Regression Testing Challenges and Solutions: An Industry-Academia Perspective

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Abstract

Background: Software quality assurance (QA) is an essential activity in the software development life cycle. Among the different QA activities, regression testing is a challenging task for large-scale software development. Regression testing is a well-researched area, and a large number of techniques have been proposed to fulfill the needs of industry. Despite the extensive research, the adoption of proposed regression testing techniques in the industry is limited. Studies show that there is a visible gap between research and practice.

Objective: This work aims at reducing the gap between industry and academia in regression testing. To fulfill this aim we have the following objectives:
1) Understanding the practitioners' goals regarding regression testing.
2) Understanding the current state of regression testing practice and challenges in the industry.
3) Investigating the testing research applicable in an industrial context.

Method: We conducted multiple studies using different methods. To explore the industry perspective on regression testing we used focus group and interview-based studies. To explore solutions from the literature, we used the systematic literature review and systematic mapping study.

Results: This thesis presents the practitioners' specific regression testing goals. The identified goals are confidence, controlled fault slippage, effectiveness, efficiency, and customer satisfaction. The challenges identified in the thesis are of two categories, 1) management related challenges and 2) technical challenges. Technical challenges relate to test suite maintenance, test case selection, test case prioritization, evaluation of regression testing. We have mapped 26 empirically evaluated regression testing techniques to the context, effect, and information taxonomies, and provided a guide to the practitioners regarding the adoption of the techniques in an industrial setting. We have also classified 56 model-based test case generation techniques regarding their strengths/limitations, input/intermediate models used, and relevance to the industrial context.

Conclusions: The challenges identified in this study are not new for research and practice. There could be two reasons regarding the presence of recurring challenges: 1) regression testing techniques proposed in the literature do not fit the companies context, 2) or, companies are not aware of the availability of the techniques that could be suitable for their context. To support the adoption of existing research on regres-

sion testing in industry, we have presented three taxonomies. These taxonomies, allow the characterization of regression testing techniques and enable to determine which of these techniques might be suitable in a given context. Furthermore, the identification of information needs for these techniques would be helpful to learn the implications regarding the cost of adoption. Regarding the support in test case generation, we conclude that current research on interaction model-based test case generation techniques did not illustrate the use of rigorous methodology, and currently, model-based test case generation techniques have low relevance for the industrial problems.

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Karlskrona, December 5, 2018

Publications

Papers included in this thesis:

Chapter 2 (Study 1) Nasir Mehmood Minhas, Kai Petersen, Nauman Bin Ali, and Krzysztof Wnuk. "Regression testing goals – View of practitioners and researchers", In *24th Asia-Pacific Software Engineering Conference Workshops (APSECW) EAST-17*, pp. 25–32. IEEE, 2017.

Chapter 3 (Study 2) Nasir Mehmood Minhas, Kai Petersen, Jürgen Börstler, and Krzysztof Wnuk. "A qualitative study on regression testing practices, challenges, improvements, and goals", to be submitted to Information and Software Technology 2018.

Chapter 4 (Study 3) Nauman bin Ali, Emelie Engström, Masoumeh Taromirad, Mohammad Reza Mousavi, Nasir Mehmood Minhas, Daniel Helgesson, Sebastian Kunze, and Mahsa Varshosaz. "On the search for industry-relevant regression testing research", Empirical Software Engineering (Accepted 2018).

Chapter 5 (Study 4) Nasir Mehmood Minhas, Sohaib Maqsood, Kai Petersen, and Aamer Nadeem. "A Systematic Mapping of Test Case Generation Techniques Using UML Interaction Diagram", Journal of Software: Evolution and Process (Submitted 2018)

Papers that are related to but not included in this thesis

Paper 1. Hasan Javed, Nasir Mehmood Minhas, Ansar Abbas, and Farhad Muhammad Riaz "Model Based Testing for Web Applications: A Literature Survey Presented", Journal of Software (JSW) 11.4 (2016):347–361.

Paper 2. Asad Masood Qazi, Adnan Rauf, and Nasir Mehmood Minhas "A Systematic Review of Use Cases based Software Testing Techniques", International Journal of Software Engineering and Its Applications 10.11 (2016):337–360.

Other Papers not included in this thesis

Paper 1. Jefferson Seide Mollri, Nauman bin Ali, Kai Petersen, Nasir Mehmood Minhas, and Panagiota Chatzipetrou "Teaching students critical appraisal of scientific literature using checklists", In *Proceedings of the 3rd European Conference of Software Engineering Education*, Pages 08–17, 2018.

Paper 2. Ricardo Britto, Muhammad Usman, and Nasir Mehmood Minhas "A quasi-experiment to evaluate the impact of mental fatigue on study selection process", In *Proceedings of the 21st International Conference on Evaluation and Assessment in Software Engineering*, Pages 264–269, 2017.

Contribution statement

Nasir Mehmood Minhas is the lead author of studies 1, 2 and 4. He led the design, execution, and reporting of these studies.

In Study 1, the co-authors provided feedback during the planning, execution and reporting stages. In this study, the second and third co-authors also participated in the data collection phases (i.e. focus group).

In Study 2, the second and the fourth authors participated in the data collection phases (i.e. interviews). The second author provided his feedback during the data analysis and reporting phases. He also reviewed the menu script in two iterations. The third author mainly reviewed the menu script he also contributed to the preparation of the menu script. The fourth author reviewed the menu script and provided input regarding the required updates.

Study 3 was a joint effort of all authors, and everybody has a significant role in this study. Nasir Mehmood Minhas contributed to the following phases of research: Study selection process, data analysis, reporting/reviews of various sections, and work on the revisions of the study.

In study 4, the first and second authors are the main contributors to the design of study protocol, selection of primary studies, data analysis, and reporting the results. The third author mainly contributed in review and updates of menu script, he also provided his guideline during some phases of analysis. Whereas the fourth author reviewed and updated the study protocol, he also reviewed the menu script and provided input regarding the required updates.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Overview

Testing is an essential activity for any software development organization. It ensures quality and reliability of the developed software by identifying defects. Testing is a complex and costly task and consumes up to 50% of the total software development cost [1, 3, 4, 7]. For large scale system development with continuous integration and delivery, the most challenging task is regression testing, and a significant share of the total testing cost is the cost of regression testing [1, 17, 40]. Regression testing is a retest activity that is performed after changes or between release cycles. The goal is to provide confidence that changes have not impacted the system negatively [2]. It implies that after changes or modifications, by applying regression testing, it can be ensured that unchanged parts of the system are working correctly as these were working before the change.

Considering the goal of regression testing a straightforward choice is to execute all test cases (re-test all). It is possible to adopt a retest all policy for smaller projects, where test suites consist of fewer test cases. Contrarily, in the large-scale software development test suites are significantly large [7]. Therefore, running all test cases in large-scale software development is often infeasible. The alternative of the re-test all policy is selective regression testing (SRT), comprising test suite minimization, test case prioritization, and test case selection. Various authors proposed techniques in support of SRT. In a literature survey [2], Yoo and Harman presented 159 studies on the approaches related to SRT. There is a large body of research on regression testing, but few approaches have been adopted in industry [2, 17]. The main reason for this is

the lacking evaluation of the proposed techniques in an industrial context [5]. For the researchers, the primary challenge is to propose solutions for regression testing on the basis of actual industrial problems. The primary step in this regard is to understand the current state of research and practice and identify the issues related to regression testing that practitioners are facing.

This work is the result of industry-academia collaboration (IAC), and the aim is to reduce the industry-academia gap regarding regression testing. Together with testing practitioners from the EASE[1] platform, we identified seven (7) software testing challenges in three (3) companies. These companies operate in mobile-communications, surveillance, and embedded software systems. The identified challenges were mainly related to regression testing.

In this regard, we have conducted two qualitative studies to identify the industry goals and challenges regarding regression testing. The first study is the result of a focus group of practitioners and researchers, and the second study presents the results of a multi-case study with two large companies. These two studies present the regression testing state of practice and goals. To link the findings of these two studies we conducted a systematic literature review (SLR) and a systematic mapping study (SMS). In the SLR we have synthesized the regression testing techniques, on the basis of three facets namely context (it refers to the applicability constraints of the technique), effect (it relates to the desired outcomes/improvements achieved by applying the technique), and information (it refers to the utilized information sources (entities) by the techniques). The goal was to enable the practitioners to determine which of the regression testing techniques could be applicable in a given industrial context and to learn the implication of the cost of adoption of these techniques. In the SMS we explored the Model based test case generation techniques, goal was to identify such techniques that can facilitate the practitioners regarding the test case generation.

The rest of this chapter is organized as follows: Section 1.2 presents a brief description of the concepts used in the thesis. Research gaps and contributions of this work are discussed in Section 1.3, whereas Section 1.4 describes the research questions that have been investigated in this work. The methods used in the studies included in this thesis are discussed in Section 1.5 and summaries of the included studies are presented in Section 1.6. Section 1.7 concludes the chapter and discusses future work.

[1]EASE – the Industrial Excellence Centre for Embedded Applications Software Engineering `http://ease.cs.lth.se/about/`

1.2 Background

This section presents a brief description of the basic concepts that have been used in this thesis.

1.2.1 Industry Academia Collaboration

Industry-academia collaboration (IAC) is a widely discussed topic in the software engineering community since the early days of software engineering. IAC is crucial for both communities (academia and industry), as it benefits the industry in terms of improvements in their methods and it is essential for the researchers to produce industry-relevant research. Success stories regarding IAC in the field of software engineering are limited [34]. Garousi and Felderer [33] argue, that differences in objectives, less scientific value in industry-related problems, and limited applicability of methods proposed in academia are hindrances for industry-academia collaboration. The communication gap between researchers and practitioners is one of the key challenges that can lower the motivation in collaboration. To improve the communication between software testing researchers and practitioners, Engström et al. [15] proposed a taxonomy (SERP test). The taxonomy comprises four facets; 1) Intervention (using a technique or a process change to improve or access testing), 2) Effect (desired target/outcome of the intervention, i.e. what should be achieved, e.g., improving effectiveness), 3) Scope (where should the intervention be applied? E.g., test planning, test design, test analysis, and/or test execution), and 4) Context (referring to the constraints/factors restricting the applicability of an intervention). The taxonomy is useful as a framework for both direct communication (industry-academia collaboration) and indirect communication (reporting of research results to the industry).

1.2.2 Regression Testing

Regression testing is an important testing activity, which is applied to a system under test after any change including a defect fix or adding a new feature. The IEEE Systems and Software Engineering Vocabulary defines regression testing as: *"the selective retesting of a system or component to verify that modifications have not caused unintended effects and that the system or component still complies with its specified requirements"* [6]. Regarding testing levels (i.e. unit, integration, & system), regression testing could be performed at all levels of testing. The goals of regression testing are to find defects and to obtain confidence about the quality of the systems under test.

Practitioners prefer to run a selected scope for regression testings, and the primary challenge for a testing practitioner is to determine the scope of regression testing (i.e.

which tests to include in the regression test suite) [1, 7]. Running all tests (re-test all) is a feasible choice for smaller systems. However, in large scale software development, running all tests is not a viable solution, as running all tests will require plenty of time and might cause a delay of releases. An alternative to a re-test all policy is selective regression testing (SRT). SRT refers to running regression testing with a smaller scope, where the key concern in this regard is the size of the test suite [7]. Test case selection, test case prioritization, and test suite minimization are of primary concern in SRT [2, 8]. While performing SRT, another relevant aspect is to measure its success, i.e. whether the desired goals have been achieved.

Test Case Selection

Researchers use the terms test case selection or regression test selection interchangeably. The concept refers to selecting a subset of test cases from existing test suites to test the modified parts of the system under test (SUT). Test case selection techniques are modification aware, as only those test cases are selected which are relevant to the modified parts of the SUT [2, 25].

Test Case Prioritization

Test case prioritization refers to the reordering of test cases in an existing test suite, to ensure to run the most critical test cases at priority. The goal of test case prioritization is to maximize the fault detection rate. Test case prioritization does not involve any procedure to select a test case; it only reorders the test cases on the basis of some predefined criteria [2, 39].

Test Case Minimization

For large-scale systems, test suites can be very large, and grow further when the software undergoes changes. New test cases can be added for new or updated features. Continuously growing test suites can contain redundant and obsolete test cases. A test case becomes obsolete, if the requirement associated to it is removed or updated during the changes in the software. Adding of new test cases can cause some existing test cases to become redundant given that new test cases satisfy the same testing requirements. Removal of redundant test cases does not effect the testing coverage [42]. The presence of redundant and obsolete test cases in a test suite increases the costs for test execution. Such test cases need to be identified and eliminated. Test case minimization techniques are meant to reduce the size of the test suites by eliminating redundant and/or obsolete test cases [2, 24].

Test Case Generation

During regression testing, new test cases need to be added to cover the newly added/ changed features. After changes in the system under test, if testers can not find bugs with the existing test cases they need to define new relevant test cases. For the creation of new test cases, automated test case generation techniques could be utilized [35]. Traditionally, test cases are generated in an unstructured manner, whereas model based testing provides a structured approach [28]. MBT offers an alternative testing method, it is a systematic approach that can be used to work with testing activities including test case generation and test result evaluation. The method relies on the explicit behavior models that represent the intended behaviors of a SUT [26, 27]. Test cases can be generated from one of the system models or combination of the models. Utting et al. define MBT as: *"MBT encompasses the processes and techniques for the automatic derivation of abstract test cases from abstract models, the generation of concrete tests from abstract tests, and the manual or automated execution of the resulting concrete test cases"* [27].

1.3 Research Gaps and Contributions

Regression testing is a well-researched area, however, the adoption of the proposed techniques in industry is limited. This has two main reasons: 1) lack of empirical evaluation of the techniques in industry [5] and, 2) the differences in goals between researcher and practitioners [15, 16]. This indicates that there is a gap between research and practice of regression testing.

The primary objective of this thesis is to reduce the gap between research and practice of regression testing. Its main contribution is a presentation of the current state of regression testing practice, and a synthesis of the existing research with respect to its applicability in industry.

While designing study 1 (**Chapter 2**), the consideration was to see if there are any differences in the goals between researchers and practitioners. Chapter 2 contributes in terms of the identification of regression testing goals and measures required to evaluate the success.

Researchers and practitioners have different perspectives and objectives while addressing the regression testing challenges, which is a hurdle for the utilization of regression testing research in industry. The researchers need to work on the regression testing challenges that are of actual concern to the practitioners. It is therefore important to work in close collaboration while identifying the challenges [8, 15]. The focus of **Chapter 3** (Study 2) is to identify the challenges, which are critical for the practi-

tioners. The contributions of Chapter 3 are the identification of: 1) the current state of regression testing practice, 2) challenges faced by the practitioners, 3) improvements suggestions, and 3) regression testing goals and criteria to evaluate the success. An important issue for the adoption of regression testing research in industry is that research results are not accessible due to discrepancies in terminology between industry and academia [5, 41]. Efforts are needed to identify and synthesize the existing research on regression testing concerning the relevance and applicability in industry. More importantly, results are supposed to be presented in terminology that practitioners can understand easily. To enable the practitioners to compare the research proposals and access their applicability and usefulness for their specific context, **Chapter 4** (Study 3) reviews the regression testing techniques from the aspect of industrial relevance. The contributions of Chapter 4 are: 1) design of three taxonomies to support the communication of regression testing research with respect to industrial relevance and applicability, and 2) a mapping of 26 industrially evaluated regression testing techniques with the taxonomies.

Test case generation is a challenging task that becomes harder for large and complex systems [19, 21, 23]. Model based testing provides a systematic mechanism to generate test cases from the design models. One class of models that could be used to generate test cases is UML interaction diagrams.

Researchers have proposed various techniques to generate test cases from UML interaction diagrams. Existing literature reviews did not put their main focus on interaction model-based test case generation techniques [20, 22, 27]. We believe that a critical review of existing MBT techniques based on UML Interaction diagrams is essential:

1) for the researchers who are intending to propose new approaches using interaction diagrams, and

2) for the practitioners who are intending to adopt the test case generation techniques based on interaction diagrams. **Chapter 5** (Study 4) contributes in terms of classification of test case generation techniques based on interaction diagrams. It compares the techniques on the basis of their capabilities and limitations, and it also accesses the studies for industrial relevance.

The contributions of this thesis can be summarized as follows:

C1. Identification of regression testing goals and measures of success (Chapter 2 & 3).

C2. Identification of regression testing challenges and improvements from an industry perspective (Chapter 3).

C3. Context specific synthesis of regression testing techniques (Chapter 4).

C4. Classification of test case generation techniques (Chapter 5).

1.4 Research Questions

The focus of this thesis is regression testing in large-scale development. The work can be distributed into two segments: (1) understanding the state of practice with a focus on goals and challenges, and (2) exploring the state of research with a focus on applicability in practice. RQ1 and RQ2 are concerned with segment 1 (i.e. understanding the state of practice), RQ3 and RQ4 relate to segment 2 (i.e. exploring the state of research). Table 1.1 summarizes which research questions are addressed in which chapters.

Table 1.1: Research questions and thesis chapters

	Chapters			
	2	3	4	5
RQs	RQ1	RQ1	-	-
	-	RQ2	-	-
	-	-	RQ3	-
	-	-	-	RQ4

RQ1 *How to evaluate success in regression testing?*
While implementing any strategy for regression testing, it is important to assess whether the implemented strategy was a good choice. A good strategy is one that can be aligned with the success goals. The purpose here is to understand the success goals for regression testing and which information should be utilized to measure the success goals. This aspect is the focus of Chapter 2 (Paper 1) and is also addressed partially in Chapter 3 (Paper 2).

RQ2 *How is regression testing performed in large-scale software development companies?*
Researchers argue that there is a gap between regression testing research and practice. Researchers are proposing their techniques by utilizing different criteria and well-managed sources of information. Whereas in industry, the most crucial criteria is the experience of the practitioners involved, and the best source of information is their knowledge about the system under test. The goal here is to

understand the practices that practitioners utilize during regression testing, how they select and/or prioritize the tests, what are the challenges that practitioners face while running regression tests, how they address the challenges and how they measure the success of regression testing. These aspects are the consideration of Chapter 3 (Paper 2).

RQ3 *How can existing research on regression testing techniques be utilized in practice?*
There is a large body of research on regression testing, researchers are focusing on mainly three areas: 1) test case selection, 2) test case prioritization, and 3) test suite minimization. There are only few studies that have been empirically evaluated on large-scale systems. The purpose of Chapter 4 (Paper 3) is to identify and synthesize the industry relevant research on regression testing to provide recommendations for future research and to provide guidelines for practitioners regarding the choice of regression testing methods.

RQ4 *To which extent are model-based test case generation techniques applicable in an industrial context?*
In software testing, test case creation is a challenging task, and it becomes more challenging for large-scale projects. Model-based testing (MBT) is one of the paradigms that facilitate a systematic test case generation mechanism. MBT utilizes the system models to generate the test cases, mainly behavioral models are used to generate the test cases. Chapter 5 (Paper 4) reviews the MBT techniques with the focus of industry relevance. The goal was to identify test case generation techniques applicable to the industrial context.

1.5 Research Methods

This thesis is the outcome of exploratory research and utilizes three research methods, 1) case study, 2) systematic literature review, and 3) systematic mapping study. Table 1.2 summarizes the methods used in different studies (chapters) It also shows the involvement of companies in the studies. Figure 1.1 describes an overall view of the thesis regarding a relationship between research questions, thesis chapters, research methods, and contributions.

1.5.1 Case Study

To address the first two research questions a focus group based study (Paper 2) and a multi-case study (Paper 3) were conducted.

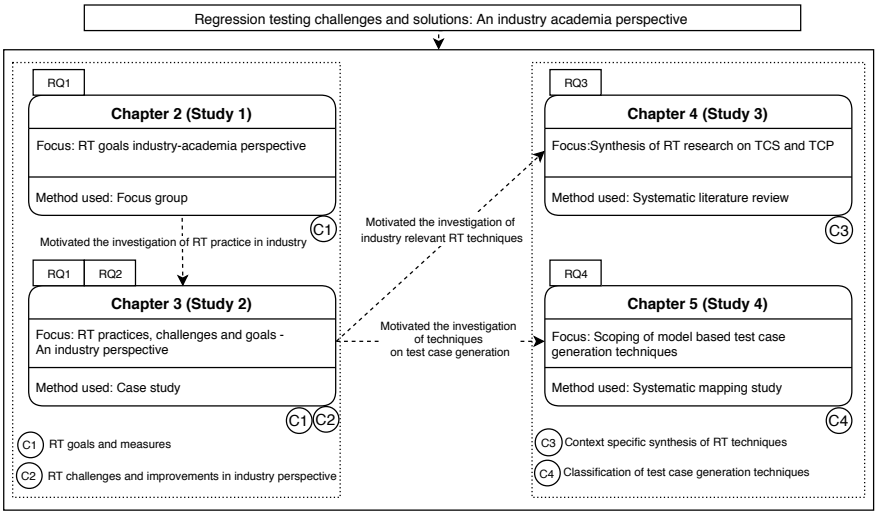

Figure 1.1: Thesis overview: Research questions, chapters, and contributions
RT: Regression testing, TCS: Test case selection, TCP: Test case prioritization

Case studies enable the researcher to get an in-depth understanding of the phenomenon under investigation [10]. A case study could be exploratory, descriptive, or explanatory [11]. Mostly case studies are based on qualitative data and are meant to provide a deeper insight into some aspects of the study [10]. Yin [11] argues that a case study would be a suitable choice when: 1) research questions are based on how or why, 2) the researcher has no or little control over the behavioral events, and 3) the focus of the study is on contemporary events.

Regarding the data collection for case studies, Runeson and Höst [10] suggest to use multiple sources of data collection for a case study, since it will improve the validity of the results. The methods/todoYou mean methods for data collection,or? adopted in the studies of this thesis are focus group, interviews, and archival data.

Focus Group

Focus group is a convenient method for data collection from a group of individuals when it is required to obtain the viewpoints of participants on a topic of shared interest. It allows people to sit together and have an open discussion about a specified topic. The role of the moderator is crucial for the success of a focus group.

A focus group should be conducted with at least three participants, the suggested upper limit for a focus group is twelve participants [9]. The data collection for Chapter 2 (Paper 1) was done by using focus groups. The first objective of the study was to identify the goals for the success of regression testing, whereas the second objective was to investigate whether there are any disparities of thoughts between researchers and practitioners. Senior researchers and practitioners participated in the study, the method was adopted mainly because of the second objective.

Interviews

Interviews are vital tools for data collection in software engineering case studies. They provide an opportunity for the researcher to have direct interaction with the subjects and to get a deeper insight into the phenomenon under study. Interview methods can be classified into three classes: 1) unstructured, 2) semi-structured, and 3) fully-structured. Conventionally, a semi-structured interview method is used in case studies [10] In semi-structured interviews, the researcher formulates the interview questions and prepares a guide/plan to conduct the interviews. The order of asking questions is flexible in semi-structured interviews. The purpose is to be able to adjust the order according to the expertise/interest of the subject [10]. Interviews were the primary data collection method for Chapter 3 (Paper 2). To conduct the interviews, a semi-structured approach was adopted. The objective of this study was to understand the current state of regression testing practice.

Archival Data

Archival data refers to the procedural documents, historical data/metrics, and documentation related to management activities (e.g., minutes of meetings), etc. [10]. This type of data enables the researcher to understand the working environment of the case company, their processes, and previous history regarding the execution of the methods. Using archival data, a researcher can validate information obtained by interviews. Archival data was the secondary source of information for Paper 2 (Chapter 3). The primary purpose was to validate some of the data points collected through interviews.

1.5.2 Systematic Literature Review

A systematic literature review (SLR) provides a way to collect the research evidence in a systematic way [12]. This method was adopted in software engineering from the medical research. With the help of this method, a researcher can collect, evaluate and interpret the available research relevant to a topic or phenomenon. The guidelines for

conducting SLRs suggested by Kitchenham [13] propose three phases of a systematic review: 1) planning the review, 2) conducting the review, and 3) reporting the review.

Planning

The crucial phase in systematic reviews is the planning phase. As a part of planning the researcher needs to establish the need for a SLR. In the planning phase, the researcher has to prepare a review protocol which includes research questions, search strategy, criteria for the selection of primary studies, quality assessment criteria, data extraction, and synthesis strategy.

Conducting

After planning the next step is to conduct the review. In this phase, a researcher follows the strategies defined in the planning phase to execute the review process. This phase consists of identification of relevant research form various research databases, selection of primary studies in the light of inclusion and exclusion criteria, quality assessment of the studies, data extraction, and data synthesis.

Reporting

The results collected during the previous phase need to be documented carefully and published in the form of a report or a paper.

To investigate RQ3, we conducted a systematic literature review of empirically evaluated regression testing techniques. The findings regarding RQ3 are presented in Chapter 4 (Paper 3). Regarding the study selection process a snowball sampling technique was followed [14].

1.5.3 Systematic Mapping Study

Systematic mapping studies provide an overview of a research area. They classify and count the contribution about the categories of that classification. A systematic mapping study provides a systematic way to search the literature and along with the publication venues for the area of research it investigate the topics that have been reported in the literature [36, 37]. Systematic literature reviews and systematic mapping studies share some common characteristics, for instance, searching and selecting of studies. But there is a visible difference in the goals and thus approaches to data analysis. The focus of a systematic literature review is to synthesize the evidence, and it also considers the

strength of evidence. Whereas, systematic mapping studies are mainly focused on the structuring of a research area [36].

To investigate RQ4 we conducted a systematic mapping study of UML interaction model based test case generation techniques. The findings regarding RQ 4 are presented in Chapter 5 (Paper 4). Regarding the study selection process, a search string based database search method was adopted [13, 38].

Table 1.2: Research methods and thesis chapters

	Chapters				
Research method	2	3	4	5	Companies
QS (Focus Group)	✓	-	-	-	Sony & Axis
CS (Interviews)	-	✓	-	-	Sony & Axis
SLR (Snowballing)	-	-	✓	-	Sony & Axis
SMS (Database Search)	-	-	-	✓	None

1.6 Summary of Studies Included in the Thesis

Each chapter of this thesis is based on an individual study, which are summarized in the following subsections.

1.6.1 Regression testing goals – View of practitioners and researchers

As mentioned previously, the aim of the studies included in this thesis is to bridge the gap between industry and academia regarding regression testing. Our first study was a step forward in the identified direction, with a focus on understanding the regression testing goals. The objective of this study was to explore the views of researchers and practitioners about the goals for regression testing.

To elicit the views of industry and academia testing experts, we conducted a focus group based workshop. A total of 7 testing experts participated in the study. The participants were the representatives of two large companies and two universities. The workshop was designed according to the GQM philosophy, and it was divided into three stages. We identified a prioritized list regression testing goals, *"Confidence"* was marked as the highest priority regression testing goal. Other goals identified in this study are, *"High precision"*, *"Fault slippage to the customer"*, *"Efficiency"*, and *'nclusiveness"*. We also identified the information needs to be required to evaluate

the success in regression testing in terms of "*Confidence*". Finally, we elicited the measures corresponding to the identified information needs. We found a certain level of agreement between the participants regarding the regression testing definitions and goals. Regarding priorities in regression testing goals, we noticed visible differences among the practitioners and researchers. Lesson learned out of this study is, that it is true that there is a gap between industry and academia. Such an environment where both can sit together could be of great value regarding the setting of a shared research agenda.

1.6.2 Regression testing for large-scale embedded software development

A majority of the regression testing techniques proposed by the research have not been adopted in industry. To increase adoption rates, we need to better understand the practitioners' perspectives on regression testing. This study aims at exploring the regression testing state of practice in the large-scale embedded software development. The study has two objectives, 1) to highlight the potential challenges in practice, and 2) to identify the industry-relevant research areas regarding regression testing. We conducted a qualitative study in two large-scale embedded software development companies, where we carried out semi-structured interviews with representatives from five software testing teams. We did conduct the detailed review of the process documentation of the companies to complement/validate the findings of the interviews.

