Simulation-Based Management for Software Dynamic Testing Processes

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***Abstract* - Managing software development projects requires the coordination of different processes which may be performed by different teams, e.g., a development team and a separate testing team. This coordination aims at optimizing the trade-off between cost, schedule and delivered quality. Simulation models are a powerful tool to explore what-if scenarios that help managers to achieve this trade-off and to fine-tune different project parameters. This paper presents a simulation model based on a multi-paradigm approach which connects development and testing processes. The testing process model is based on the process model described in the ongoing standard ISO/IEC DIS 29119-2. The simulation model is built using two different methods: the discrete-event approach, to simulate the execution of the dynamic testing processes, and the agent-based approach, to in-depth simulate defects life cycle. Results show how the simulation model is used to optimize the efficiency of the testing process.**

Keywords - software testing process; multiparadigm simulation; management

I. INTRODUCTION

Software testing is concerned with planning, preparation and evaluation of software products and related work products to: a) determine that they satisfy specified requirements, b) demonstrate that they are fit for purpose and c) detect defects [17]. In general, testing can be viewed as a means of improving the quality of a given product and mitigating risks due to poor quality.

Testing can be carried on using different approaches (e.g., scripted or exploratory), at different levels (e.g., unit, system, integration or acceptance), using different techniques and tools and with different degrees of independency (ranging from testing performed by the producer to third party testing). When testing entails the execution of the system under test, it is often referred to as dynamic testing. Testing exists in an organizational context and is carried on a given project or service. Therefore, the testing activities are tightly interrelated with the development ones, and both shall be planned, monitored and controlled. Problems of quality of the system under test or delays in the development hamper the testing process. Conversely, an inadequate or delayed testing endangers the development process. If not managed properly, both development and testing processes may jeopardize the goals of cost, schedule and quality of a project.

Both development and testing can be described as processes and take advantage of the use of simulation models for helping project and/or test managers in daily tasks of planning, monitoring and control.

Informally, a simulation model can be considered as an abstract view of a complex system comprised of a set of rules that tell how to obtain the next state of the system from the current state. Those rules can be of many different forms: differential equations, state charts, process flowcharts, schedules, etc. The outputs of the model are produced and observed as the model is running.

There is much research on simulation models of the software development process [12]. However there is lesser research on simulation models for the testing process, usually at the unit level. Furthermore, when testing is considered as part of a simulation model of the development process, it is often over simplified. The goal of this paper is to devise a multi-paradigm simulation model for the testing process to gain insights in how the testing process influences the goals of a given project.

The main contribution of this work is a multi-paradigm simulation model of the dynamic testing processes which combines a discrete-event model and agent-based model. The model can be used to simulate the testing process at the system level and to help in decision-making in the test managing processes.

The structure of the paper is as follows: Section II shows the works related to our proposal; Section III introduces the multi-layer process model proposed by the International Standards group upon which our simulation model is based; Section IV describes the simulation model; Section V shows some simulation runs. Finally, our conclusions and further work are given in Section VI.

II. RELATED WORK

The search string “simulation” AND “software testing process” AND “management” and others alike used in

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several digital libraries and citation databases of peer-reviewed literature retrieves only a few number of papers. In many of the papers retrieved, the term "simulation" is frequently used to describe experiences in which simulation is used as a tool for the testing process. In other works, the term "simulation" makes reference to a set of formulas that are solved by analytical means.

As an example of the first usage, in their collection of works, Lazić, Mastorakis and Velasĕvić [7]-[11] aim at raising awareness about the usefulness and importance of computer-based simulation in support of software testing. In their works, simulation is used to ease the design and execution of the testing processes of real military and defense systems.

Some analytical models of the software testing process can also be found. Zhang, Zhou, and Luo [19] propose a reward-Markov-chain-based quantitative model for sequential iterative processes and show how to use it to estimate the time for the software testing process. Similarly to this, Lizhi, Weiqin and Bin Zhu [12] propose an approach to model the testing process based on hierarchical time colored Petri Nets (HTCPN). However, while Petri-nets are good at modeling resources and parallel processing, simulation modeling models system components and their interactions, making it possible to conduct arbitrary time-related performance analysis, something which is not easy using Petri-nets.

Consequently to overcome the problems of analytical methods, simulation modeling can be applied in the context of testing processes mainly because: a) it enables to find solutions when analytical methods fail; b) it is a more straightforward process than analytical modeling since the structure of the simulation model naturally mimics the structure of the real system, and c) it is scalable, flexible, and easy to communicate since the modeling tools use visual languages.

