Exposition*, 1984.
- [26] M. Sherriff, M. Lake and L. Williams, "Prioritization of Regression Tests using Singular Value Decomposition with Empirical Change Records," in *Proceedings of the The 18th IEEE International Symposium on Software Reliability*, 2007.
- [27] M. Skoglund and P. Runeson, "A case study of the class firewall regression test selection technique on a large scale distributed software system," in *Empirical Software Engineering, 2005. 2005 International Symposium on*, 2005.
- [28] N. b. Ali, K. Petersen and M. Mäntylä, "Testing highly complex system of systems: an industrial case study," in *Proceedings of the ACM-IEEE international symposium on Empirical software engineering and measurement*, Lund, Sweden, 2012.
- [29] T. Zimmermann, "Mining Workspace Updates in CVS," in *Proceedings of the Fourth International Workshop on Mining Software Repositories*, Minneapolis, MN, USA, 2007.
- [30] Y. Brun, R. Holmes, M. D. Ernst and D. Notkin, "Proactive detection of collaboration conflicts," in *Proceedings of the 19th ACM SIGSOFT symposium and the 13th European conference on Foundations of software engineering*, Szeged, Hungary, 2011.
- [31] D. E. Perry, H. P. Siy and L. G. Votta, "Parallel changes in large-scale software development: an observational case study," *ACM Trans. Softw. Eng. Methodol.*, vol. 10, no. 3, pp. 308–337, July 2001.