We found that mostly, the practitioners run regression testing with a selected scope, the selection of scope depends upon the size, complexity, and location of the change. Test cases are prioritized on the basis of risk and critical functionality. The practitioners rely on their knowledge and experience for the decision making regarding selection and prioritization of test cases. The companies are using both automated and manual regression testing, and mainly they rely on in-house developed tools for test automation. The challenges identified in the companies are: time to test, information management, test suite maintenance, lack of communication, test selection/prioritization, lack of strategy, lack of assessment, etc. Majority challenges identified in the study are management related, and there is a dependency among the identified challenges. The proposed improvements are in line with the identified challenges. Regression testing goals identified in this study are customer satisfaction, critical defect detection, confidence, effectiveness, efficiency, and controlled slip through of faults.

Considering the current state of practice and identified challenges we conclude that there is a need to reconsider the regression test strategy in the companies. As a most of the identified challenges are either management related or have a dependency to test

strategy. We further suggest that researchers need to analyze the industry perspective while proposing new regression testing techniques. The industry-academia collaboration projects would be a good platform in this regard.

1.6.3 On the search for industry-relevant regression testing research

Regression testing is a means to assure that a change in the software, or its execution environment, does not introduce new defects. It involves the expensive undertaking of rerunning test cases. Several techniques have been proposed to reduce the number of test cases to execute in regression testing, however, there is no research on how to assess industrial relevance and applicability of such techniques. We conducted a systematic literature review with the following two goals: firstly, to enable researchers to design and present regression testing research with a focus on industrial relevance and applicability and secondly, to facilitate the industrial adoption of such research by addressing the attributes of concern from the practitioners' perspective. Using a reference-based search approach, we identified 1068 papers on regression testing. We then reduced the scope to only include papers with explicit discussions about relevance and applicability (i.e. mainly studies involving industrial stakeholders). Uniquely in this literature review, practitioners were consulted at several steps to increase the likelihood of achieving our aim of identifying factors important for relevance and applicability. We have summarized the results of these consultations and an analysis of the literature in three taxonomies, which capture aspects of industrial-relevance regarding the regression testing techniques. Based on these taxonomies, we mapped 38 papers reporting the evaluation of 26 regression testing techniques in industrial settings.

1.6.4 A Systematic Mapping of Test Case Generation Techniques Using UML Interaction Diagram

Testing plays a vital role for assuring software quality. Among the activities performed during testing process, test cases generation is a challenging and labor intensive task. Test case generation techniques based on UML models are getting attention of researchers and practitioners.

The aim of this study was to identify and synthesize the selected studies and provide an up to date overview of test case generation techniques based on interaction diagrams. In this work test case generation techniques were reviewed to compare them, identify their capabilities and limitations, and to assess the reporting quality. We followed the process of conducting systematic mapping as suggested by Kitchenham and Charters [38], and Petersen et al. [36]. It has been revealed that UML interaction diagrams based techniques are mainly used for integration testing. The majority of the

techniques are using sequence diagrams as input models, while some are using collaboration. A notable number of techniques are using interaction diagram along with some other UML diagram for test case generation. These techniques are mainly focusing on interaction, scenario, operational, concurrency, synchronization and deadlock related faults. Our study revealed the need for tool support to facilitate the transfer of solutions to industry. So far studies did not demonstrate the evaluation of solutions in an industrial context, which is facilitated by tool support.

1.7 Conclusions and Future work

Researchers argue that there is a gap between industry and academia [15, 33, 34]. In this thesis our aim was to understand and reduce the industry-academia gap concerning regression testing. In total, we have conducted four studies. In the first two studies (Chapter 2 and Chapter 3) the aim was to understand the state of regression testing practice, whereas the objective of the last two studies (Chapter 4 and Chapter 5) was to explore the literature to identify and classify industry-relevant solutions. From our case studies (Chapter 2 and Chapter 3), we learned that, in practice, the primary goal of regression testing is confidence, whereas other important goals are the controlled fault slippage, effectiveness, and efficiency. For the selection, prioritization and other decisions related to regression testing, the practitioners rely on their experience and knowledge about the system under test. The companies are using in-house built tools for the automation of regression testing. Various challenges have been identified in this thesis. Except some of the challenges related to management have been reported in the literature before. The most crucial challenges are lack of communication, the time to test, information management, dealing with obsolete test cases, test case prioritization, and evaluating and improving regression testing. The potential areas of improvements identified are i) test suite maintenance, ii) regression test optimization (selection, prioritization, and minimization), and iii) mechanism to evaluate success in regression testing.

In the SLR (Chapter 4), we found 26 industrially evaluated regression testing techniques proposed to provide solutions for large-scale software development. We have designed three taxonomies to capture aspects of industrial-relevance, and to support the communication of the identified solutions to the industry we mapped the identified techniques to these taxonomies.

The results of the mapping study (Chapter 5) on the test case generation techniques based on UML interaction diagrams revealed that a majority of the reviewed techniques can generate test paths. Only a few techniques generate test data and executable test cases. The reviewed techniques lack in rigor and relevance, and we conclude that there

is a need to evaluate the proposed techniques in an industry context.

From the findings of the current thesis we can infer the following areas for future research:

- **Regression test optimization:** Efforts are needed to investigate and introduce the techniques on the issues of test case selection, test case prioritization, and test suite minimization to optimize the regression testing for a given context. Study 3 (Chapter 4) is a step forward in this direction.

- **Evaluation of regression testing:** During our exploratory studies with the testing practitioners, we learned that our practitioners don't follow systematic procedures to evaluate their success of regression testing. They set goals for regression testing success, but not follow up them with actual measurements. There is a need to introduce a mechanism to evaluate the regression testing in the industrial context on the basis of defined success goals and measures. The goals and measures identified in Study 1 and Study 2 provide a basis for such a mechanism.

- **Test suite maintenance:** Another issue identified in Study 2 (Chapter 3) is the handling of obsolete test cases and adding relevant new test cases. There is a need to introduce methods for identifying obsolete test cases. It is also of critical importance to investigate and introduce test case generation techniques. Study 4 (Chapter 5) is an effort in this direction, although we could not find suitable solutions from our selected domain of techniques.

Regression test optimization and evaluation of regression testing would be the main focus for our future research. These areas are discussed in more detail in the following subsections.

1.7.1 Regression test optimization

From our industrial interactions and multicase study, we learned that the key area where companies are seeking improvement is regression test optimization. As a first step towards a solution we have identified some potential methods in the systematic literature review (Chapter 4). Embedded system testing is similar to application testing in general, but there are some distinctive features of embedded systems that need to be considered during test planning and execution. Five studies were classified as addressing regression testing in embedded systems [18, 29–32]. Some common characteristics of these studies are that the systems under test consist of several million lines of code and development processes are iterative in their nature. Four studies [18, 29, 31, 32] have been carried out in the telecommunication domain, while the study presented

in [30], was conducted in the automotive domain. In our future work, we aim to test implementations of the identified methods in industry and check if there is a need for improvement to scale the technique(s) for the industry needs.

1.7.2 Regression test evaluation

The primary focus of Study 1 and a partial focus of Study 2 was the evaluation of success in regression testing. For this, we have already identified the success goals and some factors that have a central position for the successful application of regression testing. The primary goal for the testing practitioners is confidence. Further significant success goals are precision, efficiency, effectiveness, no issue leakage/ no fault slippage (Study 1, Study 2). Precision refers to the ability of a technique to exclude test cases related to non affected areas. Efficiency means to finish regression testing in a limited time and low cost. Effectiveness corresponds to early fault detection and finding of new faults. The goal of 'issue leakage or fault slippage' means that no issues or faults should slip through to customer use. Confidence refers to whether testers are confident about the successful completion of regression testing and the achieved quality of the system under test. To accomplish the confidence goal it is essential to achieve all other goals, but it is difficult to measure levels of confidence. Rothermel and Harrold [25] proposed an evaluation framework for regression test selection techniques. This framework covers two of our identified goals (precision & efficiency). We aim to devise a mechanism to measure the other success goals, considering the underlying success factors.

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Chapter 2

Regression Testing goals - View of practitioners and researchers

2.1 Introduction

Regression testing is a well-researched area. However, the majority regression testing techniques proposed by the researchers are not getting the attention of the practitioners [5]. Communication gaps between industry and academia, and disparity in the regression testing goals are the main reasons. Close collaboration can help in bridging the communication gaps and resolving the disparities. A close collaboration between industry and academia is important to both sides, and this collaboration should be based on similar views of the studied problems and their importance [12]. Setting common goals and achieving a shared understanding is important for successful industry-academia collaboration. Having consensus on goals for collaborative research is a real challenge [21]. For a successful regression testing, it is essential to be able to manage the constraints. The key constraint of regression testing is the maintenance of the test suite (adding new test cases or updating or deleting obsolete test cases) [8, 11]. Test suite maintenance is not an easy task and if not done in a correct manner, utility of the test suite will be decreased and associated risks will be amplified [10]. To measure the success of regression testing, we need to define the regression testing goals. Chernak [17] emphasizes that test suite evaluation is the basis for the improvement of the overall testing process.

In earlier work Engström et al. [5] investigated regression testing practices and challenges using the focus group meeting and an online questionnaire with the industry practitioners. We complement these findings by exploring the value for practitioners and researchers alike. The objective is to reflect on how to evaluate regression testing. By choosing the right measures for

the goals of a successful regression testing. From the EASE [1] platform, together with the testing practitioners, we identified seven software testing challenges in 3 companies. These companies operate in mobile-communications, surveillance, and embedded software systems. To identify the testing challenges at the companies, we utilized the SERP-test taxonomy. The SERP-test is designed to support the industry-academia collaboration [6]. The identified challenges were related to test planning, test design, and test execution. Out of these challenges, three were related to regression test selection, regression test prioritization, and test suite minimization. With the consultation of companies' representatives, we find that companies were more interested to cope with the regression testing challenges. This study is a step forward in the identified direction, with a focus on understanding the regression testing goals. The broad objective of the study is to obtain the answer to the following question:

RQ : *What are the views of academics and practitioners about regression testing?*

The study aims at exploring the views of academics and practitioners about the goals of regression testing. The purpose is to investigate the commonalities and differences in their viewpoints and defining some common goals for the success of regression testing. We conducted a focus group study with industry and academic participants. Seven experts participated in the study. Among the participants, 4 were representatives of testing practitioners from 2 large companies, and 3 were senior researchers from 2 universities. The contributions of this study could be listed as, a) regression testing definition, b) success goals, c) information needed (questions) to evaluate the success and d) measures to answer the questions.

The reminder of this paper is structured as follows: Section 2.2 presents the related work, Section 2.3 presents the detail about the methodology (i.e. planning, design, and conduct of the focus group). Threats to validity have been discussed in Section 2.4. Study results have been discussed in Section 2.5, and conclusions on key findings have been presented in Section 2.6.

2.2 Related Work

Researchers believe that industry-academia collaboration in software engineering is very low [19–21]. Garousi et al. [19] emphasize the importance of collaboration between industry and academia to support improvement and innovation in the industry. Ramler et al. [18], suggest the collaboration between industry and academia for the improvement and innovation of software testing in the industry. This collaboration could be the basis for transferable and empirically evaluated results. To facilitate the collaboration between industry and academia, Engström et al. [26] proposed a taxonomy of testing. The taxonomy can assist to improve communication between practitioners and researchers. It can work for both types of communication (i.e. direct communication and indirect communication).

[1] EASE- the Industrial Excellence Centre for Embedded Applications Software Engineering `http://ease.cs.lth.se/about/`

Kapfhammer [7] pointed out the limited adoption of regression testing techniques, the reason identified is the lack of empirical evaluations. Chernak [17] stresses the importance of test suite evaluation as a basis for improving the test process. Chernak emphasizes that objective measures should be defined and built into the testing process to improve the overall quality of testing. Rothermel & Harrold [1, 2], proposed a 5 step framework to evaluate the regression testing techniques.

Engström et al. [6] suggested that more empirical evaluations conducted in industrial settings are required to facilitate the adoption of RT research in practice. The authors concluded that in order to enable practitioners to utilize the outcomes of research on testing, these outcomes must be evaluated in the actual environment. Through a focus group and an online questionnaire, Engström & Runeson [5] conducted a survey on regression testing practices, authors investigated what is considered regression testing by practitioners i.e. the definition, purpose and scope of it. They further investigated the challenges practitioners face with respect to regression testing. Our work complements the results of [5], as our subjects are the representatives of both sides (i.e. industry and academia). It is comparatively more focused, as purpose was to identify the regression testing goals.

We conducted an exploratory study to systematically elicit the goals, information needs and measures. We are focusing on industry-academia collaboration within regression testing challenges. The current focus is on regression test suite evaluation, as the first step in this study we tried to establish the regression testing goals.

2.3 Methodology

Focus groups are used to acquire the viewpoints of a group on some defined topic, which is a common area of interest for all group members. The key role in the focus groups is the moderator, who is responsible for guiding, facilitating and making sure that the discussion stays focused. Different guidelines are available for focus groups, Kontio et al. [4], [3] have deduced software engineering specific guidelines for conducting focus groups. Our approach to conducting the focus group was aligned with [4], a brief description about each step is given in the following sub sections.

2.3.1 Planning the research.

It is essential to make sure, that the focus group is suitable for the planned work [4]. Considering the research question presented in Section 3.1, our intention was to know the viewpoints of academics and practitioners about regression testing. Focus group was selected as it facilitates discussion, immediate reflection and it helps find the depth of the problem and some potential ideas for future research. As part of planning, we acquired the informed consent of the participants. We did also inform all participants about the purpose of the activity.

2.3.2 Designing the focus groups.

Focus group can comprise 3 to 12 participants, but a suitable number is between 4 and 8 [4]. We invited 7 participants from 2 Sweden based companies and 2 Swedish universities. Among the invited participants, 4 were testing practitioners from the companies (2 from each). 3 participants were senior academics from 2 universities. It is important to mention that all 3 academics are actively involved in software testing research. A brief description of the participants is shown in Table 2.1.

We followed the GQM approach for the focus group. GQM is an established method for planning and executing software engineering research and capturing software engineering related phenomena [25]. We phrased the questions using the interview guide formulated by Petersen et al. [9]. Table 2.2 shows the GQM template for the evaluation of regression testing, the template is divided into 5 activities (i.e. A1. A2, A3, A4, & A5). The purpose of A1 and A2 was to identify and prioritize the regression testing goals respectively, whereas A3 was to elicit the information needs (questions) corresponding to the identified goals. A4 was to capture the measures that could be used to answer the questions of related goal(s), while the objective of A5 was to know about the measures that the industry experts are actually using for the evaluation of test suites.

Table 2.1: Focus Group Participants

P.Id.	Organization	Participant's Expertise
P1.	Sony Mobile Communications	Testing/ Development
P2.	Sony Mobile Communications	Testing/Development
P3.	Axis Communications	Testing/Development
P4.	Axis Communications	Testing
P5.	Blekinge Institute of Techology	SE & Testing Research
P6.	Lund University	RE & Testing Research
P7.	Lund University	Regression Testing Research

2.3.3 Conducting the focus group session.

A focus group may last for 2 to 3 hours and it should have a predefined schedule. Within one session, the number of issues to be focused should be limited so that participants can have sufficient time to give their opinion on every aspect of the topic [4]. We allocated 2 hours for the activity, 30 minutes were assigned for setting up the focus group environment and introducing the basic purpose to the participants, although the overall objective was already communicated. We used the following schedule in the focus group:

1. Introduction: Short introduction to the goals of the workshop.
2. Round-the-table: What is regression testing in your view? Describe in one to 2 sentences.
3. Summarizing, presenting and verifying.
4. GQM-Activity (Table 2.2).

Table 2.2: GQM-Template for Evaluation of Regression Testing

Activity	Question	Rational
A1	Regression Testing is successful when a), b), c)... Complete the sentence (e.g. Regression testing is successful if it is a) efficient.)	Capture the goals
A2	Which success factors/goals are most important to you? Prioritize.	Prioritize success factors and goals and hence determine which measures should really be collected and whether this matches to what is collected today.
A3	What information is needed to evaluate success? Formulate as a question (e.g. How complex are our test cases, How many test cases are we running in a given test period?)	Capture the information needs (questions)
A4	What measures do we need to collect to answer the questions? (e.g. #test-steps for complexity)	Capture the measures that allow to quantify (and hence automate) the analysis of results
A5	What are you collecting today (measurements) of what has been identified in #4	Learn about input we already have available for evaluating test suites

5. Summarizing, presenting and verifying (after every GQM, i.e. A1....A5).
6. Closing (Any other reflection or discussion points? Next steps).

We used color stickers (green and yellow) for data collection, green stickers were used by the practitioners and yellow stickers were used by the researchers. Discussion points were recorded by 2 of the authors. We took several breaks in between to collect the answers (to gather the sticky notes), cluster similar answers, put logical labels on clusters. Reflect on the names of the clusters and also whether individual sticky notes belong in it. Finally, we presented the initial results and asked the participants to verify the labels according to their given options.

2.3.4 Analyzing the data and reporting the results.

We followed the inductive approach for data analysis. It is a systematic approach for analyzing qualitative data [22, 23].

According to Thomas [22],*"inductive analysis refers to approaches that primarily use detailed readings of raw data to derive concepts, themes, or a model through interpretations made from the raw data by an evaluator or researcher"*.

The inductive approach allows the findings to emerge from the raw data without imposing any restrictions, the approach revolves around 3 steps: 1) data reduction, 2) data visualization and 3) conclusions and verifications .

We collected the sticky notes from the participants and made the groups of the responses along with the labels (reduction). We displayed the results to the participants and asked them

to verify the labels with reference to their options. For example, we received the 43 options for regression testing goals, we reduced the options to 10 by making the clusters of the options on the basis of similarities. After the clustering of the data, results were displayed and the participants were invited to verify the labels according to their given options. In the second phase, together with the authors, results were reviewed by all participants in a separate review meeting, resultantly identified anomalies were fixed in the results.

The inductive approach provided us with the required flexibility to understand the viewpoints of the experts. The outcomes of focus group study are presented in Section 2.5.

2.4 Threats to Validity

This study presents the viewpoints of academics and practitioners about the goals, information needs and measures of regression testing. The results presented here are of an exploratory nature. We addressed the threats to validity according to guidelines of Runeson and Host [24].

Construct Validity: This aspect of validity is regarding the underlying operational measures, concepts and terms of the study. One potential threat to construct validity for our study is the subjects of the study representing 2 different working environments (i.e. academics and industry). Potentially they can have different understanding of concepts and terms. To mitigate the threats to this aspect of validity, we started with the exploration of the perception of participants about regression testing. To ensure the common understanding about the concept and terms during the entire focus group meeting.

Internal Validity: This aspect of validity threat is important if causal relations are examined. Generally, we can state that studying causal relationships was not in the scope of this study. It is a descriptive/interpretive study, as it presents the viewpoints of the participants. We created a mapping between information needs and measures, that is the only causal relationship presented in the study. The mapping created between information needs and measures requires empirical evaluation to determine the validity of relationships between information needs and measures.

External Validity: This aspect of the validity refers to the generalization of findings. We selected subjects of the study from academics and industry, to ensure the acceptability of results for both communities (i.e. practitioners and researchers). But as the practitioners were representing only 2 companies, so acceptability of results cannot be ensured in all companies working in the field of telecommunication. Further analytical generalization of results is possible, to support this we have reported the information of the participants in Table 2.1.

Reliability: To ensure the reliability of the study, we triangulated the results, as we presented and verified the initial results to the participants during the focus group meeting. Later after the complete analysis, results were presented to all participants in a review meeting. For detail please refer to the Section 2.3.4. Goals and measures identified in this study have not been verified through actual implementations.

2.5 Results and Analysis

2.5.1 Defining Regression Testing.

As a kick-off activity, we asked the experts to give their opinion about, *[What is regression testing in your vie* The purpose was to elicit the definition of regression testing with respect to participants' perception/experience. 5 out of 7 people came up with their definitions, presented in Table 2.3. Here an interesting fact that can be drawn from the individual definitions is the agreement between the views of academics and practitioners. We find that, the definitions presented at S.No. 1, 2 and 5 are almost the same and could be grouped together. Similarly, definitions at 3 and 4 are on same lines and we can group these 2 as well. After collecting the 5 definitions, we presented the definitions to the participants. Participants were agreed with our grouping scheme i.e. to group 1,2, & 5 and 3 & 4 in the form of the following 2 definitions:

1. *Regression testing is an activity which gives us confidence in what we have done and a trust that we have not broken anything.*
2. *Regression testing is an activity which makes sure that everything is working correctly after the changes in the system and it is a guarantee to continue in future.*

Table 2.3: Defining Regression Testing

S.No.	Perspective	Definition
1.	Academic	Make sure that we have not broken anything.
2.	Academic	Trust on what you have done
3.	Industry	To make sure that everything else work correctly
4.	Industry	To make future work possible, it is a guarantee to continue in future
5.	Industry	Trust on what you have done and make sure that we have not broken anything

Regression Testing Definitions Presented in the Literature

We selected 3 definitions from the literature to compare with the definitions presented by our experts. First definition was selected from a study presented by Engström and Runeson [5]. We selected this definition as it represents the practitioners' perspective and it could be regarded closer to our concept. Second and third are the standard definitions taken from IEEE software Engineering terminology [13], and IEEE, Systems and software engineering – vocabulary [14] respectively.

1. *"Regression testing involves repetitive tests and aims to verify that previously working software still works after changes to other parts. Regression testing shall ensure that*

nothing has been affected or destroyed" [5].

2. *"Regression testing is defined as retesting a system or component to confirm that changes cannot introduce any new bugs or causes other code errors, and the system or component can still follow the prescribed requirement specification" [13].*

3. *"Regression testing is the selective retesting of a system or component to verify that modifications have not caused unintended effects and that the system or component still complies with its specified requirements" [14].*

We observed that the definitions finalized in our study are closer to the definition presented by Engström and Runeson [5]. The distinctive factor of the definition proposed in our study is that it presents the viewpoints of both practitioners and researchers, while Engström's definition presents the viewpoints of practitioners only. On the other hand IEEE standard definitions is about that after the modification modified system or component still conforms to the specified requirements. That is system or component still works correctly after the changes. Our second definition conforms with the standard definitions. If we look at the individuals' definitions presented in Table 2.3 3 words (*make sure, guarantee, and trust*) are prominent. This indicates that through regression testing our experts are seeking some assurance about the system's correctness, a guarantee that future work is possible and a trust on what they have done. Moreover, the results indicate that practitioners and researchers have similar viewpoints on the definition of regression testing that addresses one of the challenges highlighted in Section 2.2.

Regression Testing Definition Adopted

During the second phase of the study (i.e. presentation of results and obtaining feedback from the participants), it was decided to adopt a single definition for the study. The agreed upon opinion was to merge the two definitions into a single definition in a way that it should represent the viewpoint of all participants. Later on, we combined the both definitions and created the following definition:

> *Regression testing is an activity which makes sure that everything is working correctly after the changes to the system. It builds the trust, that nothing has broken in the system and it guarantees to continue work in the future.*

2.5.2 GQM Activity.

To execute the GQM (Goal, Question, Metric) theme, we used the GQM template, the template of questions used here are the inspiration from [9]. We divided this activity as A1, A2, ..., A5 as listed in Table 2.2. The purpose of A1 was to elicit the goals and A2 was to prioritize the goals. A3 was for the elicitation of information needs (questions) to achieve the regression testing goals. With the A4 we intended to collect measures for answering the questions related

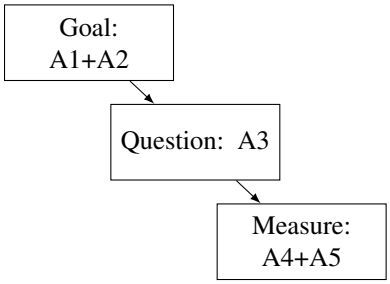

Figure 2.1: GQM Representation

to information needs. Finally, with the A5 intention was to know about the measures that are currently used by the practitioners. The concept followed in the study is represented in Figure 1.

A1–Goals Identification

To identify the goals, participants were asked to complete the following sentence, *[Regression Testing is successful when a), b), c) ?]*. Here a), b), c) indicate that the participants can state more than one goal regarding the success of regression testing. A total of 43 different options for goals were identified by the experts, we find that majority of the options were similar. For example we had the following options for G1 (Fault slippage to the customer):

1. No fault slippage through.
2. The customer/user finds no further bugs/flaws.
3. No issue leakage.
4. Ensure that the system fulfills the desired properties and no stopping bug slipped away.
5. We have no issue leakage on release.

With the consent of participants, we decided to group the identified goals on the basis of similarities and assign an appropriate label for each group. Hence the identified goals were restricted into 10 regression testing goals. The final list of the goals along with the description about each goal is shown in Table 2.4.

There are some goals identified by the participants, which are either irrelevant or too generic in scope. For example, visual overview could be taken as irrelevant or too broad in scope. Similarly, automation could be subsumed in efficiency. Achieving desired pass fail rate has been highlighted by 4 participants, if we see the goal description it can be subsumed by the effectiveness goal. It is important to highlight that visual overview and automation were identified by only one participant.

Table 2.4: Regression Testing Goals

G.Id.	Options	Goal	Goal description
G1.	5	Fault slippage to customer	The customer/user finds no further bugs/flaws
G2.	3	High precision	Non affected test cases excluded
G3.	3	Inclusiveness	Have run the most effective tests first
G4.	5	Achieved desired coverage	All desired modules have been executed when a regression test suite runs
G5.	7	Confidence	Stakeholders are confident with the reached quality and/or We can ensure that nothing is broken
G6.	7	Efficiency	Finished retesting with the limited time and low cost
G7.	7	Effectiveness	Costly faults detected early and/or finding new defects in old code
G8.	1	Visual overview	Visualization of complete software is displayed
G9.	1	Automation	Being able to automate
G10.	4	Achieving desired pass fail rate	When the expected tests pass and/or fail

Confidence, Efficiency, and Effectiveness are the goals identified by the majority of participants. Here it is important to mention that a goal identified by more participants does not refer to its importance, rather it only shows how may subjects have pointed out a particular goal. G5 (i.e. confidence) was identified by all 7 participants, but with varying descriptions. For example, some of the perceptions can be summarized as, *"Stakeholders are confident with the reached quality and/or we can ensure that nothing is broken."* To measure the desired quality or to determine that nothing is broken, requires multiple testing metrics.

A2–Goals Prioritization

Next task was to assign the priority order to the elicited goals. The question asked to the participants was, *[Which success factors/goals are most important to you? Prioritize]*. The participants were asked to assign priorities against every goal, each participant was given 10 points to prioritize. We used colored markers for priority assignment, red for researchers and Black for practitioners. As the distribution of experts was not equal on both sides (i.e. 3 researchers and 4 practitioners), we decided to normalize the priority of both sides. For normalization we devised an equation presented at (2.1).

$$NP = AP/N * 4 \tag{2.1}$$

Here NP = Normalized Priority, AP = Actual Priority and N = No. of Experts.

Table 2.5: Allocated Priorities to the Goals

G. Id	A Priority	I Priority	Total Priority
G1.	9	5	14
G2.	8	9	17
G3.	4	3	7
G4.	3	0	3
G5.	9	12	21
G6.	7	3	10
G7.	0	0	0
G8.	0	5	5
G9.	0	3	3
G10.	0	0	0

The normalized priorities along with the total points are shown in Table 2.5. G5 *(i.e. Confidence)* was marked with 21 total points, G2 *(i.e. High precision)* was given 17 points while G1 *(i.e. Fault slippage to customer)* was third in the list with 14 points. It was observed that in most cases there was a sort of agreement between researchers and practitioners. But there was a complete disagreement regarding the priority of some goals. We can see that for researchers G1 & G5 are the highest priority goals with equal priority, whereas for Practitioners G5 is the highest priority. Similarly, G8 and G9 are somewhat important for practitioners but researchers assigned *zero* to both the goals. An interesting fact, that we think is important to mention here is that the participants on both sides marked *zero* priority for G7 (i.e. effectiveness). Although this goal was identified by all 7 participants. And it is among the goals which have been cited in the literature by different authors [16, 17]. We found similarity in views of both sides, regarding the top 3 goals (i.e G5, G2, & G1 respectively). As G5 **(Confidence)** was ranked as the highest priority goal by the participants, and considering its generic nature we decided to elicit the information needs for G5, in the next phase of the focus group (i.e. A3). During the final review meeting participants were agreed to consider G1, G2, G3, G5, & G6 as the final list of goals.