However, despite these advantages there is a small number of contributions of simulation modeling in the field of software testing processes. Saurabh [15] presents a system dynamics (SD) model of software development with a special focus on the unit test phase. This work is partially based on Collofello's et al. [2] work about modeling the software testing process under the SD approach.

The motivation of these works is closely related to ours, but the models are built under a different simulation approach. System Dynamics approach operates at high abstraction level and is mostly used for strategic modeling. Hence, since a simulation model can only be used at the abstraction level in which it has been created, such a highly abstract model is not adequate for the operational and tactical levels in which decision-making regarding the testing processes takes place. In our case, since our main interest is to simulate the testing processes the discrete event (DE) modeling, with the underlying process-centric approach, has been selected. Furthermore, we have also selected the agent-based (AB) approach to be used together with the discrete-event one resulting in a multi-paradigm simulation model.

Generally, each simulation approach (SD, DE, AB) provides a set of different abstractions. If the system being modeled is complex enough, and software development is, then it is preferable to integrate different simulation methods than using one single approach, since the final model will represent the real system more realistically.

When we used the search string ("multi-paradigm" OR "multi-method") AND "simulation" AND "software testing process" and others alike in the digital libraries and citation databases, no single work was retrieved. Therefore, given the results of the systematic literature review performed, not fully documented here for space reasons, to the best of our knowledge our proposal is the first one that aims at using multi-paradigm simulation modeling to improve decision making in software testing management.

III. MULTI-LAYER TEST PROCESS MODEL

Testing processes include a variety of management and technical activities which are organized in a process model in part 2 of the draft ISO standard for software testing: ISO/IEC 29119-2 [4]. The purpose of this international standard is to define a generic process model for software testing that can be used by any organization when performing any form of software testing. Testing is structured in a multi-layer process model that defines the software testing processes at (1) the organizational level, (2) test management level and (3) dynamic test level. More specifically, the dynamic test level describes how dynamic testing is carried out within a particular phase of testing (e.g., unit, integration, system and acceptance) or type of testing (e.g., performance testing, security testing and usability testing). It is composed of four processes that are depicted in Figure 1.

- Test Design & Implementation Process: Describes how test cases and test procedures are derived; these are normally documented in a test specification, but may be immediately executed.
- Test Environment Set-Up & Maintenance Process: Describes how the environment in which tests are executed is established and maintained.
- Test Execution Process: Describes how the test procedures generated as a result of the Test Design & Implementation Process are run on the test environment established by the Test Environment Set-Up & Maintenance Process.
- Test Incident Reporting Process describes how the reporting of test incidents is managed.

The Test Execution Process is run after the tests have been specified and the environment has been established which leads to a strong dependency on the previous processes. This process may need to be performed a number of times as all the available test procedures may not be executed in a single iteration. Additionally, this process must be reentered as a consequence of detected failures after the underlying defects have been corrected (retesting).

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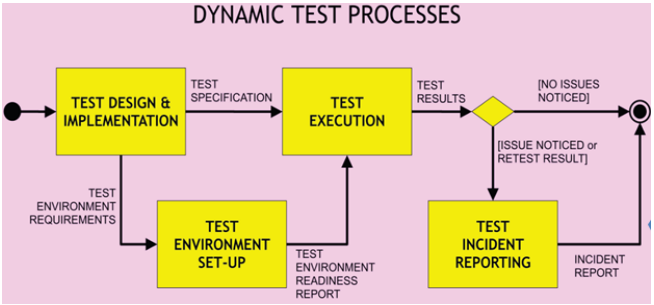

Figure 1. Dynamic Test Processes.

Besides, the Test Design & Implementation Process, and the Test Environment Set-Up & Maintenance Process may be reentered whether additional tests are needed after execution or some problems are detected in the testing environment. The Test Incident Reporting Process may be also reentered as a result of: a) the identification of test failures, b) something unusual or unexpected occurred during test execution, or c) retest activities.

IV. MODEL DESCRIPTION

The simulation model developed is described below in terms of its scope, result variables, process abstraction and input parameters. The description is organized following Kellner's proposal for describing simulation models [5].

A. Model Proposal and Scope

To determine a model proposal, the key questions that the model needs to address need to be identified. Then, model scope is set so that it is large enough to fully solve the key questions posed. In the context of this work, model proposal is to help in decision-making in software testing process management. Accordingly, the scope for this model will be a portion of the life cycle, with a short time span (i.e., the months in which the testing activities take place), one software product and two teams (i.e., development and testing teams) organizational breadth.