A3–Questions (Information Needs Elicitation)

To elicit questions (information needs), participants were asked to answer the question, *[What information is needed to evaluate the success?].* We decided to elicit information needs only for G5 (i.e. confidence), we took the decision because of the following reasons:

1. Because of the generic nature of the goal.
2. It was ranked as the highest priority goal by the participants.
3. It was highlighted that, to achieve this goal multiple metrics need to be evaluated.

47 questions (information needs) were identified by the participants. During analysis, we find that a majority questions are similar. On the basis of identified similarity, we grouped these 47 questions (information needs) into 10. The final list of information needs questions is shown in

Table 2.6: G5. Questions (Information Needs)

Q.Id.	Question	Extracted from
Q1.	What are the changes to the system?	5 similar options
Q2.	What is the experience of development and testing?	3 similar options
Q3.	Have critical parts been covered?	16 similar options
Q4.	Have modifications been tested?	5 similar options
Q5.	What are the test outcomes?	10 similar options
Q6.	What is the perception of team about confidence?	3 similar options
Q7.	What is the nature of defects in the product?	2 similar options
Q8.	What is the balance between pass fail?	1 option
Q9.	What is the complexity of the product under test?	1 option
Q10.	What has been blocked by the tests?	1 option

Table 2.6. The questions with most options were, *Have critical parts been covered? (16 options)*, and *What are the test outcomes? (10 options)*. A majority of information needs listed in Table 2.6 are quantifiable, but some information needs are relatively generic in nature. Information need listed at Q2 (Team Experience) cannot be taken as a direct testing metric, but it is important with regard to confidence. Similarly, Q6 (Confidence perception) is not a specific metric, still it can affect the measure of other factors. Product characteristics listed as Q9 can determine the complexity of the product, this can also affect confidence perception. We can draw a correlation between Q2, Q6, and Q9. After finishing with the clustering, the final list of grouped information needs was presented to the participants for the verification of the clusters. Later in the results review meeting, all the stakeholders were agreed to consider Q1, Q3, Q4, Q5, and Q7 as the final list of information needs to achieve the confidence goal. Participants were agreed about the subjective importance of Q2 and Q7 with respect to the underlying goal of confidence.

A4–Measures Identification

The aim here was to identify the suitable measures to collect the information needs and ultimately achieve the defined goal (i.e. Confidence). We asked, *[What measures do we need to collect to answer the questions?].* Our experts identified 5 measures presented in the Table 2.7. Later together with the experts we started a brainstorming activity to find the possible mapping between the questions and measures. We carried the activity in a step wise manner. That is, for every single goal we asked the experts to map it with possible measure(s). 4 measures (i.e. M1,M2,M3, & M4) were mapped to 7 questions (i.e. Q1, Q3, Q4, Q5, Q7, Q8, and Q10). The finalized GQM (goal-question-measure) mapping is shown in Figure 2.

A5–Available Measures

The last activity was to know about the actual measures that are being used in the companies. We asked the question, *[What are you collecting today? (measurements) of what has been identified in A4].* This question was to know about the actual state of the implementation of measurement

Table 2.7: Measures

MID	Measure
M1	#LOC changed
M2	#Defect fixes from test
M3	#Changed LOC covered
M4	#defect history/change
M5	#Affected Non-changed LOC/Modules

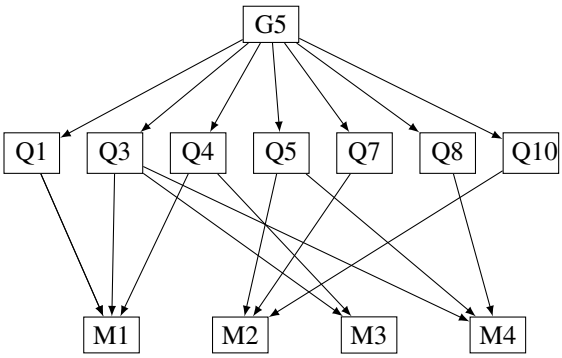

Figure 2.2: Goal-Question-Measure Mapping

program regarding the evaluation of regression testing in the industry. Therefore we asked practitioners to answer this question. We requested the researchers to sit as observers and provide their feedback on the activity. Practitioners expressed, that they do not use any explicit measures. There is no predefined measurement mechanism regarding the evaluation of regression testing that could be used. Instead, they rely on their experience, to evaluate the success. Their agreed-upon statement about the measurement was, it is a gut feeling, that we have tested enough and we are successful. To further continue and to come up with some substantial outcome, we added another question.

Do, we actually need to evaluate the success of regression testing?

We asked the participants to provide their opinion about the need for measuring the regression testing. There was a consensus among the participants about the importance of measuring the success of regression testing. It was emphasized that suitable measures need to be defined and used in the companies. It was also highlighted, that participating companies are interested to implement an evaluation mechanism/framework to measure the success.

Related Measures Presented in the Literature

To make a way towards the identification/implementation of evaluation framework, we decided to identify the measures from literature and test the identified measures in the partner companies. As a starting point we identified some measures from literature to further strengthen our findings.

Rothermel and Harrold [1, 2] presented a complete framework for the evaluation of the regression testing techniques. They suggested *inclusiveness, precision, efficiency, generality, & accountability* as measures to evaluate the regression testing. Horváth et al. [10] used *code coverage & partition metrics* for measuring fault detection capability and fault localization. They defined coverage metric (Cov) as a ratio of the number of procedures in a code group P that are covered by test group T. Whereas they defined partition metric (Part) to express the average ratio of procedures that can be distinguished from any other procedures in terms of coverage. *output uniqueness* is defined by Alshahwan and Harman [15], who define the output uniqueness as if the 2 test cases yield different kinds of output. The authors believe that this metric can help in effective fault detection capability, it also works for fault finding consistency.

Vidacs et al. [11] uses the code coverage, efficiency & uniqueness for Assessing the Test suites of large system. The authors argue that better coverage or partitioning can be achieved using more test cases, provided test cases are different. But, in case if such test cases are added to the test suite, which covers the same code, they will increase the test suite size possibly with little additional benefit. They suggested measuring the efficiency, that (refer to the relative number of test cases in test suite), to measure efficiency, they defined *coverage efficiency* (EFFCOV) and *partitioning efficiency* (EFFPART). Coverage efficiency refers to the average number of procedures covered by a test case, while partitioning efficiency shows that on average, how much a single test contributes to the partitioning capability of whole functional unit. To measure uniqueness authors used 2 metrics (*specialization* metric SPEC and *uniqueness* metric UNIQ). SPEC shows how specialized a test group is to a code group, while the UNIQ metric measures what portion of the covered elements is covered only by a particular test group.

To measure the effectiveness, Chernak [17] named his measure as *defect*, which is the ratio between the number of defects covered by a test suite to the number of defects missed by the test suite. Athanasiou et al. [16] argued that test code quality has 3 dimensions completeness, effectiveness, and maintainability. They defined *assertion density* as a measure of calculating the effectiveness of test code to detect the defects. For the effectiveness of test code authors also suggested *directness* as measure, they defined directness as it measures the extent to which the production code is covered directly. Test suite evaluation metrics and corresponding measures selected from literature are presented in Table 2.8.

Mapping between Focus Group and Literature Findings

As we mentioned already, due to the time constraint, we investigated only one goal (G5) in the subsequent steps of the focus group session. Therefore we decided, to create a mapping between the goals presented in the Table 2.4, and metrics/measures we find in the literature. Majority goals listed in the Table 2.4 are specific and measurable. Measures presented in the literature can be mapped to identified goals. For instance, G1 can be mapped to the metric “Fault detection

Table 2.8: Measures Found in Literature

S.No.	Metric	Measure	Reference
1.	Effectiveness	Defects, TestCaseEscaps, AssertionDensity, Directness	[16, 17]
2.	Fault Detection Capability	CodeCoverage, OutputUniqaueness	[10, 11, 15, 16]
3.	Fault localiztion	Partition	[10]
4.	Effeciency	EffCov, EffPart	[11]
5.	Uniqueness	UNIQ, SPEC	[11]

capability" , related measures have been discussed in the following studies [10, 15, 16]. G2 & G3 can be mapped to the metrics "precision " and "inclusiveness" defined in [1, 2]. Similarly, G6 can be linked to the metric "Efficiency" presented in [1, 2, 11]. Finally, G7 can be mapped to "effectiveness" metric discussed in [16, 17].

The measures identified from literature can also be mapped to some of the questions listed in Table 2.6. For example, Q5 could be mapped to *No. of Defects, TestCaseEscaps, & OutputUniqueness,* similarly Q7 can be mapped with *No. of Defects & CodeCoverage,* Q3 can be mapped with *AssertionDensity & Directness*.

2.6 Conclusions

In this paper, we presented the results of our exploratory study. The study presents the views of practitioners and researchers about the regression testing definition, goals of regression testing, information needed (questions) to evaluate the success, and the measures to reveal the required information. For the elicitation of information, we used the focus group method, a total of seven experts (representatives of industry and academia) participated in the study. We have identified the five priority goals for the success of regression testing including fault slippage to the customer, high precision, inclusiveness, confidence, and efficiency. The top priority and common goal among all participants was confidence' (about the system integrity). We identified information (seven questions) needed to achieve this goal. We also elicited the measures corresponding to these information needs. Finally, a mapping among goal, questions, and measures was created.

While defining the concepts and goals of regression testing, we did not observe any significant difference of opinion between researchers and practitioners. However, there were visible differences in the priority of goals. We believe that such platforms where industry and academia can sit together can be beneficial for both. Resultantly, researchers can work on actual industry problems and practitioners could be able to cope with the real challenges by using the relevant research.

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Chapter 3

Regression testing for embedded software development – Exploring the state of practice

3.1 Introduction

Testing is an essential aspect of any software development project. The companies are facing various testing challenges, especially for large and complex products [3, 17]. The most challenging testing activity in large-scale systems development is regression testing, which can consume up to 80% of the total testing cost [20, 25]. Regression testing (RT) is a retest activity to ensure that system modifications do not affect other parts of the system and that the unchanged parts of the system are still working as they did before a change.

RT is a challenge for the software industry, especially for large-scale embedded software development companies in the context of systems with continuous integration and delivery. Considering the recent systematic literature review studies conducted on the topic of regression testing [24, 27, 32, 33] we can conclude that it is a well-researched area and a large number of techniques have been proposed in the literature. Despite extensive research on RT, research results are not finding their way into practice. There are several reasons, like differences in terminology, availability of research results and a lack of empirical evaluation of RT techniques in real industrial environments [19, 25].

Other factors that affect the transition of research to the industry are, communication-gap between practitioners and researchers, consideration of testing challenges at the different level of abstraction, and differences in the vocabulary and context regarding the concepts of testing [26]. It is essential that researchers must consider real-world situations. Without a focus on real indus-

trial needs and practices, a majority of new techniques proposed in the literature will not fit with existing practices. Testing is not only a technical challenge, but it is a socio-technical issue [17].

In this paper, we have investigated the current state of regression testing practice in two large-scale embedded software development companies. The contributions of this study are as follows:

- Regression testing definition: presenting the perspective of practitioners.
- Regression testing practices: the purpose was to understand that how practitioners undertake the regression testing activity in the companies. Along with the regression testing practices, we identified selection and prioritization criteria, and the challenges regarding the regression testing practices.
- Improvement suggestions to overcome the identified challenges.
- Regression testing goals and success criteria.

The remainder of this paper is structured as follows. Section 3.2 discusses the related work. Section 3.3 describes our research methodology. Threats to validity are discussed in Section 3.4. Results of the study are presented and discussed in Section 3.5. A summary, organized along our research questions, as well as conclusions can be found in Section 3.6.

3.2 Related Work

There is a large body of research on software testing ([1, 4]), but most of this research is focused on methods and tools. There is only little work on the perspectives of testing practitioners in industry on regression testing. We found only 13 articles [10–16, 18, 22–25, 29] related to our work, which we discuss further below. Out of these 13 studies, eight deal specifically with regression testing, whereas five have a broader focus. Other than regression testing specific studies, we included those papers in the related work, where authors are discussing any aspect of regression testing.

With respect to the main focus of the related works, we organized them into four groups: (1) general testing practices, (2) testing methods and tools, (3) automated testing, and (4) regression testing.

General Testing Practices Two studies, both of them surveys, investigated general testing practices ([11, 12]). Dias-Neto et al. [11] conducted a survey-based study to identify the software testing practices in South America. The study was carried out with the practitioners from Brazil and Uruguay. The authors highlight the testing practices that the practitioners consider as essential and beneficial. For instance, the practitioners think testing documentation as useful for current and future testing activities. The practitioners acknowledge the importance of test management and error reporting tools. The essential testing types are system and regression testing. The authors also highlight some weaknesses of the companies. For example, they indicate that the companies do not measure their testing activity and the tendency of using test automation tools is not encouraging.

Kassab et al. [12] conducted a web-based survey to explore how software practitioners are using testing. The focus of their research was to study the overall testing practices. Authors indicate that the use of black box testing techniques is more common as compared to white box testing. Regression testing is one of the testing levels getting more attention of the companies. There is a trend in the companies to outsource the regression testing activity. Among the surveyed companies majority of telecommunication and gaming companies prefer the outsourcing of regression testing, and they are satisfied with this practice. The authors highlight requirement coverage as the most used metric in the companies, followed by the test execution rate. Test stopping criteria for the majority of the companies is the deadline of the project.

Testing Methods and Tools Ng et al. [18] investigated software testing practices in ICT companies in Australia. Their focus was on testing methodologies/techniques, tools, metrics, and standards. The authors highlighted that the training share for testing staff is low, according to the results presented in the study, universities and training colleges offer only 10.7% of the total training courses for testing staff. Regarding regression testing, the authors report that 69.2% of the organizations are using regression testing for all of the applications they are developing. Regarding the frequency of regression testing, 53.3% of the organizations repeat regression testing for every new version of the product and 28.9 % reported the use of regression testing after every change.

Automated Testing Two studies focused on the state of practice in testing automation ([13, 15]). Rafi et al. [13] highlighted the benefits and challenges of automated testing using a systematic literature review followed by a practitioner survey. They found only few studies discussing the benefits and limitations of automated testing. The authors conclude that automation is beneficial in an environment where excessive regression testing is performed and it helps in improving test coverage. The key limitations are initial setup costs, training, and availability of reliable testing tools. Furthermore, a majority of testers believe that automated testing cannot replace manual testing.

Kasurinen et al. [15] studied the current state of practice and required improvements in software test automation in an interview-based empirical study. The authors suggest that most of the practitioners are satisfied with their current test policy and testing practices, and they are not thinking of any change in it. Regarding automation, the authors reveal that only 26% of the test cases were automated, and the majority of these test cases are related to unit and regression testing. The automation of regression testing is a common practice among the companies, and regression testing was the most practiced testing type in the sample organizations.

Regression Testing Eight studies focused specifically on regression testing aspects ([10, 14, 16, 22–25, 29]). Brahneborg et al. [29] extracted the challenges corresponding to the existing methods of regression testing from a set of empirical studies. The authors classified the challenges into two categories, 1) method related challenges, 2) Organization related challenges. Among method related challenges they highlighted, handling failures, performance measurement, handling fault distribution, scalability of techniques, and tool support. Whereas regarding

organization related challenges, the authors describes existence of a structured test suite (test suite maintenance), information availability, knowledge and skills of testers and developers, and management support.

Minhas et al. [10] conducted a focus group based study to investigate the views of industry practitioners and software engineering researchers concerning regression testing. The authors explore the perceptions of both communities about the scope of regression testing. They also identify the regression testing success goals. The authors listed confidence, high precision, and fault-slippage as the essential goals of regression testing. They conclude that the perception of the practitioners and researchers about regression testing is alike, and there are similarities in views concerning regression testing goals. Finally, the authors indicate the need for a measurement of regression testing task to enable the testers for measuring their success. The goals identified in the study are given in Table 3.2.

Parsons et al. [23] conducted case-studies and an online survey to investigate the adoption of regression testing strategies in agile development. The authors analyzed different contextual factors that can have an impact on regression testing strategy. The focus of their research was to identify the organizational maturity regarding regression testing and operational aspects of regression testing in the surveyed organizations. The authors found that the maturity of the organization is the primary factor for successful regression testing. The authors conclude that organizations can get potential benefits of investments in regression testing. The authors highlighted the need for investigations in the areas of change and risk management regarding regression testing.

Yoo and Harman [24] surveyed the literature on regression test case minimization, selection, and prioritization. They specified the state of the art, trends and issues concerning these areas of regression testing. The authors conclude that the trend to evaluate regression testing techniques is getting a significant increase in the research. However, the majority of empirical studies are carried out with systems under test of less than 10,000 lines of code and test suite sizes of less than 1,000 test cases. They also found that almost 60% of the empirical studies on regression testing are using programs from the software infrastructure repository (SIR[1]) ([5]). It indicates that evaluation of regression testing techniques in real industrial context is limited. The authors argued that there is a potential risk of over-fitting the research on regression testing techniques to the programs that are readily available. They suggested that for the future research on regression testing, researchers should opt for alternative data sources and focus should be on the transfer of technology to industry.

Juergens et al. [14] carried out an industry case study to highlight the challenges concerning regression test selection techniques when applied in manual system tests. They suggest that the testing effort could exceed the expected limit when applying selective regression testing techniques on manual testing. The authors also think that under-specification of manual tests can reduce the conclusiveness of results. Finally, they suggest strategies to improve the manual regression test selection.

Engström and Runeson [16] investigated regression testing practices and challenges and

[1] http://sir.unl.edu/portal/index.php

pointed out that a majority of the challenges are related to testability issues and good practices are related to test automation. The authors note that most findings of their study are related to testing in general and are not specific to regression testing. However, there was a consensus among the practitioners regarding the concept and importance of regression testing. Some key findings of this study are provided in Table 3.2.

Harrold and Orso [25] analyzed the state of research and practice in regression testing. The authors conducted the review of research on regression testing and informal survey with the researchers and practitioners. They concluded that hardly a few methods and tools proposed in the research are in use of industry. The authors identified various issues that are hindering the transition of proposed techniques to practice. They also highlighted the technical/conceptual issues, needed to be addressed by the research. Issues identified by Harrold and Orso are listed in Table 3.2.

Lin [22] conducted a literature-based survey on the regression testing research and recent practices. Their goal was to identify the gaps in regression testing research and its industrial practices. The author suggests that there are some gaps and efforts should be made towards the implementation of regression testing research in industry. Addressing these gaps should be the future direction in research.

Summary A summary of related work is presented in Table 3.1. Of the 11 studies discussed above, only 6 focused on aspects of regression testing. Overall, the related work shows that there is a gap between research and practice. New techniques should have to be evaluated in the real industrial context. The researchers should work on technology transfer of the regression testing techniques.

In order to build a mapping between the existing literature and findings of our study, we extracted related information from some of the studies presented in the related work. Considering the scope and method the studies that could be regarded as closely relevant to our work are [16, 25]. Both studies are of exploratory nature and purpose to investigate the current state of practice concerning RT. We extracted information related to practices, selection and prioritization criteria and challenges from these studies. We did extract some information regarding the selection and prioritization criteria from the literature survey by Yoo and Harman [24]. For the regression testing challenges, we also utilized the study by Brahneborg et al. [29]. Regarding RT goals we extracted the information from [10, 31]. We have listed the key findings of these studies in Table 3.2. It is essential to specify that the literature findings are not exhaustive because finding practices, challenges, etc. from the literature was not the goal of this study.

3.3 Methodology

We conducted a multi-case study in two large companies to investigate the current state of practice regarding regression testing. Data were mainly collected through interviews, and the review of process documentation complemented the findings. Interviews provide an opportunity for direct interaction with the respondents and resolving issues with interpretations during the inter-

Table 3.1: Summary of related work. The first column indicates the subsection in Section 3.2 (GTP: General Testing Practices, TMT: Testing Methods and Tools, AT: Automated Testing, RT: Regression Testing).

	Ref.	Methods	Year	RT[1]	Focus of the study
GTP	[11]	Survey	2017	No	Characterizing the testing practices in South America.
	[12]	Survey	2017	No	Overall testing practices.
TMT	[18]	Survey	2004	No	Current state of testing practices, testing methodologies/techniques, testing tools, metrics, and standards in Australian ICT companies.
AT	[13]	SLR and Survey	2012	No	Benefits and challenges of automated testing.
	[15]	Interviews	2010	No	Current state and required improvement in test automation.
RT	[29]	Literature study	2017	Yes	Identification of regression testing challenges.
	[10]	Focus Group	2017	Yes	Regression Testing goals, information needs and metrics.
	[23]	Case study and survey	2014	Yes	Regression testing strategies and the factors that influence the adoption.
	[24]	Literature Survey	2012	Yes	A detailed analysis of trends and issues in regression testing concerning minimization, selection and prioritization.
	[14]	Case study	2011	Yes	Regression test selection challenges when applied to system manual tests.
	[16]	Focus group and survey	2010	Yes	Regression testing practices and challenges.
	[25]	Literature review and survey	2008	Yes	An analysis of the state of the research and the state of the practice.
	[22]	Literature survey	2007	Yes	Identification of gaps between the regression testing research and practice.

[1] Whether the work focuses on regression testing aspects.

view sessions. We choose to conduct semi-structured interviews, since it allows improvisation and exploration of the studied objects [9].

3.3.1 Research Questions

RQ1 How is regression testing perceived by the practitioners in industry?

RQ2 What is the current state of regression testing practice in industry?

- RQ2.1 How are the practitioners selecting and prioritizing test cases?
- RQ2.2 What are the key challenges for the practitioners regarding regression testing?

RQ3 What are the possible improvements regarding regression testing practices suggested by the practitioners?

RQ4 How do the practitioners evaluate their success in regression testing?

Table 3.2: Literature findings on RT state of practice

Aspect	ID	Description	Ref
RT Practices	LPr1.	In industry test suite maintenance is largely manual.	[25]
	LPr2.	For RT, many organizations rerun all test cases (retest all).	[16, 25]
	LPr3.	A most common approach is running core set of test cases.	[16, 25]
	LPr4.	In large number of organization, test case are selected randomly on the basis of experience of testers.	[25]
	LPr5.	Mostly organizations use in-house build techniques and tools	[25]
	LPr6.	Some practitioners prefer to run as many as possible.	[16]
	LPr7.	Start RT as early as possible.	[16]
	LPr8.	Run RT before each release.	[16]
	LPr9.	Complete re-test for critical parts.	[16]
	LPr10.	Focus is on functional test cases	[16]
	LPr11.	Selection of test cases depends on the situation.	[16]
	LPr12.	The amount and frequency of RT depends upon the various factors.	[16]
Prioritization	LPc1.	Change.	[16, 24, 25]
	LPc2.	Cost.	[25]
	LPc3.	Running time.	[25]
	LPc4.	Criticality.	[25]
	LPc5.	Complexity of the test cases.	[25]
Selection	LSc1.	Change.	[16, 24, 25]
	LSc2.	Historical test data on test case effectiveness.	[24, 25]
	LSc3.	Timing data on the last time a test case was run.	[25]
	LSc4	Traceability between requirements to test cases.	[24, 25]
	LSc5.	Situation based selection.	[16]
	LSc6.	Areas affected by the changes.	[16]
Challenges	LC1.	Identification of obsolete test cases.	[25]
	LC2.	Selection of relevant test cases.	[16, 25]
	LC3.	Test case prioritization.	[25]
	LC4.	Test suite augmentation.	[25]
	LC5.	Removing redundant test cases.	[16, 25]
	LC6.	Creating effective test cases.	[16, 25]
	LC7.	Manual testing (expensive and time consuming).	[25]
	LC8.	information maintenance.	[25, 29]
	LC9.	Test suite maintenance.	[16, 25, 29]
	LC10.	Test suite assessment.	[25]
	LC11.	Time to RT.	[16]
	LC12.	Balance between manual and automated RT.	[16]
	LC13.	Execution of automated RT.	[16]
	LC14.	Time to analyze results.	[16]
	LC15.	Management support.	[29]
Goals	LG1	Increasing rate of fault detection (effectiveness)	[10, 31]
	LG2	Increasing coverage of test suite (coverage)	[10, 31]
	LG3	Increasing confidence regarding the system reliability (confidence)	[10, 31]
	LG4	Identifying high risk (critical) faults	[31]
	LG5	Identifying change specific faults (effected areas)	[31]
	LG6	The customer should not find fault in the product (fault slippage to the customer)	[10]
	LG7	Finishing RT in limited time and low cost (efficiency)	[10]
	LG8	Running most effective test cases (inclusiveness)	[10]
	LG9	Excluding non effective test cases (precision) [10]	

3.3.2 Case Companies

We conducted this study from the platform of EASE [2] (An industry-academia collaboration project).The companies participated in this study are Sony Mobile Communications AB and

[2]EASE- the Industrial Excellence Centre for Embedded Applications Software Engineering `http://ease.cs.lth.se/about/`

Axis Communications AB, from hereafter we will use Sony and Axis to refer the case companies. Both Sony and Axis are large-scale embedded software development companies, and both are the collaborators in the EASE project. Sony is a multinational telecommunication company and producing smartphones and other smart products. The core part of the software is used in different versions and variants of the devices. Axis is manufacturing network cameras and other surveillance devices, and they claim to be the inventors of the first network camera. Regarding the software for the products, the core platform is similar for all products. Both the companies require a concise effort regarding regression testing of their respective products. Reason being that both companies are producing their respective products for many years and they have several releases of these products. The software update is a regular activity for both companies.

Table 3.3: Overview of interviewees. Column *Perspective* refers to the area/branch the interviewee is working in.

	PID	Team[1]	Current Role	Exp[2]
Company A	P1	SWSE	Test Architect &Team Lead	10
	P2	SWSE	Manager Verification	9
	P3	SWSE, FCS	Verification Engineer	13
	P4	FCS	Test Architect	10
	P5	FCS	Verification Engineer	10
	P6	FCS	Product Owner	11
Company B	P7	FWD	Tech Lead	6
	P8	FWD	Engineering Manager	8
	P9	FWR	Program Manager	2
	P10	PTS	Technical Coordinator	7
	P11	PTS	Test Area Maintainer	6

[1] SWSE (Software Security & Enterprise), FCS (Flash Core Security), FWD (Firmware Development), FWR (Firmware Release & Upgrade), PTS (Platform Storage).
[2] Experience in number of years the practitioner is working with the current company.

From Sony, the practitioners from two teams (Software Security & Enterprise (SWSE) and Flash Core Security (FCS)) participated in the study. These teams are working on two different parts of a product, and the software for both parts is developed within the respective teams. SWSE team is working on the enterprise part of the product, and performs testing for software security and enterprise at the system level. Testing for software security is automated, whereas testing for the enterprise part is manual. For test automation a third-party tool is used. FCS team is working on the boot & loader part and performs testing mainly at the component level. Testing for the loader is automated, whereas testing for the boot part is manual. The team uses an in-house developed tool for automated testing and currently working on complete test automation and the adoption of an open source tool.

From Axis, practitioners from three teams (Firmware Development (FWD), Firmware Release & Upgrade (FWR), and Platform Storage (PTS)) participated in the study. FWD team is responsible for the new product development and new feature additions to products. They perform testing at unit, integration, and system level. Mainly regression testing is automated except the testing of new features.

FWR team works on upgrades and new releases. Their primary responsibility is pre-release (Beta testing), performance, and stability testing. Performance and stability testing is automated, but complemented by manual exploratory testing. Regression testing is regarded as input to release. PTS team is responsible for the storage part of the platform and performs testing at the unit and system level. For regression testing, the policy of the team is to run all test suits during nightly trials. The automation framework is common for the whole platform.

3.3.3 Data Collection

The data was mainly collected through interviews, and it was complemented by the process documentation provided by the companies.

Selection of Participants

Before the actual study, with the help of project contact persons, we conducted two separate workshops at both companies. The purpose was to present our research objectives to the managers and potential participants. We did highlight the required experience and roles of the potential participants. These workshops enabled us to understand the overall hierarchy of the companies, their team structures, and the working procedures. The selection of the participants was based on convenience sampling [30]. Convenience sampling is a non-probability non-random sampling method. We refer our selection as convenience sampling because we selected those participants who were fulfilling our selection criteria of role and experience, and who were willing to participate. A summary of the participants is presented in Table 3.3.

Interview Design

Based on the research questions, we prepared an interview guide consisting of open-ended questions. We did not restrict ourselves to the pre-defined questions, we added/improvised the interview questions during the sessions. The first author developed the interview guide, while the second author helped during the revisions, and an independent researcher reviewed the interview guide. The interview guide consists of seven sections: introduction, background, current practices, selection and prioritization, challenges and improvements, and success criteria. The complete interview guide is presented in A.

Interview Execution

In total, we conducted eleven interviews (five at Axis, and six at Sony) with the representatives of five teams. The first and second author participated in the interviews at Axis, whereas the

first and fourth author participated in the interviews at Sony. The first author guided all the eleven interviews, while the second and fourth authors assisted in their respective sessions. Observer triangulation was utilized during all interviews. Besides the person guiding an additional researcher took the interview notes.

Each interview took about one hour and was audio-recorded with the consent of the participants. During the interview, we complemented our documentation with mind-maps and free text notes. The template of mind-map used for this study is presented in Figure 3.1. The template consists of six nodes, five nodes represent the main topics of our study (i.e., current practices, selection and prioritization criteria, challenges, improvements, and evaluation), whereas one node of the mid-map shows the background information of the participant.

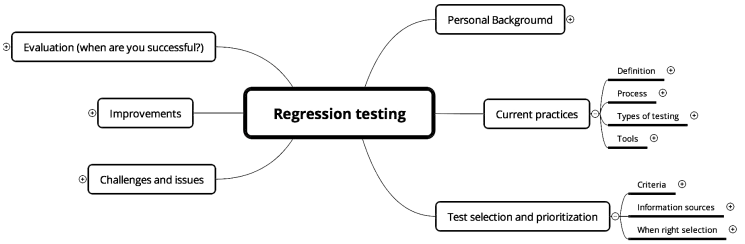

Figure 3.1: Mind-map used for data management and classification.

Process Documentation

The primary source of information for our study was the interviews, to complement our findings we requested both companies to provide us their process documentation under NDA agreement. The documentation was mainly related to test cases, test management tools, test strategy/plan, internal presentations, and training materials. We have undergone the review of these documents in detail and extracted the relevant information. The extracted information complemented some of the practices defined by the practitioners (reuse of existing test cases, when to create new test cases, at which level regression testing is performed in the companies, distribution of manual and automated work, and etc.), selection / prioritization criteria (criteria to select the scope, risks, effected areas, change related measures, and etc.,), organizational goals related to testing, and the success criteria (i.e., when to stop regression testing?). The analysis of process documentation helped us to understand the testing procedures adopted at the companies, and to validate the findings of the interviews further.

3.3.4 Interpreting, Analyzing and Validating Interview Scripts

To minimize misunderstands and misinterpretations, we documented the interviews by three different means: structured mind-maps, free text notes, and audio recordings. The mid-map was

the master document for the recording of interview results. Based on the research questions, we already structured the mind-maps according to the main themes of our study (See Figure 3.1). For the analysis of interview notes and audio transcribed transcripts we followed the steps defined by Cruzes and Dybå [8]. We also took inspiration from the method followed by the Petersen and Wohlin in their study [28].

Step 1: Transcribing the Interview Recordings The first step was to finalize the interview scripts. In this step we transcribed the audio recordings, the first author transcribed all the audio records and the second author randomly verified these transcripts. We did use the free text notes and process documentation as a separate source of raw data.

Step 2: Clustering of Categories The second step was to cluster the raw data into meaningful groups. We used color coding to separate the concepts in the scripts and identified the similarities and differences in the themes of different scripts. For example, the statements were grouped according to the categories, "current practices", "selection and prioritization criteria", "challenges", etc. As an example, we have listed some statements of interviewees in the in Table 3.4. We clustered the raw data separately for each participating team.

Table 3.4: Analysis procedure adopted for step2 and step 3.

SNo	Original Statement	Category	Subcategory	Restructured Statement
1	i) Working very close with our development team, Developers cannot merge any thing with out the approval of testers ii) Decision making approach: Before heavy documents and test plans. Scoped out a lot of overhead, now it is within the project, in collaboration with the developers and with the project manager and QA (decision within the development team).	Practice	Process	Developers and testers collaborate while deciding the scope for the testing of changes and new features.
2	i) If we don't find issues with regression testing, we try exploratory to find something ii) We do some exploratory testing to find new issues.	Practice	Testing type	Use of exploratory testing as an alternative to RT.
3.	i) Usually when we are closer to the freeze of the code deadline we try to make a little bigger scope. ii) We run full scope at the of development, when developers cannot make changes. iii) If there is a change in the core of the product we run the full scope.	Practice	Process	Regression testing is performed with full/bigger scope at code-freeze, before release, or in case of changes in the core of the system.
4.	We tag our test cases like sanity, scope, mandatory, tagged test cases are suppose to be really important test cases.	Practice	Prioritization	Use of priority tags for the test cases with respect to the relevant importance.

Step 3: Clustering of Subcategories In the third step, we assigned the labels (themes) to the statements already clustered in step 2. In this step, beside the labeling process, we also did restructure the statements where it was necessary. Table 3.4 presents the labels along with the restructured statements.

Step 4: Mapping categories and subcategories to mind-maps In this step we mapped the results generated from free text notes and audio generated transcripts to the mind-maps. Resultantly we did the necessary updates in the min-maps.

Step 5: Generation of Results From the final copy of mind-maps we generated Tables (3.5, 3.6, 3.7, 3.8, 3.9, 3.10, 3.11, & 3.12) of results according to the research questions presented in the section 3.3.1.

Step 6: Validation of Results In qualitative studies, the researcher's bias can influence the interpretation of the results. It can be avoided by validating the interpretations from the sources.

As a first validation step, we compared the results with the information extracted from the process documentation. Although the process documentation did not cover the complete results, however, at some extent it provided us confidence about the correctness of the results that we had collected through interviews.

To validate our interpretation of results, we conducted two workshops with the participants of our study and the representatives of the companies at EASE. We used validation sheets to record the issues regarding the interpretation of the results. Feedback of the study participants and companies representatives was positive, they identified a few minor revisions (mainly related to the RT practices), which we adjusted accordingly. Lately, we provided the final results to the companies representatives for the final verification, their response was encouraging, and they did not raise any issue in the final results.

3.4 Threats to Validity

This study is exploratory and based on the experience and perceptions of industry practitioners. The data was collected through semi-structured face-to-face interviews. We asked open-ended questions to capture viewpoints without any restriction. The purpose was to avoid researcher bias and get insight into current industry practices. Furthermore to triangulate the data sources, along with the interviews we also utilized the process documentation provided by the companies. In our discussion of threats to validity, we follow the guidelines by Runeson and Höst [9].

Construct Validity This aspect of validity is regarding the underlying operational measures, concepts, and terms of the study. In our case, the selection of the participants regarding their competence and relatedness to the study area was a potential threat. Similarly, missing any critical aspect from the interview design could also be a threat. To mitigate these, we conducted pre-study workshops, the goal of these workshops was to explain the purpose of the study to

the focal persons in the companies and resultantly to select appropriate participants for the study (Ref: Section 3.3.3). Regarding the interview design, we have carefully designed and reviewed the interview guide (See Section 3.3.3 and A).

Internal Validity This aspect of validity threat is essential if causal relations are examined. Generally, we can state that studying causal relationships was not in the scope of this study. Therefore we did not consider this aspect of validity threat.

External Validity This aspect of the validity refers to the generalization of findings. Participants of this study were representing five different teams of two large companies. The findings of this study represent the communication-based companies working on embedded software systems. To ensure the applicability in a larger population, we have linked our finding with the existing literature. Further analytical generalization of results is possible, to support this we have presented a detail discussion on the cases under study in Section 3.3.

Reliability To ensure the reliability of the results, we assured the correctness of the collected data and interpretation of the results. Sections 3.3.3 and 3.3.4 present the detail in this regard. For each round of interview two authors participated. To triangulate what was said in the interviews we reviewed the process documentation of the participating companies. We did ensure the results triangulation, by involving multiple authors in the results interpretations, and we did validate the results in two workshops with the participants of the study.

3.5 Results and Discussion

This section presents the results regarding the practitioners' perspectives on regression testing, test case selection and prioritization criteria, challenges, improvements, and success criteria. The subsections are organized according to the research questions presented in Section 3.3.

3.5.1 The practitioners' Perceptions of Regression Testing (RQ1)

The purpose of our first research question was to elicit what participants think about regression testing. Our first interview question was *"What is regression testing for you?"*. Instead of standard definitions of regression testing [6, 7], our participants provided practical descriptions of regression testing with close relations to the perspectives (teams) they were representing.

From Table 3.5, we can see that the practitioners covered three aspect while defining regression testing: 1) The timing or frequency of regression testing, 2) the scope of regression testing, and 3) the overall goal of regression testing. Regarding timing, the participants define the need for regression testing after changes or fixes, before release, whereas some participants suggest running regression testing continuously. About the scope of RT, the practitioners are flexible, some of the participants describe running RT with smaller scope, whereas some prefer to adopt a "re-test all" policy. Finally, the participants are agree on the goal of RT, (i.e. to get confidence

Table 3.5: The practitioners' definitions of regression testing, as response to interview question "What is regression testing for you?".

CID[1]	PID[2]	RT Definition
SWSE	P1.	To verify that introduced **changes/fixes** have not changed the behavior of the system in a negative way.
	P2.	Small sanity check on the **changing part of system**, try to figure out nothing has broken.
	P3.	Run selected test cases **continuously**, to check If something has broken or if everything has broken.
FCS	P4.	For **every release**, along with the testing of the new features, it is much important to make sure that old functionality is intact.
	P5.	To make it sure that everything still works, need to run a regression test for **every new fix** from developers. It could differ concerning what are the changes.
	P6.	It is a validation that primary use cases are working, regression testing is a hygiene thing to make sure that any basic functionalists have not broken. It is not expected to find much during regression testing.
FWWD	P7.	To test what happened with other products, did **changes** destroy other products?
	P8.	Regression testing is a **constant qualifier**, and it is a process to test over and over.
	P9.	To make sure that there is no regression, no degrades. Regression testing is **input to release**.
PTS	P10.	Regression testing is to verify that the functionality that was working previously, still works correctly or something has broken that was not expected while **making changes**.
	P11.	To verify that during **changes or adding new features** the overall quality of the functionality, performance of the database has not decreased.

[1] Company/team ID according to Table 3.3.
[2] Participant ID according to Table 3.3.

about the integrity of the system after changes, fixes or before the release). Difference in the initiation timing of RT and scope does not means that teams / companies are perceiving RT differently. In fact this represent that on which development level a team is employing the RT and how often they are making changes or adding new features to the releases.

We thus synthesized the views of all participants from both the companies and finalized the following definition:

> *Regression testing is a repetitive activity which is applied to ensure that changes/fixes/upgrades did not affect the behavior of the system/product/product-line negatively and nothing was broken or destroyed in the functionality of the system/product/product line.*

3.5.2 Regression Testing Practices (RQ2)

The objective of second research question was to understand how the practitioners conduct regression testing in their projects. Table 3.6 summarize regression testing practices identified in our study.

Table 3.6: Regression testing practices.

ID	Description of practice	SWSE	FCS	FWD	FWR	PTS	CPL [1]
Pr1.	*Collaboration*: Developers and testers collaborate while deciding the scope for the testing of changes and new features.	✓	✓	✓	✓	✓	
Pr2.	*Execution frequency*: The frequency of executing tests depends upon the type/importance of the functionality.	✓					
Pr3.	*Execution frequency*: Testing as much as possible with selected test cases near the completion of the project.					✓	LPR6
Pr4.	*Reuse of test cases*: Using existing test cases for the testing of changes.	✓			✓		
Pr5.	*Adding new test cases*: New test cases are added for new features and issue leakage.	✓	✓				
Pr6.	*Running full scope*: Regression testing is performed with full/bigger scope at code freeze, before release, or in case of changes in the core of the system.	✓	✓		✓	✓	LPr2
Pr8.	*Nightly testing*: RT is executed with full scope in nightly runs.			✓		✓	LPr2
Pr7.	*Day time testing*: Select a scope that should run (fast) in a day time and cover bigger part.	✓		✓		✓	
Pr9.	*Weekly round or RT*: Run a weekly round of RT with a smaller scope.	✓					
Pr10.	*Scope Selection*: Mostly run RT with selected scope because of time constraint.		✓				
Pr11.	*Running fix suite*: Using fix set of test cases (that cover the core/basic functionality) for RT.	✓					LPr3
Pr12.	*RT Automation*: The companies are using both manual and automated RT.	✓	✓	✓			
Pr13.	*Testing tools*: For test automation using third party tools.	✓					
Pr14.	*Testing tools*: For test automation using in-house developed tool.		✓	✓	✓	✓	LPR5
Pr15.	*RT suite size*: Regression test suites are fairly large.	✓	✓				
Pr16.	*Exploratory testing*: Use of exploratory testing to complement RT.	✓	✓		✓	✓	
Pr17.	*Test strategy*: For every new project a detailed test strategy / plan is developed.	✓	✓	✓		✓	
Pr18.	*Priority tags*: Using tags with test cases to determine the priority.		✓				
Pr20.	*Traceability labels*: Use of test case labels to link with respective modules.					✓	
Pr19.	*Tickets*: Use of tickets for highlighting the issues, it helps to identify the type and nature of the error.				✓		
Pr21.	*When to introduce RT*: Sometime early start of regression testing is preferred to catch defects at early stages.	✓				✓	LPr7
P22.	*RT level*: Applying RT at System level.	✓		✓		✓	
P23.	*RT level*: Applying RT at Component level.		✓				
Pr24.	*RT goal*: The goal of regression testing is to have confidence that product is in good shape.			✓	✓		

CPL: Corresponding practice(s) in literature.

From Table 3.6, it is evident that the practitioners do collaborate with each other while making any decision regarding RT. The companies are using a mix of automated and manual RT, at Sony the practitioners specified that almost 50% of their testing activity is automated, whereas participants from Axis claimed that majority of the RT is automated. For test automation the companies are using in-house build test tools, except one team who is currently using a third party tool. At Axis all three teams are using the same test automation and management tool. The scope of RT depends on change/fix and time-line of the project. For changes, testers prefer to run the smaller scope (selected test cases), in case of complex changes (e.g., in the core) they try to opt for a wider scope. Near the completion of project (code freeze or near the release) the practitioners favor the execution of RT with full scope (re-test all). The practitioners at Axis also highlighted that during day time they run selected test cases and during nightly testing they prefer to run full scope. The participants from SWSE (Sony) highlighted that they run weekly rounds of RT with selected scope, whereas FCS (Sony) adopt the selection of scope because of time constraints.

The practitioners reuse of existing test cases as regression test suite, they do augment new test cases in the existing test suites in case of adding of new functionality or any issue leakage. The practitioners label the test cases with "test tags" and/or "test case labels" according to the respective importance and/or modules. The use of labels conceptually differs in both the companies, at Sony labels are used to highlight the relative priority of the test case, and at Axis labels are used to link the test cases with respective modules. Regarding test strategy or test planning, two teams SWSE (Sony) and PTS (Axis) highlighted this aspect, both teams claimed it a company wide activity. At Sony, a high level test strategy exists that serves the basis for the design of detailed test strategy. For every new project test architect design the detailed strategy, it includes the details about the modules to test, scope of testing, test cases, and etc. At (Axis), there exists an organization wide test plan. Preparing and updating the project specific test plan and test scripts is the responsibility of the QA team. Some of the practices identified in our study are already defined in the existing literature (See table 3.2), we have created the mapping of literature identified practices in the last column of Table 3.6. Considering the results of a survey-based study conducted by Dias-Neto et al. [11] in which authors surveyed the overall software testing practices we can conclude that practices identified in our study are purely regression testing related. As opposed to the survey conducted by Engström and Runeson [16] where authors specified that the practices identified in their survey are general testing practices.

Test Case Selection and Prioritization (RQ2.1)

An important aspect of regression testing practices is test case selection and prioritization, which we investigated in RQ2.1. A summary of selection and prioritization criteria along with the information sources used for decision making can be found in Tables 3.7 and 3.8, respectively, we did map the information sources with the selection/prioritization criteria in Table 3.7 under the column heading "UIS". The last column "CCrL" in Table 3.7 lists the selection/prioritization criteria available in the literature (Literature findings are listed in Table 3.2).

The primary criteria for test selection and prioritization for regression test suite is the

Table 3.7: Test selection and prioritization criteria.

ID[1]	Criteria	SWSE	FCS	FWD	FWR	PTS	UIS[2]	CCrL[3]
SPCr1.	Change (size, complexity,and location).	✓	✓	✓		✓	IS1, IS2, IS7	LPc1, LPc5
PCr2.	Risk.	✓			✓	✓	IS2, IS4	
PCr3.	Critical functionality.	✓	✓				IS1, IS2, IS3, IS7	LPc4
PCr4.	Defect priorities.				✓		IS6	
SCr5.	Situation based scope assessment.		✓				IS2, IS7	LSc5
SCr6.	Coverage(feature/module).			✓		✓	IS2, IS5	
SCr7.	Affected areas.			✓		✓	IS1, IS2	LSc6
SCr8.	Deadlines.	✓	✓		✓		IS8	
SCr9.	Least recently used test cases.	✓					IS2, IS5	
SCr9.	Most frequently failed test cases.			✓			IS2, IS5	

[1] SPCr: Selection/Prioritization Criteria, PCr:Prioritization Criteria, SCr: Selection Criteria
[2] UIS: Utilized Information Sources.
[3] CCrL: Corresponding Criteria in Literature

Table 3.8: Information sources utilized for test selection and prioritization.

ID	Information sources	SWSE	FCS	FWD	FWR	PTS
IS1.	Developers' feedback.	✓	✓	✓	✓	
IS2.	Experience and Knowledge of system.	✓	✓	✓		✓
IS3.	Issue ranking.	✓				
IS4.	Team meetings.	✓		✓		✓
IS5.	Test history.	✓				
IS6.	Test tags.		✓			
IS7.	Feature to test traceability.			✓		✓
IS8.	Project managers.	✓	✓		✓	

'change'. The practitioners assess the size, complexity, and location (area) of change. The participants from all the teams highlighted this criterion. Feedback from developers, and experience and knowledge of the practitioner about the system are the information sources used to assess the change. Experience and knowledge of system and feedback from developers are the primary sources of information for majority selection/prioritization criteria. For instance, scope

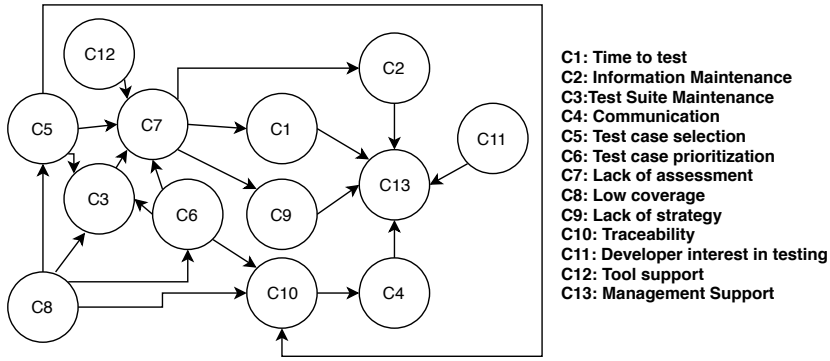

Figure 3.2: Relationship between RT challenges.

assessment, fix regression test suite, critical functionality, and coverage are the criteria where the practitioners are using their experience to access these criteria.

Other relevant criteria that are used for the test selection or prioritization are risk, deadlines, and critical functionality. Three out of five teams are using these criteria. Measurement of risk is based on change (area and complexity of change), the practitioners are sometimes using issue ranking to prioritize the risk. Knowledge of the practitioner about risk areas is another source of information for risk measurement. Deadlines are central concerning the scope selection. If the project is on schedule and deadlines are relaxed then testers prefer to run full scope (complete test suite) for regression testing. If deadlines are tight (often, it is the case), then the practitioners opt for an adaptive (selected) scope. In this case, they do prioritize the test cases on the basis of the critical (essential) functionality. The selected scope consists of the test cases that cover the critical functionality and the primary use cases (basic functionality). The companies are using a predefined test suite that covers the primary use cases (basic functionality). They update this suite (add new test case) in case developers add new functionality (features) or if they think that something (test case) is missing.

Some selection criteria are team specific. For instance, SWSE team select the test cases that have not been executed recently (least recently used test cases), they do choose the test cases concerning the date of use. The testers at FWD team are using most recently failed test cases and most frequently failed test cases during the selection process.

Key Challenges in Regression Testing (RQ2.2)

Table 3.9 summarizes the regression testing challenges reported by the practitioners.

The identified challenges can be classified into two categories, 1) management related challenges, and 2) technical challenges. Management related challenges include “C1: Time to test”,

Table 3.9: Regression testing challenges.

ID	Challenge	SWSE	FCS	FWD	FWR	PTS	CCL[1]
C1	*Time to test*: Too much testing in a short time. Lack of time is the primary hindrance for the assessments and innovation of RT.	✓	✓	✓		✓	LC11
C2	*Information management*: Because of poor information maintenance and lack of documentation it is hard to extract the required information.	✓	✓	✓	✓		LC8
C3	*Obsolete test cases*:There are tests which are not failing for a long time, a big challenge as it effect the efficiency and effectiveness.	✓	✓	✓		✓	LC9
C4	*Communication*:Lack of information about the changes and upcoming plans from the other teams.	✓	✓	✓	✓		
C5	*Test case selection*: Instead of the dynamic test scope focus is on fixed test suites. Adding value to the scope by selecting relevant test cases is a challenge.	✓	✓	✓	✓	✓	
C6.	*Test case prioritization*: Inappropriate assumptions about the priorities and what to select.		✓	✓		✓	LC3
C7	*Evaluating and improving*: Lessons learned on a project are often broad in nature, not possible to reflect on the success. Time to test is one the factors that limits the option of evaluations and improvements.	✓	✓	✓		✓	LC10
C8	*Low coverage*: Detection of new bugs is a challenge this is because of, running the same test cases for a long time that is causing the low test coverage.	✓	✓	✓			
C9	*Lack of strategy*: Focus is on project success instead of organizational success, no long-term strategy.		✓	✓			
C10	*Traceability*: Finding trace-links between tests and other artifacts is a challenge.	✓		✓			
C11	*Developers interest in testing*: Developers' least interest in quality, delivering their code without testing.	✓					
C12	*Tool support*: The testers have to go through excessive manual work in RT because of the unavailability of good verification tools.	✓					LC13
C13	*Management support*: Lack of understanding about the importance of verification.		✓				LC15

[1] CCL: Corresponding challenges in literature

"C2: Information management", "C4: Communication", "C9: Lack of strategy", "C11: Developers interest in testing", and "C13: Management support". Whereas technical challenges are "C3: Obsolete test cases (Test suite maintenance)", "C5: Test case selection", "C6: Test case prioritization", "C7: Evaluating and improving (Lack of assessment)", "C8: Low coverage", "C10: Traceability", and "C12: Tool support". Figure 3.2 presents the relationship between the identified challenges, from the figure we can see that the central challenge is C13 (i.e., Management support) and it could cause all other related problems. Time to test (C1), information

management (C2), and lack of strategy (C9) are the root cause of technical challenges. Among the technical challenges C7 (i.e., Lack of assessment) is the basis of other technical challenges including C3, C5, C6, C8, & C12). Similarly, C10 (i.e., traceability) can effect the C5 (selection) and C6 (prioritization). Finally C3, C5, C6, & C10 cause the low coverage (C8).

In the last column of Table 3.9 we mapped the challenges identified from the literature (See Table 3.2) with the challenges identified in our study. Seven challenges (C1, C2, C3, C6, C7, C12, & C13) identified in our study are similar to the challenges identified in the studies [16, 25, 29]. Interesting aspect is that first study by Engström and Runeson [16] was conducted in 2010 and the other study by Harrold and orso [25] was carried out in 2008. Despite the voluminousness research on regression testing [24], it is evident that the challenges are not fully addressed after 10 years. It is an indicator that either published research is not fulfilling the industrial needs or the industrial stakeholders are unable to exploit the intended benefits from the available research. Along with the identification of challenges with the help of practitioners, it is also important to work on improvements in a close collaboration with the practitioners.

3.5.3 Suggested Improvements for Regression Testing (RQ3)

In RQ3, we investigated improvements that the practitioners seek in their testing environment. Table 3.10 summarize the possible improvements we identified with the help of the practitioners.

A majority of identified improvements correspond to the challenges presented in Table 3.9. Last column (CC) of Table 3.10 list the challenges that could be addressed by the respective improvements. There is often a one-to-one mapping between the challenges and the suggested improvements. For instance, C2 (information management) is identified as a challenge in both the companies, the practitioners even who did not recognize it as challenge agree to build and maintain a standard information repository (I-1). Similarly, C3 (test suite maintenance) is highlighted as a challenge. To address the issue, the practitioners suggest to work on the elimination of irrelevant and obsolete test cases (I-2: Test suite minimization) and updating test suites by adding new relevant test cases (I-3: Test suite augmentation). Working on test suite minimization will also be helpful for reduction of testing time, that ultimately will be helpful to cope with the challenge of time to test (C1). Another important suggestion that can be helpful for the reduction in time to test is to introduction of parallelized testing (I-12). Overall test optimization (I-14) will also improve the situation.

Availability of good verification tools (C12) is an issue of concern for the companies, because of this fact testers have to do a lot of manual work in RT. In this regard, it is suggested to identify and adopt the verification tools (I-4) appropriate for the companies environment. To cope with the challenge of communication (C4), the practitioners think that there is a need to work for the improved collaboration (I-5). Although, the practitioners (developers and testers) do have a certain level of communication, but there is no formal mechanism for the communication. Specifically, with reference to information sharing regarding changes and change plan. In the presence of well maintained information repository this issue should be minimized. Test case selection and test case prioritization are of central importance in regression testing, especially for the large-scale development. Because right selection with appropriate priority order can improve

Table 3.10: Identified Improvements.

ID	Improvements	SWSE	FCS	FWD	FWR	PTS	CC[1]
I-1.	*Information repository*: Need to build and maintain a standard information repository, to make information extraction easier and faster.	✓	✓	✓	✓		C2
I-2.	*Removing irrelevant test cases*: Need to identify and remove irrelevant/obsolete test cases, to reduce the test cost and improve the efficiency and effectiveness.	✓		✓	✓	✓	C1, C3
I-3.	*Test suite augmentation*: Need to update test suites by adding new relevant test cases, to improve the coverage and effectiveness.	✓					C3
I-4.	*Good verification tools*: Need to identify and add good verification tools, to reduce the dependence on manual testing.	✓	✓				C12
I-5.	*Improved collaboration*: There is a need to regulate the collaboration mechanism between developers and tester, to improve the information sharing (What developers are changing? and what testers have to test?)	✓	✓	✓		✓	C4
I-6.	*More exploratory testing*: To find new bugs, need to do more exploratory testing.	✓	✓				C8
I-7.	*Evaluate*: To measure success and improve RT, need to collect test execution statistics and evaluate.		✓	✓		✓	C7
I-8.	*Improved test strategy*: Need to improve the testing strategy and innovate testing methods.		✓				C9
I-9.	*Test History*: Need to maintain test execution history dynamically, so that it could be reused to innovate testing.		✓			✓	C5, C6
I-10.	*Early start of regression testing*: To ensure the stability, need to introduce early start of regression testing.				✓		C1
I-11.	*Test case classification*: To classify test cases according to severity, need to introduce a standard template for error reporting, that should allow linking tests to errors.				✓		C6, C10
I-12.	*Parallelized testing*:To cope with the time constraints, need to introduce the concept of parallelized testing.					✓	C1
I-13.	*Selective RT*: Need to improve the selection mechanism of test cases, selection should be without any compromise.					✓	C5
I-14.	*Test optimization*: To shorten the release cycle, need to work on overall optimization of RT.				✓		C1, C3, C5, C6

[1] CC: Corresponding challenge(s).

the coverage and defect detection rate. The companies lack in both areas (C5: Test case selection and C6: Test case prioritization). From the identified improvement (I-7, I-8) provides the basis for the improvement in selection and prioritization methods. Exploratory testing (I-6) could be an immediate solution choice for the practitioners.