B. Result Variables

The result variables are the information elements needed to answer the key questions regarding the purpose of the model. In our model, several process metrics have been identified to help us understand the simulated process capability. According to this, process metrics have been classified into effectiveness and efficiency process metrics.

Effectiveness process metrics measure the extent to which a process produces a desired result [1].

The following result variables fall into this category:

- Defect Closure Period (DCP). The longer a reported defect takes to go from discovery to resolution, the higher the project risk associated with the underlying defect. Unresolved defects may: a) delay testing, b) make development less efficient or c) prevent the delivery of the software to the final customers. DCP measures the difference between the time required to repair a defect and the time required to confirm the defect is repaired.
- Defect Open Count. This measure tracks the number of times a defect report is opened. When the report is first submitted this count is set to one. This count is incremented each time the same defect report is reopened due to a failure in the confirmation test (retest).
- FixBacklog: Shows the percentage of defects closed per all the defects opened in a given time.
- Total Planned Test: The metric shows the evolution of the number of planned test cases along the testing project.
- Total Executed Tests: Shows the evolution of actual test cases which are executed along the project.
- Total Passed Tests: Shows the actual test cases which are executed and successfully passed (e.g., did not find any defects).
- Total Failed Tests: Shows the actual test cases that are executed and failed (e.g., did find defects).

Efficiency process metrics measure the extent to which a process produces its desired results in a not wasteful way and, ideally, minimizing the resources used [1].

Result variables in this category follow:

- Actual test time: Shows the total length of the testing process.
- Total team size and number of people per activity: Shows the total size of the testing team and the number of resources allocated to each activity of the process, respectively.
- Process efficiency: Shows the ratio of the number of defects closed per the number of defects found.

C. Process Abstraction

When developing a simulation model, the key elements of the process, their inter-relationships, and behavior need to be identified. The focus should be on those aspects of the process that are especially relevant to the purpose of the model, and believed to affect the result variables [5].

One of the decisions that need to be made in this phase is the simulation paradigm that it is going to be used to build the model. A simulation paradigm is a general framework for mapping a real world system to its model. The choice of paradigm should be based on the system being modeled and the purpose of the modeling. When modeling complex systems, it is frequent that different parts of the system are most naturally modeled using different paradigms. In this case, a multi-paradigm model is built.

In order to build our model, the multi-paradigm approach has been selected. First, to model and simulate the dynamic testing processes, the paradigm selected has been the discrete-event or process centric approach. Under this approach, the system being modeled is considered as a process, i.e., a sequence of operations being performed across entities, and this makes this paradigm the most natural and adequate to build process simulation models. The model is specified graphically as a process flowchart, where blocks represent the operations to be done along the process.

Although a simulation model following this approach allows us to analyze the evolution of the testing activities,

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the resource consumption and the number of defects detected, it would be interesting to add an extra functionality to the simulation model allowing the user to track the life of every defect since it is found until it is closed. It is important to notice that to achieve this aim the level of abstraction used needs to be changed from process-centric to individual-centric. Agent-based modeling is a simulation approach that allows the modeler to build a model under a bottom-up perspective, that is, describing the behavior of individuals (e.g., agents) and, if needed, their interactions. Frequently, the behavior of an agent is formalized by means of a state chart-like diagram. Therefore, this approach seems to be most natural and adequate to describe the lifecycle of defects found during the testing phase. As a consequence, a multi-paradigm simulation model was our choice for our modeling problem.

In summary, the model consists of two connected models. A description of each of these models follows:

1) Discrete event model (DE).

The discrete event model represents the Dynamic Test Processes in ISO/IEC 29119-2 [4] previously described in Section III.

The development process produces two main artifacts that are the input for the testing processes:

1. The test basis, usually the software specification, which is modeled as a set of features.
2. The executable code that is to be exercised by the tests.

The availability of the test basis enables the execution of the Test Design & Implementation Process which leads to a number of test cases. However, test cases are not ready to be executed until the test environment has been established (Test Design & Implementation Process) and the executable code released. Once the code is installed in the testing environment, the Test Execution Process can begin. Failed test cases are the input for the Test Incident Reporting Process and the results communicated to the development processes through the Agent-based model. Test execution reenters when previously detected defects have been fixed by development.

2) Agent-based model (AB).

During the software development process, each defect has a lifecycle in which it reaches different states. In order to simulate the different states that a defect reaches the agent-based paradigm has been used. Under this approach, we formalize the defects found as agents and their behavior as a state chart that reflects the different states and transitions of defect lifecycle. A description of each state in which the agents can be follows:

- *New*: An agent reaches this state when a defect is reported by the tester for the first time and is yet to be approved.
- *Analyzed*: Once a defect is reported, the manager has to analyze it in order to approve it as a genuine defect, reject or defer it. The agent remains in this state during the time in which this activity takes place. When the activity is done, the information for deciding what to do with the defect is available, and so, the agent moves to the next state which can be one of the following: a) *Rejected*: If a defect is found to be invalid, b) *Deferred*: If a defect is decided to be fixed in upcoming releases, and c) *Assigned*: If a defect is found to be valid and assigned to a member of the development team to fix it.
- *Fixed*: An agent moves to this state once the developer communicates the defect is fixed. The defect goes to the testing team for validation by injecting a task in the DE model to indicate that the test case that found this defect has to be executed again (retest). The result of this execution will determine the next state of the agent.
- *Closed*. If the tester finds that the defect is indeed fixed and is no more a cause of concern, the agent moves to the state Closed. Otherwise, if the defect is not fixed or partially fixed, the agent will go again to the state Assigned in which the work of a developer working on its fixing will be simulated again.

D. Input Parameters

The input parameters to include in the model largely depend upon the result variables desired and the process abstractions identified. Input parameters allow setting up different scenarios for simulation. The input parameters of the simulation model are the following:

- Software size: Size of the software product under development.
- FPA per Feature: Adjusted Functional Points per feature.
- Number of Test Cases per Feature: Number of test cases that need to be designed and executed per feature.
- Initial number of tasks in Environment Setup. Initial number of tasks that need to be done for the common and global environment setup.
- Estimated Time for Environment Setup. Time estimated to develop each environment setup task.
- Environment Setup Resources. Number of people allocated to the Environment Setup processes.
- Estimated Time for Test Design and Implementation. Time estimated to develop each task of the Test Design and Implementation processes.
- Test Design and Implementation Resources. Number of people allocated to the Test Design and Implementation process.
- Estimated Time for Test Execution. Time estimated to develop each task of the Test Execution processes.
- Test Execution Resources. Number of people allocated to the Test Execution processes.
- Estimated Time for Test Incident Reporting. Time estimated to develop each task of the Test Incident Reporting processes.
- Test Incident Reporting Resources. Number of people allocated to the Test Incident Reporting Processes.

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- Estimated time to fix a defect. Time estimated to a fix a defect by a developer.
- Code released for Test Execution. Indicates when the code is released for testing. This value is provided as a percentage of delay measured regarding the initial estimated time for the testing project.
- Probability of finding a defect per Test Case Execution. Probability that a Test Case finds a defect when the test case is executed the first time.
- Probability of finding a defect per Test Case in Retest Execution. Probability that a Test Case finds a defect when the defect has been reported as fixed.

In order to achieve more realistic results, the model accepts a triangular distribution for most of the above input parameters.

V. SIMULATION RUNS

The model implementation and the simulation runs have been performed using Anylogic™ software [18] with the Enterprise Library. The model logic is written in Java.

a) Base scenario (BS). In this scenario the base simulation is run to determine the values of the result variables and, analyze the results of the process. In order to obtain a set of reasonable parameters we have estimated the costs of the different activities using a set of ratios observed in average risk profiles [6]. We consider functional testing for a system test phase in a project with waterfall development, experienced builders and a structured test approach driven by risk. Ratios of functional design, realisation and functional test are 1:2:1. In relation with the test processes, the ratios of test design & implementation, execution, reporting and environment set-up are 50:40:5:5, respectively. The values of the input parameters in this scenario are displayed in TABLE I.

TABLE I. SCENARIO CONFIGURATION

Input parameter	Value
Software size	800 FPA
FPA per Feature	5
Number of Test Case per Feature	(0.5, 2, 4)
Initial number of tasks in Environment Setup	5 tasks
Estimated Time for Environment Setup	(10, 14.4, 20) hours
Environment Setup Resources	1 person
Estimated Time for Test Design and Implementation	(3, 4.5, 6) hours
Test Design and Implementation Resources	4 people
Estimated Time for Test Execution	(1.5, 3.2, 4.5) hours
Test Execution Resources	4 people
Estimated Time for Test Incident Reporting	(1.5, 3, 4.5) hours
Test Incident Reporting Resources	1 person
Estimated time to Fix a defect	(3, 4.5, 6) hours
Code released for Test Execution	15%
Probability of finding a defect per Test Case Execution	(5%, 15%, 25%)
Probability of finding a defect per Test Case in ReTest Execution	(10%, 20%, 30%)

Figures 2 and 3 contain a summary of the main process metrics. Figure 2 shows that 160 test cases were planned, which were able to find 116 defects (see Figure 3), 6 of them were rejected and 9 of them deferred. 101 defects were closed and 26 reopened. The Test Efficiency reached with this setting is 87%, which is reasonable in practice, showing the consistency of the model when using the above parameters.