3.5.4 Goals and Criteria for Successful Regression Testing (RQ4)

In response to our question "How do you evaluate the success in regression testing?" the majority of the participants responded that we don't use any metrics to measure the success, and we do the subjective measurement. Subsequently, we did change our question, "If you have to evaluate the success, which would be your success goals?" Tables 3.11 and 3.12 summarize goals and criteria regarding the success of regression testing. The success criteria refer to the conditions that are essential to achieving the regression testing goals.

Table 3.11: Regression testing Success goals.

ID	Goal	SWSE	FCS	FWD	FWR	PTS	CSC[1]	CGL[2]
SG1.	*Customer satisfaction*: The released product is working and the customer is not complaining.	✓	✓				SC6	
SG2.	*Critical defect detection*: RT is regarded as successful if it can find the critical bugs (no critical bugs should be delivered to the customer).	✓	✓	✓	✓	✓	SC1, SC2, SC3, SC7	LG4
SG3.	*Confidence*: The tester should be confident about the achieved quality.	✓	✓		✓	✓	All SCs	LG3
SG4.	*Effectiveness*: In term of fault detection, the goal is to find as many bugs as it is possible.	✓	✓	✓	✓	✓	SC1, SC2, SC3, SC5, SC7	LG1
SG5.	*Controlled fault slip-through*: How many issues have slipped to the customer is important, it provide a measure to success. The goal is to keep fault-slip through as low as possible.	✓	✓	✓			SC1, SC2	LG6
SG6.	*Efficiency*:Running the planned scope for RT in a limited time.	✓	✓	✓	✓	✓	SC1, SC2, SC3	LG7

[1] CSC: Corresponding Success Criteria.
[2] CGL: Corresponding goals in the literature

We identified six regression testing goals along with the seven success criteria. From Table 3.11 it is evident that the goals "Critical defect detection", "Confidence", "Effectiveness", and "Efficiency" are highlighted by the majority of the participating teams. Regarding success criteria, mainly there were defined by three teams, one team defined only one success criterion, and one team did not did not discuss any success criteria. In Table 3.11, we mapped the success criteria with the respective goals, we did map all criteria with the goal "confidence". Infect confidence is a subjective term, and we cannot measure the confidence, a tester could be confident about his testing results based on the experience and knowledge. However, to have confidence in regression testing, testers have to achieve other success goals. We identified RT goals from the previous studies [10, 31], these goals are listed in Table 3.2. The goals identified from litterateur are mapped to the goals identified in this study (see last column in Table 3.11)

Despite the fact mentioned earlier regarding the initial response of practitioners on the as-

Table 3.12: Regression testing Success criteria.

ID	Criteria	SWSE	FCS	FWD	FWR	PTS
SC1.	*Right selection*: Based on requirements selecting and defining the right test cases. Selection of appropriate test cases is the key for successful RT.	✓	✓	✓		
SC2.	*Knowledge of changes*: For successful regression testing, QA should be well aware of changes in the system.	✓		✓		
SC3.	*Early start of RT*:The success criteria in RT is to start of RT as early as possible.			✓		
SC4.	*Coverage*: Coverage is one the criteria to evaluate the success.	✓	✓	✓		
SC5.	*Tester's Experience*: Knowledge and experience of tester is the subjective measure of confidence in RT.	✓	✓			
SC6.	*Customer's feedback*: The customer feedback is the measure of confidence in the software testing.	✓	✓			
SC7.	*Quality of test cases*: Carefully designed test cases can guarantee the finding issues and good coverage.	✓	✓			✓

sessment of success, the results are encouraging. The practitioners are aware of the importance of success, and they know how to measure the success. Presently, they are not making any objective assessments because of environment support, availability of resources, and an appropriate mechanism for the assessment.

3.6 Summary and Conclusions

We have conducted an interview-based study in two large communication companies and investigated various aspects of regression testing in practice. In the following, we summarize our findings regarding each research question.

The definition of RT that emerged from the practitioners **(RQ1)** (see Section 3.5.1) is in line with the standard definition presented in ISO, IEEE, system and software engineering vocabulary [7]. The goal of regression testing is to get confidence that the system changes have not introduced unwanted system behavior rather than to find errors. The scope of regression testing depends on the timing in the projects (e.g.small fix or a major release) and risk analysis for incoming changes. This study confirms our previous viewpoints [10] and Engström et al. [16].

Looking at the regression testing practices **(RQ2)**, our respondents are using manual and automated regression testing, there is a lot of manual work that practitioners have to do. For test automation mainly the companies are relying on in-house developed tools. Inability to find a third party tool is an interesting findings that points towards specific testing requirements or processes that can not be captured by a general regression testing tool support. Another possible explanation is that our respondents prefer to change the tools rather than wait for tool vendors to provide the necessary adaptations. This allows for faster and better alignment between the testing process, testing strategy and the tool support. Test strategy definition seems to be an ad

hoc practice among our respondent which confirms the need for in-house and flexible tooling.

The testers and developers collaborate in the decision making regarding various aspects of RT. Only SWSE and FWR respondents confirmed to reuse test cases. This may explain who exploratory testing is used as a replacement for regression testing when they fail to find issues with fixed regression suites. Greater test reuse seems to be hindered by a lack of traceability labels (mentioned by one group) or tickets (also mentioned by one group), see Table 6 for details.

The scope and time of change drive regression testing activities. Our practitioners mostly run a static regression testing scope that cover the basic/core functionality of the respective systems. Size, position and complexity of change drive test case selection, supported by domain knowledge and experience and dialog with developers. When pressed by short deadlines, our practitioners limit the scope of regression testing. The selection/prioritization criteria identified in our study is closely related to the selection/prioritization criteria available in the related studies [16, 24, 25].

Looking at the 12 identified challenges (RQ2.2), information management, test suite maintenance, communication, test case selection, and test case prioritization are common to both the companies. We identified fourteen challenges from the related studies [16, 25]. There are six challenges identified in our study are also available in the related work (See Table 3.9). Interestingly, communication is frequently mentioned by traceability is mentioned only by one group. This may mean that our respondents underestimate the role of traceability mechanisms in enriching and supporting communication between the roles involved in regression testing. Similarly, traceability could be supporting test suite maintenance mentioned by almost all respondents involved. We believe that more research should be directed towards understanding the relations between the challenges and how the solutions can mitigate them.

We identified two improvement categories for regression testing practices **(RQ3)**: 1) Improvements related to the management affairs, 2) improvements related to technical interventions, these improvements are related to test case selection, test case prioritization, test suite minimization, test suite augmentation, and assessment of regression testing. Yoo and Harman [24] presented a literature survey of 159 papers on test case selection, minimization and prioritization techniques, it includes a large number of techniques proposed in these three areas. Despite the lot of work in these areas, the practitioners still think that there is a need for improvement. Which indicates either the techniques proposed in the literature are not fulfilling the requirements of industry or the practitioners are not aware of these techniques. Surprisingly, our respondent pointed good verification tools as a necessary improvement despite developing in-house and heavily tailored solutions themselves. Another interesting aspect is the identification of irrelevant or obsolete test cases that appears to be a similar challenge that the identification of obsolete software requirements surveyed by Wnuk et al. where over 80% of the respondents confirmed negative influence of obsolescence on their processes [2].

The success goals identified in our study are, customer satisfaction, critical defect detection, confidence, effectivenss, controlled fault slip-through, and efficiency **(RQ4)**. Our study also reveals some preconditions which can guarantee the success of RT. For instance, right selection of test cases, and knowing the changes are the conditions that are essential for the success of RT. Regarding goals findings of this study complement the findings of previous studies [10,

31]. Similarity in the success goals identified in two different studies indicate that there is an awareness and urge in the industry regarding evaluating the success of regression testing.

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Appendix A

Interview Guide

Introduction

Personal introduction Interviewers tell the participant about themselves, their background and training, and interest in the area of software testing.

Study goal The lead interviewer explains the study goal to the participant.

Goal: The goal of the study is to know the state of regression testing practice in the large-scale embedded software development. The purpose is to know that how companies are managing their test systems, specially with reference to regression testing. The following points are the focus of the interview.

- Current Practices ,
- Test Selection and prioritization,
- Challenges and issues,
- Improvements, and
- Evaluation of success goals.

Benefit: This study will provide the basis for improving the different aspects of regression testing considering the different views of people within the organization. We believe your opinion is valuable. This investigation gives you (interviewee) a chance to contribute to the improvement of the regression testing environment.

Interview process Interviewer describes the overall process, that how the interview will take place.

- *Interview duration:* The interview will be completed in about an hour time.

◦ *Interview questions:* there may be some questions that the interviewee perceives as stupid, silly, or difficult to answer. It is possible that an appropriate question for one person may not be suitable for the other.

◦ *Counter questions:* The interviewee may feel free to ask counter questions for the clarification of an interview question and can disagree with any statement of the interviewer.

◦ *Answers:* We believe that in an interview, we can not rate any answer as right or wrong. The interviewee need not worry about in this regard, and we expect he/she will answer the questions on the basis of knowledge and experience.

Respondent Background

The purpose of this section is to know about the participant's professional background, current role and responsibilities.
Question 1: Could you please briefly describe on your professional background?
- ◦ Your qualification,
- ◦ Overall Experience,
- ◦ Time in the current company.

Question 2: How you will define your expertise?
- ◦ Software Engineering,
- ◦ Software Development,
- ◦ Software testing.

Question 3: Please specify about your current job.
- ◦ Your current team,
- ◦ Your role in the team.

Question 4: Can you please brief us about your current project(s).

Interview Part to explore the RT state of practice

This is the central part of this interview, and we are interested to know about the current practice, selection and prioritization criteria, challenges, and improvements regarding regression testing. In the final part of the interview, we will discuss the regression testing success goals. We will start by asking our questions regarding current practices. Please feel free to add detail at any point of the interview that you think we missed to ask or you forget to describe.

Defining regression testing The purpose is not to get the academic definition of regression testing. The interviewers are interested to know the perception of the practitioner.
Question 1: What is regression testing for you?

Questions regarding current practices The aim is to know how practitioner's team is performing regression testing.
Question 1: Can you please give us a walk-through of overall process and highlight where and how often regression testing is performed?

Question 2: Have you been involved in decision making regarding (When to do regression testing? Which test cases should be executed? How to select a subset of candidate test cases?)?
Question 3: In your team regression testing is manual or automated?
Question 4: For automation which tools are in use of your company / team?
Question 5: Decision are taken by the individuals or by the QA team? (Who are the people involved in decision making?)

Selection and prioritization Although, selection and prioritization are regarding as the part of practice. Considering the importance of selection and prioritization, we are asking focused questions.
Question 1: Do you use some predefined criteria for the selection and / or prioritization of test cases?
Question 2: Which information you use while making decisions for selection and/or prioritization?
Question 3: Do you or your team maintain the required information? Is this information readily available?
Question 4: When have you made the right selection of test cases?
Question 5: How do you evaluate / know whether the selection was right?

Challenges and Improvements Challenges are the obstacles that can hinder the smooth and successful execution of the operations. Like other working environments, practitioners working in software development organizations are facing different issues. Our interest is to know those issues which are recurring and require attention.
Question 1: What are the challenges for testers regarding regression testing?
Question 2: Do you have any mitigation strategies to overcome these challenges?
Question 3: What are the challenges, you think need to pay more attention?
Question 4: Considering the underlying challenges, can you identify the areas of improvement?

Success Criteria To determine the success of any activity, we measure it with the predefined goals, that is, if the goals have met or not.
Question 1: What is your criteria of success of regression testing? Do you measure the success?
Question 2: At your company / team do you define success goals?
Question 3: For a successful regression testing what are the goals that should be achieved?
Question 4: How will you determine that the desired goals have been achieved?

Closing Questions We mentioned earlier that the goal of this research is to identify potential problems and come up with suggested solutions. Your opinion counts!
Question 1: In your opinion which is the most important area that should have to be the focus of this research?

Question 2: Do you want to share some more information which you think is important to consider, that we may have missed?

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Chapter 4

On the search for industry-relevant regression testing research

4.1 Introduction

Regression testing remains an unsolved and increasingly significant challenge in industrial software development. As a major step towards quality assurance, regression testing poses an important challenge for the seamless evolution (e.g., continuous integration and delivery) of large-scale software. Similarly, dealing with variability (e.g., in software product lines/product variants) makes regression testing of industrial software a non-trivial matter. Testing is highly repetitive at all levels and stages of the development, and for large and complex systems precision in regression test scoping becomes crucial.

These challenges have led to a large body of academic research. There is even a multitude of systematic literature reviews classifying and analysing the various proposed techniques for regression testing. For example, there are eleven literature reviews on regression testing published since 2010 ([16, 17, 36, 39, 43, 54, 66, 70, 72, 78, 79]).

Despite this extensive body of research literature, research results have shown to be hard to adopt for the practitioners ([5–8, 74, 76]). First of all, some results are not accessible for practitioners due to the discrepancies in terminology between industry and academia, which in turn makes it hard to know what to search for in the research literature. Furthermore, many empirical investigations are done in controlled experimental settings that have little in common with the complexity of an industrial setting. Hence, for practitioners, the relevance of such results is hard to assess. [74] surveyed regression testing practices, which highlighted the variation in

regression testing contexts and the need for holistic industrial evaluations.

There are today a significant number of industrial evaluations of regression testing. Unfortunately, also these results are hard to assess for the practitioners, since there are no conceptual models verified by practitioners to interpret, compare, and contrast different regression testing techniques. [8] conducted an in-depth case study on the procedures undertaken at a large software company to search for a relevant regression testing technique and to evaluate the benefits of introducing it into the testing process at the company. This study further emphasises the need for support in matching the communication of empirical evidence in regression testing with guidelines for identifying context constraints and desired effects that are present in practice.

To respond to this need, in this paper, we review the literature from a relevance and applicability perspective. Using the existing literature reviews as a seed set for snowball sampling [20], we identified 1068 papers on regression testing, which are potentially relevant for our study. To gain as many insights as possible about relevance and applicability we have focused the review on large-scale industrial evaluations of regression testing techniques, as these studies in many cases involve stakeholders and are more likely to report these issues.

Both relevance and applicability are relative to a context, and we are not striving to find a general definition of the concepts. In our study, we are extracting factors that may support a practitioner (or researcher) in assessing relevance and applicability in their specific cases. We define relevance as a combination of desired (or measured) effects and addressed context factors and include every such factor that have been reported in the included studies. Similarly, applicability, or the cost of adopting a technique, may be assessed by considering the information sources and entities utilised for selecting and/or prioritising regression tests. For each of these facets, we provide a taxonomy to support classification and comparison of techniques with respect to industrial relevance and applicability of regression testing techniques.

The original research questions stem from an industry-academia collaboration[1] (involving three companies and two universities) on decision support for software testing. Guided by the SERP-test taxonomy [75], a taxonomy for matching industrial challenges with research results in software testing, we elicited nine important and challenging decision types for testers, of which three are instances of the regression testing challenge as summarised by [17]: regression test minimisation, selection, and prioritisation. These challenge descriptions (i.e., the generic problem formulations enriched with our collaborators' context and target descriptions) guided our design of the study.

To balance the academic view on the regression testing literature, we consulted practitioners in all stages of the systematic review (i.e., defining the research questions, inclusion and exclusion criteria, as well as the taxonomies for mapping selected papers).

The main contributions provided in this report are:

- three taxonomies designed to support the communication of regression testing research with respect to industrial relevance and applicability, and

[1] EASE- the Industrial Excellence Centre for Embedded Applications Software Engineering `http://ease.cs.lth.se/about/`

- a mapping of 26 industrially evaluated regression testing techniques (in total 38 different papers) to the above-mentioned taxonomies.

The remainder of the paper is structured as follows: Section 4.2 summarises previous research on assessing the industrial relevance of research. It also presents an overview of existing systematic literature reviews on regression testing. Research questions raised in this study are presented in Section 4.3. Section 4.4 and Section 4.5 detail the research approach used in the study and its limitations, respectively. Sections 4.6 to 4.8 present the results of this research. Section 4.9 and Section 4.10 present advice for practitioners and academics working in the area of regression testing. Section 4.11 concludes the paper.

4.2 Related work

In this section, we briefly describe related work that attempts to evaluate the relevance of software engineering research for practice. We also discuss existing reviews on regression testing with a particular focusing on the evaluation of the industrial relevance of proposed techniques.

4.2.1 Evaluation of the industry relevance of research

Software engineering being an applied research area continues to strive to establish the industrial practice on scientific foundations. Along with the scientific rigour and academic impact, several researchers have attempted to assess the relevance and likely impact of research on practice.

[62] proposed a method to assess the industrial relevance of empirical studies included in a systematic literature review. The criteria for judging relevance in thier proposal evaluates the realism in empirical evaluations on four aspects: 1) subjects (e.g. a study involving industrial practitioners), 2) context (e.g. a study done in an industrial settings), 3) scale (e.g. evaluation was done on a realistic size artifacts) and 4) research method (e.g. use of case study research). Several systematic reviews have used this approach to assess the applicability of research proposals in industrial settings (e.g. [1, 85]).

Other researchers have taken a different approach and have elicited the practitioners' opinion directly on individual studies ([59–61]). In these studies, the practitioners were presented a summary of the articles and were asked to rate the relevance of a study for them on a Likert scale.

The *Impact project* was one such initiative aimed to document the impact of software engineering research on practice [46]. Publications attributed to this project, with voluntary participation from eminent researchers, covered topics like configuration management, inspections and reviews, programming languages and middle-ware technology. The approach used in the project was to start from a technology that is established in practice and trace its roots, if possible, to research [46]. However, the last publications indexed on the project page[2] are from 2008.

[2] https://www.sigsoft.org/impact.html

One of the lessons learned from studies in this project is that the organisations wanting to replicate the success of other companies should *"mimic successful companies' transfer guidelines"* ([40, 46]). Along those lines, the study presently read attempts to identify regression testing techniques with indications of value and applicability from industrial evaluations [57].

To address the lack of relevance, close industry-academia collaboration is encouraged ([19, 46, 57]). One challenge in this regard is to make research more accessible to practitioners by reducing the communication-gap between industry and academia [75]. SERP-test [75] is a taxonomy designed to support industry academia communication by guiding interpretation of research results from a problem perspective.

4.2.2 Reviews of regression testing research

We identified eleven reviews of software regression testing literature ([16, 17, 36, 39, 43, 54, 66, 70, 72, 78, 79]). Most of these reviews cover regression testing literature regardless of the application domain and techniques used. However, the following four surveys have a narrow scope: [43] and [16] target testing web-based applications, and [70] focus on identifying security-related issues, while [79] only considers literature where researchers have used Genetic Algorithms for regression testing. The tertiary study by [68] only maps the systematic literature studies in various sub-areas of software testing including regression testing. Instead of focusing only on regression testing research, [47] reviewed the literature on test case selection in general. They identified that only six of the selected studies were performed on large-scale systems, and only four of these were industrial applications.

In the most recent literature review, [54] reviewed empirical research on regression testing of industrial and non-industrial systems of any size. They mapped the identified research to the following dimensions: evaluation metrics used in the study, the scope of the study, and what they have termed as the theoretical basis of the study (research questions, regression testing technique, SUT, and the dataset used). Their approach indicates a similar aim as other literature reviews: to identify "the most effective" technique considering the measures of "cost, coverage and fault detection". However, they do not take into consideration the aspect of the relevance and likely applicability of the research for industrial settings.

Among the identified reviews, only five discuss aspects related to the industrial application ([17, 36, 66, 72, 78]). [78] found that 64% of the included 120 papers used datasets from industrial projects in their evaluation. They further recommend that future evaluations should be based on non-proprietary data sets that come from industrial projects (since these are representative of real industrial problems) [79]. [17] identified that a large majority of empirical studies use a small set of subjects largely from the SIR[3] repository. They highlight that it allows comparative/replication studies, and also warn about the bias introduced by working with the same small set of systems. Similarly, [72] concluded that most empirical investigations are conducted on small programs, which limits the generalisation to large-systems used in industry. [36] also found that 50% of the 65 selected papers on regression test prioritisation included in their review

[3] Software Infrastructure Repository http://sir.unl.edu/

use SIR systems. Furthermore, 29% of the studies use the same two systems from the repository.

[66] reviewed the state of research and practice in regression testing. Authors presented the synthesis of main regression testing techniques and found that only a few techniques and tools developed by the researchers and practitioners are in use of industry. They also discussed the challenges for regression testing and divided the challenges into two sets (transitioning challenges and technical/conceptual issues). Along with the review of research on regression testing authors also presented the results of their discussions (an informal survey) with researchers and practitioners. They were intended to understand the impact of existing regression testing research and the major challenges to regression testing.

Unlike existing literature reviews, this study has an exclusive focus on research conducted in industrial settings. This study provides taxonomies to assist researchers in designing and reporting research to make the results more useful for practitioners. Using the proposed taxonomies to report regression testing research, will enable synthesis in systematic literature reviews and help to take the field further. One form of such synthesis will be the technological-rules [33] (as extracted in this paper) with an indication of the strength-of-evidence. For practitioners, these taxonomies allow reasoning about the applicability of research for their own unique context. The study also presents some technological-rules that are based on the results of this study which practitioners can consider research-informed recommendations from this study.

4.3 Research questions

In this study, we aggregate information on regression testing techniques that have been evaluated in industrial contexts. Our goal is to structure this information in such a way that it supports practitioners to make an informed decision regarding regression testing with a consideration for their unique context, challenges, and improvement targets. To achieve this goal we posed the following research questions:

RQ1: *How to describe an industrial regression testing problem?* Regression testing challenges are described differently in research ([38]) and practice ([74]). To be accessible and relevant for practitioners, research contributions in terms of technological rules ([33]) need to be interpreted and incorporated into a bigger picture. This, in turn, requires alignment in both the abstraction level and the terminology of the academic and industrial problem descriptions. To provide support for such alignment, we develop taxonomies of desired effects and relevant context factors by extracting and coding knowledge on previous industrial evaluations of regression testing techniques.

RQ2: *How to describe a regression testing solution?* Practitioners need to be able to compare research proposals and assess their applicability and usefulness for their specific contexts. For this purpose, we extract commonalities and variabilities of research proposals that have been evaluated in industry.

RQ3: *How does the current research map to such problem description?* To provide an overview of the current state of the art, we compare groups of techniques through the lens of the taxonomies developed in RQ1 and RQ2.

4.4 Method

To capture what information is required to judge the industrial-relevance of regression testing techniques, we relied on: 1) industrial applications of regression testing techniques reported in the literature, 2) existing research on improving industry-academia collaboration in the area of software testing, 3) and close cooperation with practitioners.

To develop the three taxonomies presented in Section 4.6 and 4.7 and arrive at the results presented in Section 4.8 we conducted a systematic literature review of regression testing research, interleaving interaction with industry practitioners throughout the review process.

The process followed can be divided into six steps, which are visualised in Figure 4.1. Research questions were initially formulated within a research collaboration on decision support for software testing (EASE). To validate the research questions and the approach of constructing a SERP taxonomy [75] a pilot study was conducted (Step 1, Section 4.4.3). Based on the pilot study, a preliminary version of the taxonomy was presented to the researchers and practitioners in EASE, together with a refined study design for the extensive search. Through the extensive search of the literature (Step 2, Section 4.4.4) we identified 1068 papers on regression testing. This set was then reduced (Step 3, Section 4.4.5) by iteratively coding and excluding papers while refining the taxonomy (Step 4, Section 4.4.6). Finally, the constructed taxonomies were evaluated in a focus group meeting (Step 5, Section 4.4.7) and the regression testing techniques proposed in the selected papers were mapped to the validated version of the taxonomies (Step 6, Section 4.4.8).

4.4.1 Practitioners' involvement

As shown in Figure 4.1 (ovals with shaded background), practitioners were involved in three steps. For validating the selection criteria (Step 3a) a subset of selected papers was validated with practitioners. In Step 4a, the initial taxonomy was presented to EASE partners in a meeting. This meeting was attended by five key stakeholders in testing at the case companies. In Step 5, for taxonomy evaluation, we relied on a focus group with three key practitioners. The three practitioners came from two companies which develop large-scale software-intensive products and proprietary hardware. The participating companies are quite different from each other; *Sony Mobile Communications* has a strict hierarchical structure, well-established processes and tools, and is globally distributed, while the development at *Axis Communications AB, Sweden* still has the entrepreneurial culture of a small company and has less strictly defined processes. The profiles of the practitioners involved in the study are briefly summarized below:

Practitioner P1 is working at Axis. He has over eight years of experience in software development. At Axis, he is responsible for automated regression testing from unit to system-test levels. His team is responsible for the development and maintenance of the test suite. The complete regression test suite comprises over 1000 test cases that take around 7 hours to execute. He was also involved in previous research-based initiatives to improve regression testing at Axis [76].

Practitioner P2 also works at Axis communications. He has over 12 years of software de-

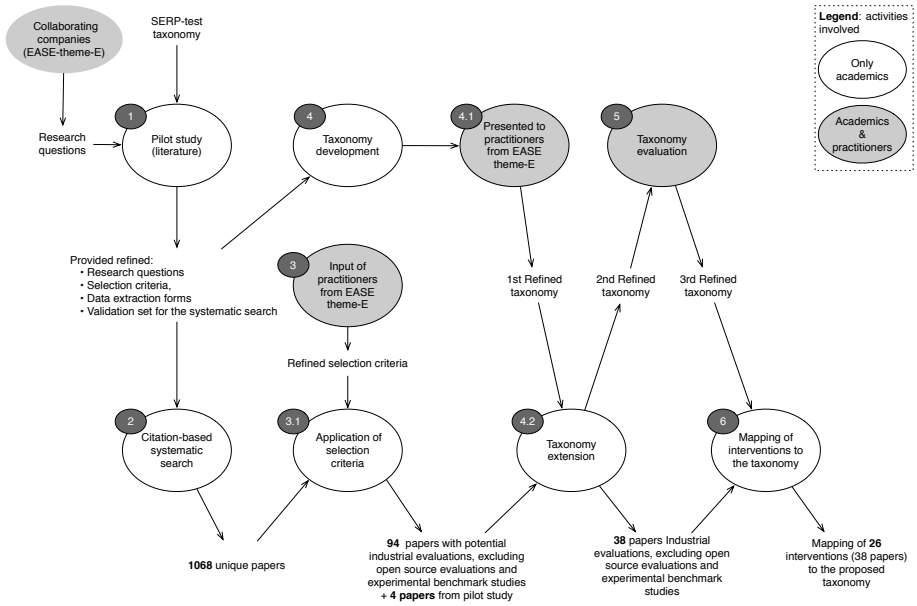

Figure 4.1: A description of the flow of activities including alternately reviewing the literature and interacting with practitioners from the research project EASE.

velopment and testing experience. He is responsible for both automated and manual regression testing at the system-test level. He has recently overseen a complete assessment and review of the manually executed test-cases in the regression test suite.

Practitioner P3, works at Sony Mobile Communications. He has over 18 years of experience in software development with responsibilities primarily include software testing and overall automation and verification strategies. His current role as verification architect covers testing at all levels including regression testing. Within the EASE project, he has collaborated with researchers in several research-based investigations at his company.

4.4.2 Need for a literature review

The broader context of this study is a collaborative research project EASE (involving two academic and three industrial partners) working towards decision support in the context of software testing. As shown in Figure 4.1, the research questions and the need for a systematic literature review were identified in the context of this project. We considered the literature to answer the following two questions in the pilot study:

1. *Have existing systematic literature reviews taken into consideration the industrial rele-*

vance and applicability of regression testing techniques? We identified 11 systematic literature studies ([16, 17, 36, 39, 43, 54, 66, 70, 72, 78, 79]), and they have been briefly discussed in Section 4.2. These studies have not addressed the research questions of interest for the current study.

2. *Are there sufficient papers reporting an industrial evaluation of regression testing techniques?* Once we had established the need to analyse the existing research from the perspective of industrial relevance, we conducted a pilot study to:
    - identify if there are sufficiently many published papers to warrant a systematic literature review,
    - develop an initial taxonomy that serves as a data extraction form in the main literature review, and
    - identify a set of relevant papers that serve as a validation set for our search strategy in the main literature review.

4.4.3 Pilot study

By manually searching through recent publications of key authors (identified in previous literature reviews discussed in Section 4.2) and by skimming through the top most-relevant results of keyword-based searches in Google Scholar, we identified 36 papers. Using a data extraction form based on the SERP-test taxonomy [75], data were extracted from these papers. Data extraction was done independently by at least two reviewers and results were consolidated by discussion. This validation was considered useful for two reasons: firstly, through the cross-validation, we developed a shared understanding of the process. Secondly, since the results were to be used as a guide for data extraction in the main literature review, it was necessary to increase the reliability of this initial step.

The pilot study indicated that sufficient literature exists to warrant a systematic literature review. The results of analysing the extracted information were useful for formulating the data extraction forms for the main literature review.

4.4.4 Search strategy

Using the following search string, we identified the existing systematic literature studies on regression test optimization as listed in Table 4.1:
(“regression test” OR “regression testing”) AND (“systematic review” OR “research review” OR “research synthesis” OR “research integration” OR “systematic review” OR “systematic overview” OR “systematic research synthesis” OR “integrative research review” OR “integrative review” OR “systematic literature review” OR “systematic mapping” OR “systematic map”))

Additionally, we also used [17] survey as it has a thorough coverage (with 189 references) and is the most-cited review in the area of regression testing. Using the references in the papers listed in Table 4.1, and the citations to these papers were retrieved in August 2016 from Google

Scholar. We identified a set of 1068 papers as potentially relevant papers for our study. One of the systematic reviews, by [54] as discussed in Section 4.2, was not used for snowball-sampling as it was published yet when the search was conducted.

Table 4.1: Systematic literature studies used as start-set for snowball sampling

ID	No. of References.	No. of Citations
[70]	75	5
[43]	69	1
[16]	71	0
[79]	24	4
[36]	80	14
[78]	24	25
[72]	73	135
[47]	46	1
[39]	59	0
[17]	189	515

Using the 36 papers identified in the pilot-study (see Section 4.4.3) as the validation-set for this study, we calculated the precision and recall ([15, 53]) for our search strategy. 36 papers in a validation-set are reasonable for assessing the search strategy of a systematic literature review [53].

Recall = *100 * (# of papers from the validation-set identified in the search) / (total # of papers in the validation set).*

Precision = *100 * (total # of relevant papers (after applying the selection criteria) in the search results) / (total # of search results).*

$$Recall = \frac{32}{36} * 100 = 89\%$$

Only four of the papers in the pilot-study were not identified by our search strategy ([18, 37, 48, 49]). These papers neither cite any of the literature reviews nor were they included by any of the literature reviews comprising the starting set for search in this study. We also included these four papers to the set of papers considered in this study.

As shown in Figure 4.1, after applying the selection criteria 94 relevant papers were identified. These papers were used to extend the taxonomy. Using this number, we calculated the precision of our search strategy as follows:

$$Precision = \frac{94}{1068} * 100 = 8\%$$

An optimum search strategy should maximise both precision and recall. However, our search strategy had high recall (with 89% recall it falls in the high recall range, i.e. $\geq$ 85% [15]) and low precision. The precision value was calculated considering the 94 papers that were used in extending the taxonomies.

The value of recall being well above the acceptable range [15] of 80% adds confidence to our search strategy. Furthermore, such low value of precision is typical of systematic literature reviews in software engineering e.g. approx. 5% [79] approx. 2% ([9, 85]), and below 1% ([36, 43, 72]).

4.4.5 Selection of papers to include in the review

We applied a flexible design of the study and inclusion criteria were iteratively refined. The notion of "industrial" was further elaborated after the first iteration. To make the set of papers more manageable, we decided to exclude open source evaluations and industrial benchmark studies. The assumption was that such reports contain less information about application context and limitations in terms of technology adoption. The following inclusion-exclusion criteria were the ones finally applied:

- **Inclusion criteria:** peer-reviewed publications that report empirical evaluations of regression testing techniques in industrial settings. It was detailed as the following, include papers that:
  - are peer-reviewed (papers in conferences proceedings and journal articles)
  - report empirical research (case studies, experiments, experience reports ...)
  - report research conducted in industrial settings (i.e. uses a large-scale software system, involves practitioners or reports information on the real application context including the process).
  - investigate regression testing optimization techniques (i.e. regression test selection, prioritization, or minimization/ reduction/ maintenance)
- **Exclusion:** exclude papers that:
  - are non-peer reviewed (Ph.D. thesis, technical reports, books etc.)
  - report a non-empirical contribution (analytical/ theoretical/ proposals)
  - report evaluation in non-industrial settings.

We decided to use lines of code (LOC), if reported, as an indicator for the scale of the problem instead of the number of test cases in the test suite or turnaround time of a test suite (and similar metrics) for the following reasons:

- LOC/kLOC is the most commonly reported information regarding the size of a SUT.
- Size and execution time of individual test cases in a test suite varies a lot, therefore, an aggregate value reporting the number of test cases or the execution time of test cases is not very informative.

Techniques that work well on a small program may work on large programs. However, this is yet to be demonstrated. Practitioners seem to trust the results of research conducted in environments similar to their [2]. Previous research on assessing the industrial relevance of

research has also relied on the realism in the evaluation setting regarding the research method, scale, context and users ([62, 85]).

We performed pilot selection on three papers to validate the selection criteria and to develop a shared understanding among the authors. Each author independently applied the selection criteria on the these randomly chosen papers. We discussed the decisions and reflected on the reasons for any discrepancies among the reviewers in a group format.

After the pilot-selection, remaining papers were assigned to each author randomly to apply selection criteria. Inclusion-exclusion was performed at three levels of screening: 'Titles only', 'Titles and abstracts only', and 'Full text'. If in doubt, the general instruction was to be more inclusive and defer the decision to the next level. Each excluded paper was evaluated by at least two reviewers.

Additionally, to validate that the studies we were selecting were indeed relevant, during the paper selection phase of this study, a sample of eight papers from the included papers was shared with practitioners. They labelled the paper as relevant or irrelevant for their companies and also explained their reasoning to us. This helped us to improve the coverage of information that practitioners are seeking, which they consider will help them make informed decisions regarding regression testing.

After applying the selection criteria on 1068 paper and excluding open source and industrial benchmarks we had 94 remaining papers. Four papers from the pilot-study were also added to this list. These 98 papers were randomly assigned to the authors of this paper for data-extraction and taxonomy extension. After full-text reading and data extraction, 38 papers were included as relevant papers (see list in Table 4.2), which represent 26 distinct techniques. All excluded papers were reviewed by an additional reviewer.

4.4.6 Taxonomy extension

Table 4.3 presents an abstraction of the data extraction form, which was based on the first version of our taxonomy that was developed in the pilot study (see Step-4 onwards in Figure 4.1 that produced the "1st Refined taxonomy" and Section 4.4.3 for details of the pilot study). We followed the following steps to validate the extraction form and to develop a shared understanding of it:

1. Select a paper randomly from the set of potentially relevant papers.
2. All reviewers independently extract information from the paper using the data extraction form.
3. Compare the data-extraction results from individual reviewers.
4. Discuss and resolve any disagreements and if needed update the data extraction form.

This process was repeated three times before we were confident in proceeding with data extraction on the remaining set of papers.

The extracted information was used to develop extensions of SERP-test taxonomy [75] relevant to our focus on regression testing techniques. Separate taxonomies for "addressed context factors", "evaluated effects" and "utilised information sources" were developed (shown as step 4.2 in Figure 4.1). The initial version of these taxonomies was developed in a workshop where

Study ID	Reference.	Study ID	Reference.
S1	[76]	S20	[41]
S2	[37]	S21	[52]
S3	[48]	S22	[32]
S4	[49]	S23	[58]
S5	[81]	S24	[71]
S6	[35]	S25	[21]
S7	[23]	S26	[73]
S8	[22]	S27	[30]
S9	[13]	S28	[63]
S10	[11]	S29	[34]
S11	[14]	S30	[64]
S12	[12]	S31	[45]
S13	[24]	S32	[65]
S14	[27]	S33	[51]
S15	[28]	S34	[84]
S16	[26]	S35	[50]
S17	[29]	S36	[77]
S18	[25]	S37	[80]
S19	[42]	S38	[67]

Table 4.2: The list of papers included in this study

Table 4.3: Data extraction form

Item	Value	Remarks
1) Meta information		
2) Description of testing technique		
3) Scope of technique		
4) High-level Effect/Purpose		
5) Characteristics of the SUT		
6) Characteristics of the regression testing process		
7) Required sources of information		
8) Type of required information		
9) Is this an industrial study?		
10) If yes, could the SUT be categorised as closed source?		
11) Is the paper within the scope of the study? If not, please explain the reason.		

six of the authors participated. Each of the taxonomies were then further refined by two of the authors and reviewed independently by a different pair of authors. This resulted in what is referred to as "2nd refined taxonomy" in Figure 4.1. This version of the taxonomy was further validated with practitioners, which is discussed in the following section.

4.4.7 Taxonomy evaluation

Once data analysis was complete, and we had created the three taxonomies presented in Section 4.6, Section 4.7 and Section 4.8, we conducted a focus group with three key stakeholders from the companies (brief profiles are presented in Section 4.4.1). In this focus group, moderated by the second author, we systematically collected practitioners' feedback on the context and effect taxonomies because these two taxonomies are supposed to describe the practitioners' need.

Practitioners were asked to assess the relevance of each of the nodes in the taxonomies (as presented in Table 4.4) and grade these from 1 to 3, where 1) means very relevant (i.e. we are interested in this research), 2) possibly relevant and 3) means irrelevant (i.e. we are not interested in such research). The practitioners were asked to respond based on their experience and not only based on their current need.

The feedback from the practitioners was taken into account, and some refinements to the taxonomies were made based on it. As this is primarily a literature review, we decided not to add factors that were not presented in the included papers although initial feedback pointed us to relevant factors in the studies. Neither did we remove factors completely from the taxonomies (although we removed some levels of detail in a couple of cases). The feedback was mainly used to evaluate and improve understandability of the taxonomies and changes were mainly structural.

4.4.8 Mapping of techniques to taxonomy

As shown in Figure 4.1 after incorporating the feedback from the practitioners in the taxonomy, we mapped the 26 techniques to our multi-faceted taxonomy. The reviewer(s) (one of the authors of the study) who were responsible for data extraction from the papers reporting the technique mapped the paper to the taxonomy. Two additional reviewers validated the mapping, and disagreements were resolved through discussion and by consulting the full-text of the papers. The results of the mapping are presented in Table 4.5.

4.5 Limitations

In this section, we discuss validity threats, our mitigation actions, and the limitations of the study.

4.5.1 Coverage of regression testing techniques:

To identify regression testing techniques that have been evaluated in industrial settings, we used snowball sampling search strategy. Snowball sampling has been effectively used to extend systematic literature reviews ([69]). The decision to pursue this strategy was motivated by the large number of systematic literature studies (as discussed previously in Section 4.2) available on the topic. Some of these reviews (e.g. [17] and [72]) are well cited, indicating visibility in the community. This increases the likelihood of finding recent research on the topic.

The search is not bound to a particular venue and is restricted to citations indexed by Scopus and Google Scholar before August 2016. We choose Scopus and Google scholar because of their comprehensive coverage of citations [4]. We are also confident in the coverage of the study as out of the 36 papers in the validation set, only four were not found (see Section 4.4).

To reduce the possibility of excluding relevant studies, we performed pilot selection on a randomly selected subset of papers. Furthermore, all excluded papers were reviewed independently by at least two of the authors of this paper. In cases of disagreement, the papers were included in the next phase of the study, i.e. data extraction and analysis.

4.5.2 Confidence in taxonomy building process and outcome

The taxonomies presented in this paper were based on data extracted from the included studies. To ensure that no relevant information was omitted, we tested the data extraction form on a sample of papers. This helped to develop a shared understanding of the form.

Furthermore, to increase the reliability of the study, the actual data extraction (from all selected papers) and the formulation of facets in the taxonomies were reviewed by two additional reviewers (authors of this paper).

As shown in Figure 4.1, the intermediate versions of the taxonomy were also presented to practitioners and their feedback was incorporated in the taxonomy. Possible confounding effects of their participation is due to their representativeness. The impact of practitioner feedback was mainly on the understandability and level of detail of the proposed taxonomies and a confounding effect could be that the understandability of the taxonomy is dependant of dealing with a context similar to our practitioners'. The two companies are large-scale and the challenges they face are typical for such contexts [75, 86]. All participants have many years of experience of testing (as described in Sec 4.4.1). Therefore, their input is considered valuable for improving the validity of our study, which focuses on regression testing research of large-scale software systems.

The taxonomies presented were sufficient to capture the description of challenges and proposed techniques in the included studies and the practitioners consulted in this study. However, new facets may be added by both researchers and practitioners to accommodate additional concerns or aspects of interest.

4.5.3 Accuracy of the mapping of techniques and challenges

All mappings of included papers to the various facets of the three taxonomies were reviewed by an additional reviewer. Disagreements were discussed, and the full-text of the papers was

consulted to resolve them. Despite these measures, there is still a threat of misinterpretation of the papers, which could be further reduced for example by consulting the authors of the papers included in this study to validate our classification. However, due to practical reasons we did not implement this mitigation strategy.

4.6 RQ1 – Regression testing problem description

In response to RQ1, we created taxonomies of addressed context factors and desired effects investigated in the included papers.

The taxonomies created in this study follow the SERP-taxonomy architecture [3], i.e. they cover four facets, *intervention*, *context constraints*, *objective/effect* and *scope*. A SERP-taxonomy, should include one taxonomy for each facet. In our case, we create the regression testing taxonomies by extending an existing SERP-taxonomy (i.e. SERP-test [75]) by adding the details specific to regression testing. More precisely, we develop extensions for three out of four SERP facets: *context factors* (extends context in SERP-test), *desired effects* (extends objective\improvements in SERP-test) and *utilised information entities and attributes* (extends intervention in SERP). We do not extend the scope taxonomy further since regression testing is in itself a scope entity in SERP test, which all reviewed techniques target.

The taxonomy creation was done in three steps (considering both the researcher's and the practitioner's perspective on the regression testing challenge): firstly we, together with our industry partners, defined an initial set of factors and targets which were important to them; secondly we extracted information regarding these factors in the included papers and extended the taxonomies with details provided in the reports, and finally we evaluated the extended taxonomies in a focus group meeting with our industry partners to get feedback on its relevance and understandability to them in their search for applicable regression testing techniques. The items of the final taxonomies are visible in Table 4.4

At the highest abstraction level, all categories of our proposed taxonomies were considered relevant when describing a regression testing challenge (i.e. characteristics of the system, the testing process and test suite and people related factors in the context taxonomy and similarly improved coverage, efficiency, effectiveness and awareness in the effect taxonomy).

The taxonomies reported in this paper are the revised version that addresses the feedback from this focus group. Due to the dual focus when creating the taxonomies, we believe they could provide guidelines for both researchers and practitioners in defining the real-world regression testing problems they address, or wish to address consistently to support the mapping between research and practice.

4.6.1 Investigated context factors

The purpose of the context taxonomy can be summarised as: *Provide support for identifying characteristics of an industrial environment that make regression testing challenging and hence support the search for techniques appropriate for the context.*

Table 4.4: A taxonomy of context, effect and information factors addressed in the included papers and considered relevant by our industry partners

Context taxonomy		Factors along Study ID
Investigated context factors	System-related factors	**Size** e.g. Large-scale S1, S2, S5 – S35 **Complexity** e.g. Heterogeneneous S1, S6, S9 – S12, S19, S20, S26, S29, S30, S31, S35 or Customizeable or using product-line approach S3, S4, S6, S13 – S18, S24 – S26, S35, S38 **Type of the system** e.g. Web-based/SOA S3, S4, S6, S30, S31, S36 Real time S3, S4, S7,S8, S13 – S18, S27 Embedded S1, S24 – S27 Database applications S19, S20, S36 Component-based S6, S9,S10,S11,S12, S31
	Process-related	**Testing process** (e.g. Continuous S1, S3, S4, S26) **Test technique** e.g. Manual testing S5, S33, Combinatorial S19, S20 Scenario-based testing S6 or Model-based testing S35
	People-related factors	**Cognitive factors** e.g. lack of experience S13 – S18, S26 or that new tools need to be easy to implement and use S22 **Organizational factors** (e.g. Distributed development S6)

Effect taxonomy		References
Desired effects	Test Coverage	**Feature-coverage** S3,S4, S13 – S18 **Input (Pairwise)** S19,S20
	Efficiency and effectiveness	**Reduction of test suite** S5 – S18, S23 – S25, S27 S28, S30 – S32, S35 – S37 **Reduced testing time** S1, S3, S4, S5, S7, S8, S13 – S18, S23, S28, S29, S30, S32, S33, S36 **Improved precision** S1, S7 – S12, S24, S25 **Decreased time for fault detection** S2 – S4, S21, S22, S26, S29, S37 **Reduced need for resources** S2, S13 – S18, S29, S30 **Fault detection capability** S7, S8, S13 – S21 – S4, S24 – S26, S28, S29, S34 **Severe fault detection** S3, S4, S21 **Reduced cost of failure** S9 – S12, S19, S20, S33
	Awareness	**Transparency of testing decisions** S26

Information taxonomy		References
Utilised information entities and attributes	Requirements	**No. of changes in a requirement**, **Fault impact**, **Subjective implementation complexity**, **Perceived completeness**, **Perceived traceability** S21 **Customer assigned priority** S21, S33
	Design artefacts	**System models** S13 – S18, S27, S35 **Code dependencies** S19,S20S37
	Source code	**Code changes/ Revision history** S1, S2, S5, S7,S8, S24, S25, S38 **Source file** S2, S7, S8, S30, S37 **No. of Contributors** S32
	Intermediate code	**Class dependencies** S6 **Code changes (method or class)** S2, S6, S28
	Binary code	**Revision history** S6, S29 **Component changes** S9 – S12, S31 **Binary files** S6, S9 – S12, S23, S29
	Test cases	**Target variant** S26 **Type of test** S26 **Model coverage** S13 – S20 **Functionality coverage** S3, S4**Static priority** S26 Age S26 **Fault detection probability (estimated)** S22, S29, S33 **Execution time (estimated)** S22, S29 **Cost (estimated)** S22, S33 **Link to requirements** S21, S22 **Link to faults** S21 – S4 **Link to source code** S6 – S8
	Test Execution	**Execution time** S29, S32 **Database-states** S36 **Invocation counts** S28 **Invocation chains** S28, S31 **Runtime component coverage** S31 **Method coverage** S28 **Code coverage** S5, S23, S29, S37 [67] S38 **Browser states**S36 **Class coverage** S6
	Test reports	**Execution time** S4, S13 – S18, S3, S28 **Verdicts** S1 – S4, S13 – S18, S26, S32, S34 **Severity** S28, S33 **Link to packages and their revisions** S1 **Link to branch** S32 **Build type** S32 **Link to failure** S13 – S18 **Test session** S13 – S18, S26 **Variant under test** S32
	Issues	**Link to fixed file / link to source code** S24, S25 **Fix-time** S32 **Link to test case** S24, S25, S37 **Failure severity** S3, S4

Table 4.4 shows a taxonomy of contextual factors that were investigated in the included papers, as well as considered relevant by our industry partners. To be classified as an investigated context factor the mere mentioning of it in general terms was not considered sufficient, only in cases where the authors of the study include a discussion or explanation of the effect a factor has on regression testing and why it is considered in their study we include it as an investigated context factor.

Since we only include factors that have been discussed in the literature, the context taxonomy is not extensive but can still be used as a guideline for describing regression testing problems and solutions. We identified three main categories of relevant contextual factors (*system related, process related*, and *people related*) that have been addressed in the included papers.

System related context factors

System related context factors include factors regarding the system (or subsystem) under test, such as *size, complexity* and *type*. How size and complexity are measured varies in the studies, but a common measure of size is lines of code. Factors that are reported to add to the complexity are *heterogeneity* and *variability* (e.g. in software product lines). Some techniques are designed to address the specific challenges of applying regression testing to a certain type of systems (e.g. *web-based systems, real-time systems, embedded systems, databases* or *component-based systems*).

In the focus group meeting, *embedded systems* as a type of system were considered to be a relevant factor, characterising the regression testing challenges, but the other suggested system types were not - mainly on account of them not being applicable to the specific situation of the practitioners in the group. We interpret that the abstraction level is relevant and choose to keep the system types in the context taxonomy only where an explanation of what makes the context challenging from a regression testing perspective is given in any of the included studies (i.e. system types that are mentioned but not explained from a regression testing challenge perspective are removed from the taxonomy). A similar approach was used for the other system related factors of which only one, *variability*, was considered very important by the practitioners.

Process related context factors

Process related context factors include factors of the development or testing process that may affect the relevance of a regression testing technique, such as currently used *processes* and *testing techniques*. Some regression testing techniques address new regression testing challenges arising with highly iterative development strategies such as continuous integration (which also was the first and main challenge identified by our collaborators and a starting point for this literature review). How testing is designed and carried out (e.g. *manual, black-box, combinatorial* or *model based*) may also be crucial for which regression testing technique is relevant and effective.

Of the testing process characteristics, *use of a specific tool* was considered irrelevant while the *use of testing technique* (all three examples) was considered very important. Thus, we removed the testing tool as a context characteristic and kept the examples of testing techniques,

manual testing, and *combinatorial testing*. Black box testing was removed as it is covered by the information taxonomy. From the literature, we added two more examples of test techniques that affect the applicability of regression testing solutions, *Scenario based testing* and *Model based testing*. *The frequency of full regression test* (i.e. how often is the complete regression test suite run) was considered important, and we rephrased it to *continuous testing* in the final taxonomy. Also, *size* and *long execution times of test suites* were considered important but since it is covered by the desired effects, we removed it from the context taxonomy.

People related context factors

People related context factors refer to factors that may cause, or are caused by, distances between collaborating parties and stakeholders in the development and testing of the software system. The terminology used stems from [82]. *Cognitive* context factors include the degree of knowledge and awareness, while *organisational* factors include factors that may cause, or are caused by, differences in goals and priorities between units.

People related issues were important to all participants in the focus group, but the message about which factors were most important was mixed. *Ease of use* got the highest score. A new node *Cultural distances* was proposed as well, however, we have not found any such considerations in the selected set of papers, and thus did not include it in the taxonomy. This branch of the taxonomy showed to have overlaps with the effect taxonomy (e.g. *Lack of awareness* and *Need for quick feedback*), and we decided to remove such nodes from the context taxonomy and add them to the effect taxonomy instead.

General reflection

A reflection about the overall context taxonomy is that it is not obvious which characteristics are relevant to report from a generalisation perspective. Even in industrial studies, the problem descriptions are in many cases superficial and many context factors are mentioned without any further explanation as to why they are relevant from a regression testing perspective. Some factors mentioned are crucial only to the technology being evaluated, and not necessarily an obstacle preventing the use of other technologies. One such example is the type of programming language - it was initially added to the taxonomy, as it is a commonly reported aspect of the cases used for empirical evaluation. However, it was finally removed as it was considered a part of the constraints of a solution, rather than characterising trait of the addressed problem context.

4.6.2 Desired effects

The desired effect of a technique is basically about the reported types of improvement(s) achieved by applying the technique, such as ‘improving efficiency’ or ‘decreasing execution time’. To be recognised as a desired effect, in our setting, the effect of the technique has to be evaluated in at least one (industrial/large scale) case study, rather than just being mentioned as a target

of the technique without any evidence. Accordingly, the effect has to be demonstrated as a *measurement* showing the effect of the proposed technique on regression testing.

Table 4.4 shows a taxonomy of effect (-target) factors. The proposed effect taxonomy provides a categorisation of the various effects (improvements) identified in the research while simultaneously, it meets the level of information (or detail) required (or considered relevant) by our industrial partners. The improvements (effects) of techniques are categorised into three main categories: *Improved test coverage*, *Improved efficiency and effectiveness* and *increased awareness*.

Improved test coverage

Improved coverage refers to the effects aiming at improving (increasing) the coverage of any type of *entity* by the selected test suite. The type of entity, which is under consideration, depends on the context and the proposed solution. We identified two main desired effects for coverage in the included papers, namely *increased feature coverage* and *improved combinatorial-input coverage (Pairwise)*.

Improved efficiency and effectiveness

Efficiency and effectiveness cover cost reduction factors such as *reduced number of test cases* and *reduced execution time* with a consideration for how comprehensively faults are detected. In principle, efficiency does not look into how well a testing technique reveals or finds errors and faults. Improving only the efficiency of a technique will lead to a testing activity that requires less amount of time or computational resources, but it may not be effective (i.e. comprehensively detect faults). Efficiency and Effectiveness are often distinguished in the research literature, while in practice they are equally important objectives and are most often targeted at the same time. Thus, we treat them as one class in our taxonomy. *Reduction of test suite* often leads to a set of test cases requiring less resource (memory) and less amount of time to be generated, executed, and analysed. Note that test suite reduction in the research literature is often referred to as a technique as such ([17]). It is then used interchangeably with test suite maintenance referring to the permanent removal of test cases in contrast to the temporary removal or ordering of test cases in "test case selection" or "test case prioritisation. However, "reduction of the number of test cases" is at the same time the most common measure of the effectiveness of a regression test selection technique in industrial evaluations. It is used in evaluation of regression testing techniques when comparing with the current state of practice (both in the maintenance case and the selection case) in a particular context. Thus, we add it as a desired effect in our taxonomy.

Reduction of testing time considers any time/resource-related aspect, also referred to as 'cost' in some studies. *Improved precision* refers to the ability of a selection technique in avoiding non-fault revealing test cases in the selection. High precision results in a reduction of test suite while it also indicates a large proportion of fault detecting test cases. Hence, precision is considered a measure of both efficiency and effectiveness. *Decreased time for fault detection* i.e. the aim is

to reduce the time it takes to identify faults, which is relevant when reflecting on the outcomes of a prioritisation technique for regression testing. *Reduced need for resources* i.e. reduces the consumption of a resource e.g. memory consumption. *Improved fault detection capability* also referred to as 'recall' or 'inclusiveness', measures how many faults are detected regardless of their severity. *Improved detection of severe faults* refers to the extent to which a technique can identify severe faults in the system. *Reduced cost of failures*, here the focus is on the consequence (measured in cost factors) of false negatives in the selection.

Increased awareness

Increased awareness refers to improvements related to the testing process (activities) per se and the people involved in the process. *Improved transparency of testing decisions* has been considered in the existing research and identified as a relevant target by our industrial partners. It aims at transparently integrating regression testing techniques into daily/normal development activities such that the stakeholders understand the working of the technique and trust the recommendations regarding the test-cases they produce.

General reflection

A general reflection regarding the effect-taxonomy is that "what is measured in research is not always what matters in practice". The taxonomy was initially based solely on the different variants of measurements used in the studies and rather fine-grained in some aspects. Different levels of code coverage are for example a popular measurement in literature but were not considered relevant by the practitioners in the focus group. All proposed coverage metrics except feature coverage were considered irrelevant by the participants. Our interpretation is *not* that code coverage is considered useless as a test design technique, but that improving code coverage is not a driver for applying regression testing (not for the practitioners and not for any of the stakeholders in the industrial evaluations). Although code coverage is not presented as a desired effect in our taxonomy, it still appears as a characteristic of a technique (information attribute) since there are some examples of techniques in our included papers that utilise measures of code coverage to propose a regression testing scope.