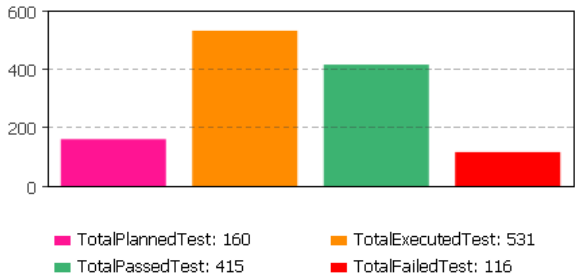

Figure 2. Different process output metrics in base scenario

b) Optimization. Even though simulation runs are useful to visualize the effect of different values of the input parameters in the process performance, that is, to execute what-if scenarios in managerial decision-making, a key benefit can be obtained when we use together simulation and metaheuristic optimization algorithms in a process called simulation optimization. In this case, it is possible to obtain which values need to take the input parameters in order to maximize or minimize an output variable. To show this

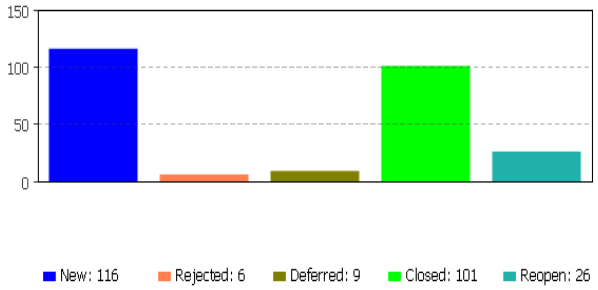

Figure 3. Number of defects in each state at the end of the simulation

application in our field of study we run an optimization experiment to determine wheter it is possible to improve the efficiency of the test process by controlling the moment in which the executable code is available for testing. The optimization will determine the distribution of the human resources that maximizes test efficiency when the code is released for testing in an range that varies from 5% to 50% from the moment the testing process begin. The optimizer OptQuest® [14] built-in Anylogic™ has been used for this optimization. Table II shows the input values for the control parameters of the experiment, the constraints impossed and the results obtained in the optimized process compared with the base case.

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TABLE II. OPTIMIZATION CONTROL PARAMETERS AND OUTPUTS COMPARED WITH BASE SCENARIO

Input parameter	**Control Input**	**Result (Base scena.)**	**Result (Optim.)**
Initial number of tasks in Environment Setup	3-5 tasks	5	5
Environment Setup Resources	1-4 people	1	1
Test Design and Implementation Resources	1-4 people	4	2
Test Execution Resources	1-4 people	4	3
Test Incident Reporting Resources	1-4 people	1	1
Code released for Test Execution	5% - 50%	15%	27%
Constraints	**Value**		
Testing Team Size	<= **7** people		
Maximum Testing Time Overrun	<= 1 month		
Process Efficiency obtained		87%	97%

The results of the optimization experiment show that under the constraints imposed it is possible to achieve 97% of efficiency in the process allocating 7 people to the process and having a maximum delay of the code released for testing of 27% of the initial time estimated. This will result into a process which is 97% in closing defects but finishes one month later than the base scenario. The conclusion drawn from this particular experiment with regard to the base scenario is that if the project is adequately scheduled, it is possible to reduce the total number of test resources as well as increase the process efficiency. In other situations simulation can help to find the best input values for project schedule, resource allocation and quality objective from among all that lead to the optimization of the key process outputs.

VI. CONCLUSION AND FURTHER WORK

This paper presented a simulation model for the dynamic testing processes which allows a seamless integration between the testing and development processes. The model is devised as a multi-paradigm model composed by a discrete event simulation model, to simulate the execution of the dynamic test processes, and an agent-based simulation model, to in-depth simulate the defects life cycle. Results show that the simulation model can be effectively used to optimize different project parameters and then help managers to achieve a trade-off between cost, schedule and quality.

This is a first step in the use of multi-paradigm simulation models for testing. Further work will include, although not limited to, the consideration of agent-based models to simulate parts of the dynamic test processes, the integration into a more complex project development simulation model [3] and experimentation in different projects using different lifecycle models and including different test levels of testing. After calibrating and validating the model with historical data from the industry, it will be also possible to exploit it as an operating tool for decision-making in the industrial domain.

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