Regarding the variants of measurements under effectiveness and efficiency, the granularity level was considered too high and many of the nuances in the measurements were hard to interpret from a practical point of view. Only three of the low-level categories were considered relevant for at least one of the participants, 'detection of severe faults' was important for all three while 'precision' and 'test suite reduction' were important to one of the participants.

4.7 RQ2 – Regression testing solution description in terms of utilised information sources

To answer RQ2, i.e., *"how to describe a regression testing solution?"*, we considered the following choices for developing a taxonomy: 1) based on the underlying assumptions (e.g., history-based and change-based), 2) based on the techniques (e.g., firewall, fixed-cache, and model-based), or 3) based on the required information (e.g., test case execution information, code complexity, and version history).

We decided in favour of the third option, in particular, because it allows for reasoning about what information is required to implement a regression testing technique. From a practitioner's point of view the concerns regarding: a) whether a technique would work in his/her context, and b) whether it can help achieve the desired effect, are already covered with the context and the effect taxonomy. Thus, while the effect and context taxonomies enable narrowing down the choice of techniques, the aim of the information taxonomy is to support practitioners in reasoning about the technical feasibility and the estimated cost of implementing a technique in their respective unique context.

Hence, the purpose of the information taxonomy can be summarised as *to provide support in comparing regression testing solutions by pinpointing relevant differences and commonalities among regression testing techniques (i.e., the characteristics affecting the applicability of a technique)*. We consider this classification particularly useful for practitioners as it helps one identify relevant techniques in their context. For example, if a certain test organisation does not have access to source code, they can focus on techniques that do not require it.

Similarly, knowing what information is required to implement a technique, the interested reader can: 1) identify if this information is currently available in their organisation 2) investigate how to derive it from other available information sources, or 3) analyse the feasibility of collecting it. Hence, a practitioner can make an informed decision about the applicability of a technique in their context by considering the possibility and the cost of acquiring the required information.

The information taxonomy (as shown in Table 4.4) uses the structure <entity, information> to identify what information is required to use a certain technique. Thus, we coded the entities and the utilised information about their various attributes/facets used by each of the techniques. Some examples of entities, in this case, are design artefacts, requirements or source code. The respective information about the various attributes/facets of these three example entities may include dependencies between various components, the importance of a requirement to a customer or code metrics.

From the papers included in this review, the following nine entities (and different information regarding them) were used by the regression testing techniques: 1) Requirements, 2) Design artefacts, 3) Source code 4) Intermediate code, 5) Binary code, 6) Closed defect reports, 7) Test cases, 8) Test executions, and 9) Test reports.

4.7.1 Requirements

Very few regression testing techniques included in this study have used information related to requirements (such as the importance of required functionality for the customer). Only two papers explicitly make use of information regarding the requirements [51, 52]. Such information can be coupled with requirement coverage (i.e., the number of requirements exercised by a test case) to optimise regression testing with respect to the actual operational use of the SUT [32, 52].

The information about several attributes of requirements such as their priority and the complexity of their implementation are stored in requirement management systems. However, the information regarding requirement coverage may as well be stored in the test management system with respect to their corresponding test cases.

One reason for the lack of techniques utilizing requirements as input for regression testing could be that often the traceability information from requirements to source code to test cases is not maintained [31]. Furthermore, it is significantly more difficult to recreate these traceability links than, e.g., linking source code to test cases.

The following five techniques are based on the requirements and feature coverage by test-cases: RTrace [52], MPP [48, 49], TEMSA [25, 26, 29], and FTOPSIS [32].

FTOPSIS [32] uses multi-criteria decision-making as well as fuzzy logic, where both objective and subjective (expert judgement) data about requirements can be used to prioritise test cases in a regression suite. Krishnamoorthi and Mary's approach RTrace [52] expects an explicit link between test cases and requirements for their proposal. However, they do not describe how the case companies were documenting this information. They also do not suggest how such links can be generated. TEMSA [25, 26, 29] develop and use feature models and component family models, to ensure feature coverage in regression test selection of a software product line system. MPP [48, 49] uses the coverage of functionality of the system by individual test cases as a criterion to prioritise test cases.

4.7.2 Design artefacts

Wang et al. [24–29] use feature models and component feature models. These models along with an annotated classification of test cases are used for test case selection. Similar to the approach of Wang et al., Lochau et al. [50] also exploit models (in their case, delta-oriented component test models and integration test models). They also used existing documentation from the industrial partners and interviews with practitioners to develop and validate these models.

For an automotive embedded system, Vöst and Wagner [30] propose the use of system architecture (system specifications) for test case selection. System specifications and test case traces were used to create a mapping between components and test cases using them.

4.7.3 Source code

In IEEE standard for software test documentation, regression testing is defined as: "selective retesting of a system or component to verify that modifications have not caused unintended effects and that the system or components still complies with its specified requirements" [10].

Therefore, several regression testing techniques attempt to leverage available information to localise changes in a software system that can then inform the decision of which test cases to run and in which order. Some such techniques, work with source code and its version history to identify the change. Using source code has two advantages, first, several static and dynamic approaches exist to link test-cases to source code (e.g. once we have localised the change, identifying change traversing test-cases to select or prioritise is possible). The second advantage is that most commercial organisations use a configuration management system. Thus, the techniques that utilise revision history are relevant for industrial settings.

For example, FaultTracer [67], CCB [81], Fix-cache [21, 71], EFW [22, 23], and Difference-Engine [76] utilise revision history of source code for regression testing. Similarly, THEO [65] uses the number of contributors to the code base as input.

Several techniques require access to actual source code to work. Carlson et al. [80] propose the use of a clustering approach that computes and uses code metrics as one of the criteria for test case prioritisation. REPiR [37] uses information retrieval techniques to prioritise test cases that cover the changes in source code. It relies on the likelihood that similar keywords are used in source code literal and comments as in the test cases.

GWT-SRT [64] instruments source code to be able to generate traces that are used to connect test-cases and source code. This information along with control flow graphs (to isolate code changes) are used for selective regression testing in the context of web applications.

4.7.4 Intermediate and binary code

In cases when the source code is either not available, or it is not feasible to use it, there are some techniques that work on intermediate and binary code instead of source code to localise change between two versions of a software system. REPiR [37] and CMAG [63] use intermediate code to identify changes. While I-BACCI [11–14], Echelon [34], OnSpot [58] and Pasala and Bhowmick's proposed technique [45] work with binaries to localise change.

4.7.5 Issues

Some techniques utilise information typically residing in issue management systems [21, 65, 71]. Provided that an issue originates in a fault revealed by a test case, the attributes of that issue may be used to recreate a link between the said test case and the source files that were updated to fix the issue [21, 71]. Herzig et al. [65] utilise information about the closed defect reports (e.g. the time it took to fix the issue) in a cost model weighing the cost of running a test case against skipping it. The technique described by Marijan et al. [48, 49] uses the severity information from defect reports, prioritising test cases that reveal faults of high severity.

Among the included papers, no proposal presents an approach to recreate links between defect reports and mapping to related test cases. Therefore, if practitioners want to use one of the techniques that leverage fault coverage by test cases or other fault-related information (like the severity of faults etc.) they must document and maintain the links between these artefacts.

4.7.6 Test cases

Test cases refer to the specification of the tests and are static information entities (i.e., the information is documented at the design of the test and stored and maintained in a repository typically a test management system). 50% of the evaluated techniques rely on such information. What attributes of the test specifications being used vary between the different techniques, but it could be divided into traceability information and properties of the test case per se.

Traceability information is typically used for coverage optimisation selection [11, 22, 26, 32, 35, 42, 49, 52, 80, 81]; e.g. links to other information entities such as source code and requirements, or explicit coverage targets such as model coverage [26, 42] or functionality coverage [49].

Three techniques utilise the property attributes of the test cases (e.g age and estimated cost) solely for test prioritisation [34, 51, 73] and hence they are not dependent on static traceability links. Two are risk-based [51, 73] while one recreates traceability links dynamically [34], see Section 4.7.7.

4.7.7 Test executions

Test executions refer to an implicit information entity, meaning that its information attributes may be dynamically collected but are not stored and maintained for other purposes. Just as for the 'Test cases' described above the attributes of the 'Test executions' could be divided into coverage information (e.g. 'invocation chains' [45, 63], 'covered system states' [77], 'runtime component coverage' [45] and 'code coverage' [34, 35, 58, 63, 67, 80, 81]) and intrinsic properties of the executions (e.g. 'execution time' [34, 65], or 'invocation counts' [63])

Dynamically collected coverage information is used for similarity-based and coverage-based optimisation of regression tests [77, 80, 81] as well as change-based prediction of regression faults [34, 58, 67] while dynamically collected property attributes of the test executions are typically used for history-based cost optimisation of regression tests faults [63, 65].

4.7.8 Test reports

Test reports refer to the static records of the test executions, this information could either be automatically captured or entered manually by the testers. Such attributes are used for history-based optimisation of regression tests and most commonly used for regression test optimisation are verdicts [26, 49, 65, 73, 76, 84], time stamps [26, 49, 63] and links to the tested system configuration [65, 76]. Several information attributes of the test reports are similar to the test execution attribute or the test case attribute, but differ in how it is derived and maintained. As an example, test execution time could be an attribute of all three test information entities but as an attribute of a test case it is an estimation; as an attribute of a test execution, it is measured at runtime; and as an attribute of the test report, it is further recorded and maintained.

4.8 RQ3 – Mapping of current research

26 different techniques (reported in 38 papers) were classified under three taxonomies: context, effect and information (see Table 4.4). This mapping (see Table 4.5) helps to select techniques that address relevant context factors and deliver the target benefits for a given scope (regression test selection, prioritization or minimization). The information taxonomy helps to reason about whether the information is available or can be reasonably acquired in the unique context of a particular company. We demonstrate the use of this taxonomy in Section 4.9 in the form of technological rules [33] derived from this mapping (see Section 4.9.

4.8.1 Addressed context factors

In terms of system-related factors, when describing the context where the proposed techniques are applicable, 22 of the included techniques consider the scalability of techniques for large-scale software systems. Another 13 techniques take the complexity and the type of system under test into account. 9 techniques consider process related context factors. While only 4 techniques consider people-related factors.

4.8.2 Desired effects

Most techniques (25 out of the total 26) target improved effectiveness and efficiency in terms of finding known faults. Three techniques focus on improving coverage (which is considered a proxy for achieving confidence in the testing or confirming the quality of a system). Only one technique targets increased awareness in the decision-making process in the scope of regression testing.

4.8.3 Information sources

Except regression testing techniques that rely solely on the history of test-cases, most techniques use information beyond the test cases to select, prioritise or minimise the regression testing suite. Such approaches rely on documented/generated links between test cases and other artefacts. The 26 techniques included in this study utilise information contained in nine different types of software engineering artefacts.

Only two and five techniques use information related to requirements and design artefacts, respectively. Attributes of source code are used in nine techniques while seven techniques only rely on intermediate or binary code among other information sources. Ten techniques use information about test cases. Moreover, ten and eight techniques use information from test executions and test reports. Only four techniques make use of the issue reports.

Table 4.5: Mapping of techniques to the taxonomy

Technique	Study ID	Scope			Addressed context factors			Desired effects			Utilised information (entities)								
		Selection	Prioritization	Minimization	System-related	Process-related	People-related	Test coverage	Efficiency and Effectiveness	Awareness	Requirements	Design artefacts	Source code	Intermediate code	Binary code	Test cases	Test execution	Test reports	Issues
TEMSA	S13 – S18	✓	✓	✓	✓		✓	✓	✓			✓				✓		✓	
History based prioritization (HPro)	S26	✓	✓		✓	✓	✓		✓	✓						✓		✓	
classification tree testing (DART)	S19, S20	✓			✓	✓		✓	✓			✓				✓			
I-BACCI	S9 – S12	✓			✓				✓						✓				
Value_based	S33		✓		✓	✓			✓		✓					✓		✓	
multi-perspective prioritisation (MPP)	S3, S4		✓		✓	✓		✓	✓							✓		✓	✓
RTrace	S21		✓		✓				✓		✓					✓			
Echelon	S29		✓		✓				✓						✓	✓	✓		
Information retrieval (REPiR)	S2		✓		✓				✓				✓	✓					
EFW	S7, S8	✓		✓	✓				✓				✓			✓			
Fix-cache	S24, S25	✓			✓				✓				✓						✓
Most Frequent Failures	S34	✓			✓				✓									✓	
Continuous Multi-scale Additional Greedy prioritisation (CMAG)	S28	✓	✓		✓				✓					✓			✓	✓	
GWT-SRT	S30	✓			✓				✓				✓						
Clustering (based on coverage, fault history and code metrics)	S37	✓	✓						✓			✓	✓				✓		✓
FTOPSIS	S22		✓		✓		✓		✓							✓			
Difference engine	S1	✓			✓	✓			✓				✓					✓	
Change and coverage based (CCB)	S5	✓			✓	✓			✓				✓				✓		
Similarity based minimisation	S36			✓	✓				✓								✓		
THEO	S32	✓			✓				✓				✓				✓	✓	✓
DynamicOverlay / OnSpot	S23	✓			✓				✓						✓		✓		
Class firewall	S6	✓			✓	✓	✓		✓					✓	✓	✓	✓		
model-based architectural regression testing	S35	✓			✓	✓			✓			✓							
component interaction graph test case selection	S31	✓			✓				✓						✓		✓		
keyword-based-traces	S27	✓			✓				✓			✓							
FaultTracer	S38	✓			✓								✓				✓		

4.9 Suggestions for practitioners

Practitioners may utilise the results of this study in different ways. The mappings of techniques to each category may guide the practitioner looking for relevant research. The taxonomies could also be used to compare a set of possible solutions found in the research, or those designed by engineers at a company.

In Table 4.4, three taxonomies for describing regression testing problems and techniques were introduced. In Table 4.5, we present a mapping of the included papers to the three taxonomies. A practitioner can use the taxonomies and the mapping to identify recommendations that are likely to help them design a solution in their unique context. The mapping of techniques to the three taxonomies may be read as technological rules [33] i.e., "To achieve <**effect**> in <**context**> apply <**technique**>", which in turn should be interpreted as recommendations (or advise) extracted from research.

Such rules could be formulated in detail for a single technique (i.e. one row in the mapping, as in example TR1) or with fewer details for a set of techniques (by including only the common denominators for that set, TR2) or in more general terms by selecting nodes at a higher level in the taxonomy (TR3). Three illustrative examples (TR1-3) are given:

TR 1: To reduce the regression test suite and testing time when regression testing large scale software systems utilise the following information attributes: #contributors of a piece of code, measured execution time, verdict, build type, variant under test and link to tested branch from test reports and fix time in issue reports. This example was extracted from an evaluation of a tool called THEO ([65]).

TR 2: To increase feature coverage, reduce testing time and improve fault detection capability when regression testing customisable, real-time systems, utilise information about verdicts and execution time in test reports. (This rule is based on the intersection of the classification of two different techniques, Multi-perspective prioritisation [49] and TEMSA [28], which have been evaluated in several studies [24–29, 48, 49].)

TR 3: To improve efficiency and effectiveness when regression testing large scale complex systems, utilise information attributes of the test reports. (This rule is a generalisation of TR2 and is supported by the same studies and another two [73, 76].)

From the research communication perspective, we argue that formulating such rules (albeit by compromising some details) will help to communicate our research in particular to industry practitioners.

By selecting the most important aspects of the two problem-defining taxonomies (i.e. desired effects and addressed context factors), for the organisation, one or more research-based recommendations (in terms of technological rules) may be extracted from the mapping in this study together with pointers to the matching literature. These recommendations could then be used as input to the design of the specific solution for the organisation.

4.10 Recommendations for researchers

As for testing, in general, the value of a regression testing technique could be measured either in terms of its ability to increase confidence in testing or in terms of its ability to improve fault detection with limited time and resources. Those high-level goals are shared by researchers and practitioners but with some variations when it comes to details and priorities [88]. The recommendations given here are based on our comparison of what we found in the literature and the feedback from our industry partners.

Evaluate coverage of regression testing techniques at the feature level Confidence is achieved by measuring any type of coverage. However, of the facets of our effect taxonomy, coverage was the least important for the practitioners and at the detailed level of our taxonomy only feature coverage was considered relevant. This is also reflected in the literature [26, 37, 49]. Few techniques were evaluated with respect to coverage and of the few the majority focused on feature coverage.

Focus evaluation on the detection of severe faults and reduction of cost From the practitioners' perspective, the ability of a technique to detect severe faults and to reduce cost in terms of man- and machine-time was considered more important. While confidence, and coverage, always being priorities in the design of new tests, the pursuit of trust in the regression test suite is often the root cause of increasing costs and decreasing the effectiveness of regression testing - as more and more test cases are added just in case [74]. Hence, the main driver for most industrial studies on regression testing is cost reduction and precision of regression testing. 70% of the techniques in our study were evaluated with respect to cost reduction. Furthermore, effectiveness should be considered in terms of the number of severe faults, rather than in the number of faults in general as there is also a cost-benefit trade-off in the issue backlog. Only 40% of the techniques in our study were evaluated with respect to fault detection and of those only two considered severity [49, 52].

Report addressed context factors in industrial evaluations To support generalisation of results between industrial contexts, relevant contextual factors need to be identified and clearly reported. Here relevant context factors denote context factors that are either causing the problems to be solved or affecting the applicability or effect of the solution. Such relevance may be observed or assumed by the stakeholder or the researcher.

Despite being a selection of industrial evaluations, reporting the context factors seems to be of low priority. In 10% of the evaluations, we did not find any context descriptions at all. For the remaining 90% at least system factors such as size, complexity and type of system under test are reported. Only 30% described the current process, which will affect (or be affected by) the adoption of the technique and only 15% reported people-related factors.

Rather than providing a general and extensive description of the case context, as proposed in previous research [44] we recommend a careful selection of context factors to report and discuss. Such selection could be guided by the context-taxonomy provided in Table 4.4.

Study if and how the proposed context factors are relevant In most cases, the relevance of the context factors described in the included papers is assumed rather than observed. Furthermore, they are described on a rather high abstraction level. Thus, there is room for more research on the relevance of various context factors for regression testing.

Study people-related factors As a research area struggling to gain traction in industry [55, 56, 83] we believe that there is a need to investigate people-related factors. The need for transparency and understandability that leads to trust in the results of regression testing techniques was highlighted by the industry partners. Only one study in our included set has investigated these factors [73]. Future research in this direction that takes into account the needs and concerns of potential users may increase the likelihood of successful adoption of regression testing techniques in the industry.

4.11 Conclusion

In this paper, we report an extensive search for and an in-depth analysis of applicability and relevance of regression testing techniques reported in the literature. We focused on techniques that have been applied to large-scale software systems in industrial contexts. Based on the literature review and in collaboration with our industrial partners, we propose three taxonomies that enable practitioners and researchers to assess and compare the relevance and applicability of regression testing techniques for a given industrial context.

The taxonomies extend three out of the four facets of the SERP-test taxonomy [75]: i.e. addressed context factors, desired improvements and characteristics of the techniques from an applicability point of view (required information and underlying assumptions). It allows for characterisation of regression techniques and helps to determine which of these techniques could be suitable in a given context and to indicate what benefits could be expected from its application. The identification of information needs for these techniques further assists a reader to reason about the implications regarding the cost of adoption [87]. In this report, we apply the taxonomies on the 38 papers that are included in the review. However, initially, we identified more than 1000 papers on regression testing and there are many techniques, not included in the review, that may still be relevant and applicable in some industrial contexts. The aim of the taxonomies is to support assessment also of them and of new proposals or adaptations of techniques.

In our interaction with the practitioners, we identified some discrepancies in researchers focus and the perceived needs in the industry. One such example is the commonly used measure of effectiveness in terms of various levels of code coverage. Some types of information (such as coverage information) that are extensively studied in the literature were found to be only partially relevant to the practitioners (e.g., only at the feature level) for evaluating the benefits of a regression testing technique. At the same time, some extremely relevant information in choosing technique (e.g. the context information) is completely neglected in some existing studies.

For academia, this study can help to use evaluation criteria and contexts that are representative of industrial needs. This work also supports reporting the research results to facilitate readers

making an informed decision with a consideration for relevance to their context, potential benefits and the likely investment required to use the technique.

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Chapter 5

A Systematic Mapping of Test Case Generation Techniques Using UML Interaction Diagram

5.1 Introduction

Testing is an integral part of the software development life cycle to improve the quality and reliability of software [36]. It is one of the most expensive and labour intensive tasks. Organizations spend more than 50% of their total budget to test the software [21, 65]. Testing can be automated to various degrees, such as completely manual, semi-automated or fully automated. Automated testing has a benefit in terms of cost reduction, ease of use and better coverage [21, 61].

The main objective of testing is to verify that the software meets the acceptance criteria as documented in requirements specifications [30]. There are two main aspects of this objective (1) to demonstrate that the requirements specifications are correct and (2) to demonstrate that design and code of software fulfills with requirements [30].

Among several testing activities the generation of test cases is an intellectually challenging task [7, 10, 36, 61]. In recent times, the complexity of software is increasing rapidly, which requires sufficient testing mechanisms to identify and eliminate the defects. Researchers and practitioners proposed various automated test case generation techniques during the last decade. Model Based Testing (MBT) is one of testing techniques. In the MBT approach, Unified Modeling Language (UML) models are commonly used as a means to generate test cases. Different

system aspects could be tested from different UML models. UML models can be classified according to static or dynamic aspects of a system (c.f. [74]). Static aspects of a system can be represented by the structural models whereas dynamic aspects of the system can be represented by the behavioral models. Interaction diagrams fall under the category of behavioral models. Other diagrams related to this category are *use case diagram, stat chart diagram and activity diagram*. Whereas, structural models are represented by *class diagram, component diagram, deployment diagram, object diagram, package diagram, profile diagram, and composite diagram* [74]. In this study we focus on dynamic models as testing focuses on the dynamic aspects of the system during its execution. Interaction diagrams are of high relevance in later testing activities (such as integration testing) as the interaction between different components have to be considered.

The first step to test software automatically is to describe its behavior or structure either statically or dynamically by using UML models [45, 61]. By using UML models, practitioners may perform unit [43, 65], integration [38, 40, 57, 58], system [22, 26, 30] and conformance testing [50].

Looking at existing literature reviews, the reviews so far did not put their main focus on interaction diagrams, and the reviews did not follow a documented systematic procedure [8, 15, 48]. Practitioners and researchers have proposed various techniques to generate test cases from UML interaction diagrams during the past few years. We believe that a classification of existing MBT techniques based on UML Interaction diagrams is essential for researchers before proceeding toward proposing new approaches using interaction diagrams. Furthermore, practitioners and researchers currently utilizing interaction diagrams have an inventory of results as well as a documentation of their capabilities and limitations. Furthermore, the quality of the study is assessed. In order to complement the existing literature reviews, we investigate the use of interaction diagrams making the following contributions:

- C1: Identify the approaches for MBT test case generation proposed in the literature.
- C2: Identify the capabilities and limitations of the approaches.
- C3: Characterize the study quality using the rigor and relevance scoring framework by Ivarsson and Gorschek [67].

As a research method we utilized the guidelines for systematic mappings by Petersen et al,. [75, 76]. Furthermore, for quality assessment the rigor and relevance scoring framework by Ivarsson and Gorschek [67] was used. Rigor focuses on the scientific quality with regard to the research process and method used. Relevance is focused on whether evaluations have been conducted in a realistic environment with regard to scale, context, and subjects.

The rest of this paper is structured as section: Section 5.2 discusses the related work regarding the already presented surveys/ reviews in area of model base testing. Section 5.3 describes the research methodology. The MBT test case generation approaches along with their capabilities and limitations compared and the results of the quality assessment are presented in Section 5.4. The results are summarized and discussed in Section 5.5. Section 5.6 concludes the paper.

5.2 Related work

A number of literature reviews related to model based testing have been published. An overview of related literature reviews is provided in Table 5.1. The table states the objectives, the research method, as well as the number of primary studies that were included in the literature reviews. Several studies were generic without a particular focus on interaction diagrams, such as [8, 12, 44, 46]. Only a small set of studies included were discovered focusing on interaction diagrams. For example, the review by Shirole and Kumar [48] focused on behavioral models. Dias Neto [12] and Shirole and Kumar [48] identified 21 and 29 studies based on interaction diagrams, retrospectively.

Looking at the methodologies applied, three reviews conducted a traditional literature review [8, 14, 15, 48]. Three studies [12, 44, 47] referred to the guidelines by Kitchenham and Charters [77] as their guide for conducting their systematic literature reviews. One mapping study [46] was reported. From a methodological perspective it is also noteworthy that no quality assessment has been conducted.

We complement the existing literature reviews with an explicit focus on interaction-based diagrams (finding a total of 55 articles with a focus on interaction diagram) and hence expanding the findings by Shirole and Kumar [48]. Furthermore, we complement the existing work by analyzing the strength of evidence provided through the means of the quality assessment rubric proposed by Ivarsson and Gorschek [67]. The rubric describes rules by which reported studies may be assessed for their scientific rigor and practical relevance. The details of the rubric are described in the following section.

5.3 Research method

In this study, we have adopted the systematic mapping study (SMS) as our research method. Systematic mapping studies are meant to provide an overview of a research area. SMS classify and count the contribution about the categories of that classification. Like systematic literature review, it provides a systematic way to search the literature, to know what are the topics that have been reported in the literature and what are the publication venues for the area of research [75, 76].

We followed the guidelines provided in [76], in these guidelines the authors included some important aspects from the SLR guidelines proposed by Kitchenham and Charters [77].

5.3.1 Planning adn conduction the mapping

This section describes the decision making regarding the conduct of systematic mapping study.

Research Questions

The objective of this paper is to analyze the research on UML interaction diagram based test case generation. Research questions and objectives are highlighted in Table 5.2. The research

Table 5.1: Existing Secondary Studies on MBT

Authors/Ref.	Aim	Method	#Studies
Sing, [8]	Present test generation techniques for software testing of object oriented systems	LR	55
Dias Neto, [12]	Characteristics, application, and limitations of MBT approaches	SLR	78
Häser et al., [44]	Classification of model-based testing approaches;characterize the type of assessment done to guide the testing process; determine the coverage of non-functional requirements by MBT approaches	SLR	83
Shafique and Labiche, [47]	Identification of MBT testing tools; extraction oft the capabilities of tools	SLR	12
Utting et al., [15]	Proposal of a taxonomy to classify MBT approaches; Classification of four tools to demonstrate the use of the taxonomy	LR	55
Shirole and Kumar, [48]	Provide an overview of solutions to generate tests from behavioral models (sequence diagram, state machine, activity diaram)	LR	29
Mohi-Aldeen et al., [46]	Coverage criteria used to drive automated testing; methods used for test generation; benefits of approaches	SM	85

questions map directly to the objectives stated in the introduction, namely to identify approaches for MBT test case generation (RQ1), extraction of merits and demerits (RQ2) and assessment of the quality of the studies with respect to rigor and relevance (RQ3).

Developing and validating the study protocol

The development and validation of study protocol is critical. The developed protocol is critically reviewed by the fourth author, who is an experienced researcher. He has more than 80 research publications, mainly from the testing domain. He has published 15 survey/ review papers. He has 28 years of industrial, teaching and research experience. He is serving as an associate professor at Faculty of Computing Capital University of Science and Technology (CUST), Islamabad, Pakistan. Modifications were suggested in research question, publication selection, inclusion/exclusion criteria and data extraction phase. After modifying this suggestion, the same expert again critically reviewed developed protocol. Thus, this was a means of using observer triangulation to increase the quality of the research.

Table 5.2: Research questions

ID		**Research question**
RQ1		What are various proposed MBT test case generation approaches based on UML interaction diagrams?
	RQ1.1	What are the publication trends of test case generation approaches based on UML interaction diagrams?
	RQ1.2	How can we classify the test case generation techniques based on UML interaction diagrams?
RQ2		What capabilities and limitations are observed in relation to the approaches?
RQ3		What is the rigor and relevance of the included primary studies according to the rigor and relevance scoring rubric proposed by Ivarsson and Gorschek?
	RQ3.1	How primary studies refer to each other?

Identifying the related literature

To identify the relevant literature, the main and alternative search term were identified in Table 5.3 by specifying the Population and Intervention. Even though Comparison and Outcome were proposed to consider during the search, additional search terms are likely to reduce the set of identified studies, as the Comparison and Outcome variables may not be mentioned in the abstract and title [16, 17]. In our case the Population is *"UML diagrams"* and the Intervention is *"test case generation*. Major terms used to search the literature include *"test case generation"*, *"sequence diagram"*, *"collaboration diagram"*, *"model based testing"* and *"UML diagrams"*.

Table 5.3: Search terms

Main search Terms	Alternative search
Test Case Generation	Automated Test case generation, Test Path generation
Sequence Diagram	UML sequence Diagram, Interaction Diagrams, UML Interaction diagrams
Collaboration diagram	UML collaboration diagram, Communication diagram, UML interaction diagrams
Model based testing	Testing using UML models
UML diagrams	UML models, UML behavioural diagram

Search string construction

Three different search strings have been constructed. One search string focuses on sequence diagrams (Category *"SD"*), one on collaboration diagrams ("CD"), and one to identify testing for UML diagrams in general, combining sequence and collaboration diagrams and other UML models ("Combination/ Hybrid"). The search strings were as follows:

- *Sequence diagrams (SD):* ("Test case generation" OR "Automated test generation" OR "Test Path Generation") AND "Model based testing" AND ("Sequence diagram" OR "UML sequence diagram" OR "UML interaction diagrams")
- *Collaboration diagrams (CD):* ("Test case generation" OR "Automated test generation" OR "Test Path Generation") AND "Model based testing" AND ("Collaboration diagram" OR "UML collaboration diagram" OR "Communication diagram" OR "UML interaction diagrams")
- *Hybrids (H):* ("Test case generation" OR "Automated test generation" OR "Test Path Generation") AND "Model based testing" AND ("UML diagrams" OR "UML models" OR "UML behavioural models")

How the individual databases have been used for the search is specified in Appendix B. To collect the required literature the search strings were executed on various online resources. Table 5.4 summarizes the selection procedure adopted as well as the number of papers identified and selected. Title and abstract screening was performed on the identified publications. If a publication's title is related to testing (test case generation) and UML models, then this publication is selected further for abstract screening. During abstract screening we determined whether the publication is relevant to model based test case generation and it is using interaction diagrams. A total of 55 primary studies were selected (See Table 5.5). Among these 55 studies, 25 studies were found directly from the publishing databases (i.e. 17 from IEEE, 3 from Elsevier, & 5 from ACM). While other 30 primary studies were found through Google Scholar. Out of these 30 studies, 10 were from Springer, 8 from Scopus indexed journals, and 12 studies were selected from other sources. The following inclusion criteria were applied:

- IC1: Publication must be related to model based testing.
- IC2: Studies that proposed model based testing by the means of interaction diagrams.
- IC3: Studies that describe the capability of model based testing with respect to interaction diagrams
- IC4: Surveys (e.g. questionnaires or interviews) performed on MBT test case generation techniques
- IC5: Select only those studies written in English language

The following studies have been excluded:

- EC1: Studies which do not use interaction diagram although they belong to MBT technique

- EC2: Studies that are duplicated (i.e. If the same study found from more than one search engine)
- EC3: Studies with missing full-text
- EC4: Secondary studies (e.g. systematic reviews or mapping studies)

Table 5.4: Database results

Database	Search results	Selected(title screening)	Selected(abstract screening)
IEEE	250	65	17
Science Direct (Elsevier)	110	24	3
ACM	347	54	5
Google Scholar	656	107	30
Total	1363	240	55

Table 5.5: List of Primary Studies

Reference	Study ID	Reference	Study ID
[73]	S1	[59]	S29
[68]	S2	[60]	S30
[69]	S3	[61]	S31
[71]	S4	[62]	S32
[72]	S5	[7]	S33
[10]	S6	[64]	S34
[29]	S7	[9]	S35
[23]	S8	[24]	S36
[13]	S9	[19]	S37
[58]	S10	[37]	S38
[28]	S12	[56]	S39
[31]	S13	[22]	S40
[27]	S14	[30]	S41
[50]	S15	[54]	S42
[53]	S16	[32]	S43
[18]	S17	[63]	S44
[55]	S18	[26]	S45
[35]	S19	[49]	S46
[52]	S20	[51]	S47
[40]	S21	[11]	S48
[21]	S22	[36]	S49
[34]	S23	[42]	S50
[57]	S24	[65]	S51
[20]	S25	[33]	S52
[55]	S26	[43]	S53
[39]	S27	[66]	S54
[38]	S28	[41]	S55

To reduce the threats of biases and potential mistakes in the selection of studies the study selection was carried out by the first and second authors jointly, studies included or excluded by

the first author were crosschecked by the second author, while studies included or excluded by first author were crosschecked by the second author. Duplicate studies were eliminated during the crosscheck. Finally, a random crosscheck was applied by the fourth author.

Quality assessment

To assess the quality of the included primary studies we utilized the scoring rubric proposed by Ivarsson and Gorschek [67]. Rigor was evaluated based on three criteria (the description of context, study design and validity). Relevance was evaluated based on four criteria (subject, context, scale and research method). The criteria for rigor were scored on an ordinal scale as suggested by [67], namely strong, medium and weak description. The first author scored the studies, which were all reviewed by the third author. In case of corrections proposed, these were discussed and agreed upon with the first author. In the following the quality evaluation criteria are explained.

*Rigor:*The research rigor criteria check whether the methodology is described in a way so that the rigor of the research may be judged [67].

Context (C):

- *Strong description:* Context is strongly described and comparable with other context. We emphasize the subjects type (academic, industrial), development methodology and experience of subjects. If these factors are presented, then C evaluates to 1.
- *Medium description:* In absence of any factor (see strong description) C evaluates to 0.5.
- *Weak description:* If these factors are completely ignored then C evaluates to 0.

Study design (D):

- *Strong description:* The research design is clear to readers by documenting expected outcomes, measurement criteria, data selection and collection, etc., then D evaluates to 1.
- *Medium description:* In absence of an essential factor in the research design C evaluates to 0.5.
- *Weak description:* No description of the research design is provided, then D evaluates to 0.

Validity threats (V):

- *Strong description:* If internal, external, construct, and conclusion validity threats are highlighted then V evaluates to 1.
- *Medium description:* In case of subset of these threats are provided then V evaluates to 0.5.
- *Weak description:* If validity threats are not discussed then V evaluates to 0.

Relevance: Several measures are used to evaluate academic relevance in research. The impact of industrial relevance is hard to measure. The assessment criteria proposed by Ivarsson and Gorschek [67] assume that the relevance is higher if the study is conducted with realistic subjects, scale, and using research methods that facilitate investigations in realistic environments.

Subjects (U):

- Contribution to relevance: Subjects or users are delegate of real user such as for industry professional, then U evaluates to 1.
- Partially contribute to relevance: If subjects are researchers or students, then U evaluates to 0.5
- No contribution: If subjects are not mentioned, then U evaluates to 0.

Context (C):

- Contribution to relevance: The study is conducted in a real industrial setting, then C evaluates to 1.
- No contribution: The study is not conducted in a real industrial setting, then C evaluates to 0.

Scale (S):

- Contribution to relevance: The used application is representative of real (industry) systems in terms of scale, then S evaluates to 1.
- No contribution: Application is a toy example or down-scaled, then S evaluates to 0.

Data extraction and analysis

The selected studies are saved for the purpose of data extraction. The data extraction was performed jointly by authors. The second and third author randomly selected included primary studies and reviewed the results produced by the first author. The data extraction comprised of the following elements:

- *Publication data:* Publication ID, publication title, year of publication, type of publication, source of publication, author name, keywords
- *Test scope:* Type of testing, test objective
- *Input to tests:* UML model used, intermediate models constructed for test data generation
- *Data generation approach:* Description of test data generation process, algorithms used, tool support
- *Assessment:* Coverage criteria, research method, rigour and relevance scores
- *Outcome:* Merits and demerits, proposed future works and identified gaps

We utilized content analysis to group and assign studies to categories (e.g. categorizing the studies with regard to testing type, and type of intermediate models for test data generation). This shows which areas are covered by the literature, and is similar to the intent of a mapping study where an overview of an area is provided. Furthermore, narrative summaries for the different types of test generation approaches are provided.

5.3.2 Validity threats

The limitations of the study are discussed with regard to different types of validity threats, namely theoretical (internal) validity, generalizability, objectivity, and interpretive validity.

Theoretical validity: The scoring rubric used in this study assesses the reporting of studies, while the actual study design may not be described completely. Thus, the actual rigor and relevance may not be determined, but rather what is possible to judge from the presentation in the paper. The rubric favors results reported from practical applications. This is not to say that the results are not of value for practice, though given the current presentation evidence of a wide-spread technology transfer to industry was not found.

Generalizability: Generalizability is concerned with the ability to generalize the findings from this study to the population of studies. Given that searches are limited and may not always find all relevant studies the threat is relevant to this study. However, the results obtained from the papers are consistent and reveal a pattern of how test case generation approaches based on interaction diagrams are designed, consisting of the main steps of creating an intermediate form and applying an algorithm to generate test paths, and in some cases test cases. We also did not limit our search with regard to the evaluation done (e.g. only including case studies).

Objectivity: Objectivity determines the degree to which we can report our observations accurately reflecting the reality of the field. Multiple threats are of relevance here, which are shortly discussed:

- Missing relevant studies: Our search focused on interaction diagram types and not model-based testing in general. Thus, some studies from the population might have been missed. However, the search returned a high number of relevant studies with little noise. We also included a much larger set of studies on the topic when compared to previous previous literature reviews (see Section 5.2). This indicates that the systematic search helped to cover a larger portion of the population. However, given that the search terms were very specific, there is a risk of still missing studies from the population
- Biases in study selection, data extraction and analysis: The selection, data extraction and analysis activities are prone to biases and mistakes. Thus, multiple researchers have been involved and cross-checking of the studies has been done among the authors of the paper. The use of a research protocol is also a means of reducing bias. Though, the research protocol itself was only evaluated by one researcher, hence posing a threat to objectivity.

Interpretative validity: From the findings of the study conclusions are drawn. We utilized observer triangulation and discussed the implications and key findings among the authors. This reduces the threat of drawing wrong conclusions from the data.

5.4 Results

This section presents the findings of our study. We have organized the presentation of the results according to the research questions listed in Table 5.2.

5.4.1 RQ1: What are various proposed MBT test case generation approaches based on UML interaction diagrams?

RQ1 was divided into two sub-questions (RQ1.1 & RQ1.2). The purpose of the first sub-question was to see the trends of test case generation techniques which are using interaction diagrams as input. Whereas the second sub-question was designed to classify these test case generation techniques by different factors, for instance, by the input model, intermediate model, and the outcome of the techniques.

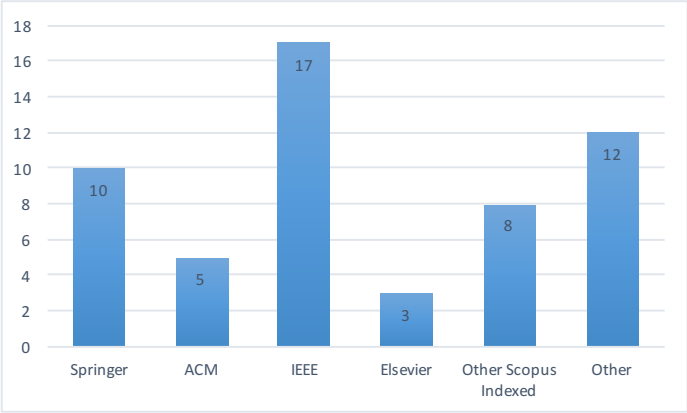
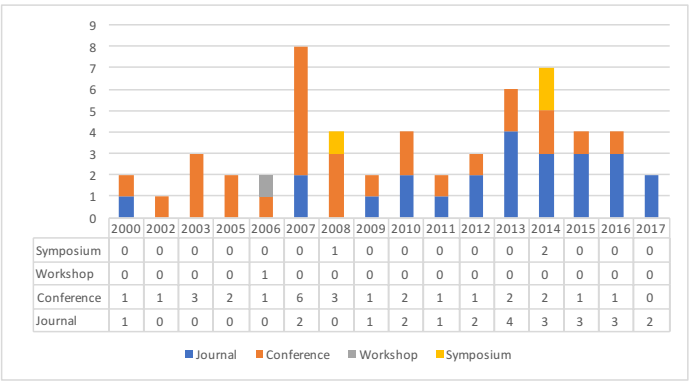


Figure 5.1: Publishing Venues of Primary Studies

RQ1.1:What are the publication trends of test case generation approaches based on UML interaction diagrams?

In response to this research question, we present the demographics of the studies, including the number of publications over time, and the publication forums targeted.

A majority of the primary studies (65%) included in this study are from the four publishing venues (IEEE, Springer, ACM, and Elsevier). Figure 5.1 presents the distribution of primary studies with respect to publishing venues. An increasing trend in the number of publications is seen with peaks in 2007 and 2014 (Figure 5.2). The publication trend shows that the research



	2000	2002	2003	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Symposium	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0
Workshop	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Conference	1	1	3	2	1	6	3	1	2	1	1	2	2	1	1	0
Journal	1	0	0	0	0	2	0	1	2	1	2	4	3	3	3	2

Figure 5.2: Year and Venue Wise Distribution of Primary Studies

area is growing gradually. A complete list of primary studies and the corresponding publication venues is presented in Table C.1 (See Appendix C). It is apparent that only a few well known journals in the field of software engineering have been published in (e.g. Information and Software Technology and ACM SIGSOFT Software Engineering Notes). In addition, many different publication forums have been targeted. Hence, no clear recommendation could be given where to start to look for papers on the topic.

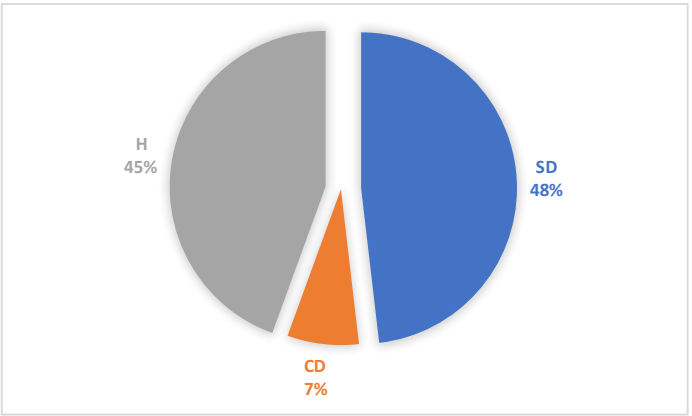


Figure 5.3: Distribution of studies according to input model used

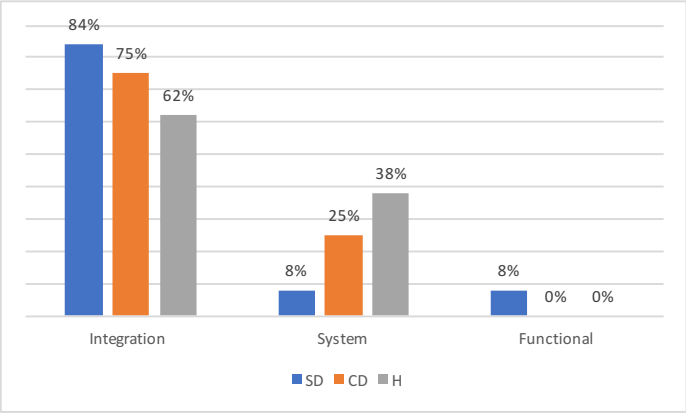


Figure 5.4: Distribution of studies according to testing types covered

RQ1.2: How can we classify the test case generation techniques based on UML interaction diagrams?

The selected UML interaction diagram based testing techniques are reviewed regarding their similarities and differences. The majority of the techniques reported in the literature use UML sequence diagram as input for test case generation and are marked as category *"SD"*, in the selected primary studies 48% techniques are based on sequence diagram. UML collaboration diagram based approaches are also identified and marked as category *"CD"*, only 7% of the selected primary studies belong to this category. 45% of the selected studies are using interaction diagrams along with some other UML model as input for test case generation, we refer these techniques as hybrid solutions and mark as category *"H"*. Figure 5.3 shows the distribution of the primary studies according to the type of test case generation techniques.

Regarding the testing types, 84% of the SD-based studies are proposed for the integration testing, while 8% for the functional, and 8% studies are proposed for the system testing. Similarly, 75% of the CD-based studies are proposed for integration testing, and 25% for system testing. Finally, 62% of the hybrid solution based studies are proposed for integration testing, and 38% of these solution work for system testing. Figure 5.4 presents the classification of proposed techniques according to the testing types covered. A complete overview of the categories of techniques with regard to their testing types and intermediate models generated is presented in Table 5.6. The models form the basis to generate the test paths. Some techniques only determine the test paths that should be covered. However, in order to execute the paths the test data still needs to be generated (e.g. in the case of a decision node, the two input values for it to either evaluate to true or false need to be determined). The input values are also referred to as test data, i.e. concrete inputs to be given to the system under test.

Table 5.6: Overview of Solutions

Category	Testing type	Intermediate model	References
SD	Integration	Graph	[13, 18, 20, 31, 34, 40, 50, 52, 53, 55, 58, 68, 69]
		XMI	[38, 39]
		Dependency table	[27, 28]
		Tree	[21]
		SLT	[73]
		ETDA	[71]
	System	Graph	[35]
		Activity	[72]
	Functional	Graph	[23, 29]
	Conformance	Graph	[50]
CD	Integration	Graph	[59, 60]
		Tree	[61]
	System	Graph	[62]
H	Integration	Graph	[7, 11, 36, 37, 49, 63, 65]
		XMI	[9, 33, 51, 54]
		Tree	[19],
		Petal files	[32]
		SCOTEM	[64]
	System	Graph	[22, 24, 26, 30, 42, 56, 70]
		Activity Diagram	[41, 66]

In the following sub-sections we provide a synthesis of how the approaches proposed in the literature (SD, CD and H) are structured.

Solutions Using SD

We found a total of 26 studies that are using the sequence diagram as an input model, Figure 5.5 presents an overview of these. The activity diagram shows the different possibilities described in the literature. The references in the diagram show how the techniques in the papers are structured. The first step towards the test case generation is that sequence diagram is transformed into intermediate forms, which are then used as a basis for generating the tests.

Common intermediate forms are LTS (Labelled Transition Systems) [29], XML Metadata Interchange (XMI) [38, 39], sequence dependency table [27, 28] and graphs [10, 13, 18, 20, 21, 23, 27, 31, 34, 35, 40, 52, 53, 55, 68, 69]. Two studies [58, 72] transform the sequence diagram into activity diagram. One study [73] generates the stimulus link table (SLT) from the sequence diagram. The techniques presented in [50, 55, 57] do not use an intermediate form. While the technique presented in [71] make use of event deterministic finite automata (ETDA).

SD based Solutions Using Graph and its variants as intermediate form: Graphs are the most commonly used intermediate form, 65% of the SD based solutions use the graph as intermediate form, though the type of graph differs, as is shown in Figure 5.5.

Bao-Lin et al. [21] converted the sequence diagram into a tree representation. The tree is traversed to select the conditional predicates. Bao-Lin et al. use of OCL to describe the pre- and post-conditions. Finally, function minimization is used to generate test data from conditional

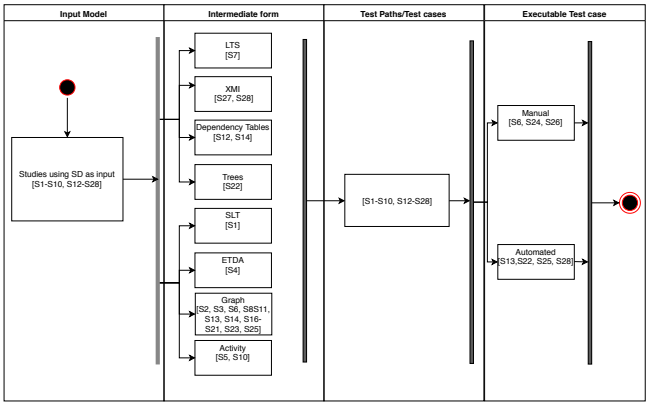


Figure 5.5: Solutions using sequence diagram (SD) as input

predicates.

A wait-for graph was used by Patnaik et al. as well as Fraikin and Leonhardt [38, 53] to identify deadlock points. The primary objective of their techniques is to identify concurrency issues. Both techniques [38, 53] only generate test paths.

Hoseini and Jalili [34] generated a control flow graph and thereafter used a prime path extraction algorithm to generate the test paths. A message control flow graph is used as an intermediate form by Jena et al. as well as Lei and Lin [10, 52]. Thereafter the graph is traversed using the depth first search algorithm. Lei and Lin [52] also provide an automated tool that can transform sequence diagrams into control flow graphs and then generate the test paths automatically. Their technique also works for test case generation. The techniques presented in [10, 34] use a genetic algorithm to calculate the fitness value for generated test paths to optimize them. A sequence graph was used by Samulatah et al. [40] as an intermediate form. The sequence graph was traversed using genetic algorithm to generate the test paths. A fitness function was defined calculating the fitness value of the generated test paths. Chandnani et al. [68] presented a model based test case generation technique to test the interaction of objects. A sequence dependency table form the sequence diagrams is created and then a control flow graph is generated. The intermediate graph is traversed into depth first manner to obtain test paths. Finally test cases are generated using particle a swarm optimization algorithm (PSO). Rhmann and Saxena [69] converted sequence diagram into message flow graphs. They used a depth first search algorithm to traverse the message flow graph and generated the test paths.

The technique presented by Shirole and Kumar [58] uses activity diagrams as an intermediate model. Test scenarios are generated by using concurrent queue search (CQS). Test scenarios generated here are useful for detecting data safety errors. Seo et al. [72] presented a test case generation technique based on sequence diagrams. The sequence diagram is transformed into an activity diagram, which represents the scenario of sequence diagram. In the next step, the activity

diagram was fragmented into sub activities. UML testing-profile based test case were designed, on the basis of the principal that each individual activity represents a test scenario. A concurrent composite graph was used by Khandai et al. [18] who generated test paths by traversing the graph with the help of a message sequence graph algorithm. Khandai et al. also make use of the Object Constraint Language (OCL). Both techniques [18, 58] are meant to detect concurrency errors.

A sequence dependency graph was used as an intermediate form in multiple studies [20, 23, 27, 31, 35] . Dhineshkumar et al [23] define pre-and-post conditions using OCL. Test paths are generated by traversing the sequence dependency graph with the help of an iterative depth first search algorithm. Panthi and Mohapatra [31] also use the depth first search algorithm to traverse the message sequence graph and predicate are selected. Using the selected predicates the source code is produced and then test cases are generated. The sequence dependency graph is traversed by the algorithm and test sequences are generated in [35]. Sequence dependency graph was also used as intermediate form by Samuel et al. [20]. They use the concept of dynamic slicing to generate test cases automatically. Priya and Malarchelvi [27] generate a sequence dependency table from the sequence diagram, which is further transformed into a sequence dependency graph. The depth first search algorithm is used to generate test paths from the sequence dependency graph. A sequence dependency table is also used by Shanti and Khumar [28] who use a genetic algorithm to generate test paths from the dependency table.

SD based Solutions Using other intermediate forms: XMI is used as intermediate form by Beyer et al. and Frain and Leonhardt [38, 39]. A test case generation tool called "MaTeLo" has been proposed by Beyer et al. [39]. The tool makes use of Markov chains as an intermediate model. It converts the sequence diagram into XMI format, thereafter using the Markov Chain Markup Language (MCML) to generate a Markov Chain Usage Model (MCUM). The main objective is to derive test cases compatible with the Testing and Test Control Notation version 3 (TTCN-3). This approach mainly focuses on statistical usage testing. A test tool for object oriented applications has been presented by Frain and Leonhardt [38]. They transform a Sequence diagram into XMI format. Their "SeDiteC" tool extracts the necessary information from XMI. The tool enables early testing and provide facilities such as automatic test stub generation and initialization of objects. Cartaxo et al. [29] introduced the functional (feature) test case generation method.In this method sequence diagrams are converted into a labeled transition system (LTS). In a LTS transitions are represented as states. Loops and alternative flows are also modeled in LTS. Cartaxo et al. used a depth first search (DFS) to generate test paths from the LTS.
SD based Solutions without any intermediate forms: Furthermore, solutions were available that did not use any intermediate form. The technique presented in [57] does not use any intermediate form, instead it makes use of a genetic algorithm to generate valid and invalid test paths and related test cases. To test the web applications a method has been suggested by Cho et al. [55]. Test cases are generated for single, mutual and integrated web pages. For single web pages, test cases are generated from self-call message in the sequence model. For mutual web pages test cases are extracted from messages passed between web pages. Integrated test cases are designed from messages, which are passed to the system. Moreover, a tool has been proposed, though it is not available online. Lund and Stolen [50] proposed an algorithm to derive test cases from UML sequence diagram. The sequence diagram is specified using neg (unary operator to specify

negative behavior) and assert (operator used to specify universal behavioral) operators. Lund and Stolen propose the STAIRS semantic, which is used for conformance testing. Zhang et al. [71] presented a test case generation approach based on sequence diagrams and event deterministic finite atuomata (ETDA). The objects participating in the sequence diagram are transformed into ETDA. Propositional projection temporal logic (PPTL) was used for model checking and the ETDA is verified. Finally, they get the composite automata by synthesis rules and generated the test cases. Mani and Prasanna [73] proposed a test case generation approach using sequence diagrams. A stimulus liking table (SLT) is generated from the sequence diagram. Using SLT the stimulus paths are derived and from the stimulus paths test cases were generated. Finally, they used boundary value analysis for test case reduction.

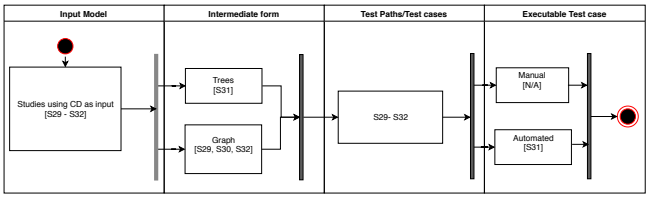


Figure 5.6: Solutions using collaboration diagram (CD) as input

Solutions Using CD

Test case generation techniques using collaboration diagrams as input models are presented in [59–62] (see Figure 5.6). All the techniques presented in [59–61] use different variants of graphs as an intermediate form. Trees are used by Samuel et al. [61] while a weighted graph is used by Ahmed et al. and Prasanna et al. [59, 60]. The weighted graph is then traversed using Prims and Dijkstra algorithms. An advantage of [60] over [59] is that mutation analysis is performed to evaluate the effectiveness of the proposed technique. Samuel et al. [61] convert a collaboration diagram into tree format. The predicates are selected from the tree structure in an iterative manner. At the end, a function minimization technique is applied to generate test data for the selected predicates. Abdurazik and Offutt [62] identified four items that could be used for static checking. The items that have been identified are classifier roles, collaborating pairs, message or stimulus, and local variable definition usage link pairs. For dynamic testing, they make use of message sequence paths. It is stated that message sequence paths includes all variable def-use link pairs, object def-use link pairs, object creation-usage link pairs, and object usage-destruction link pairs. The techniques proposed by [59, 60, 62] only generate test paths, the only technique which generates test data and test cases is proposed by Samuel et al. [61].

Hybrid Solutions

In this study, we found 24 techniques which are presenting hybrid solutions (combining interaction diagram with some other UML model) for integration testing [7, 9, 11, 19, 22, 24, 26, 30, 32, 33, 36, 37, 41–43, 49, 51, 54, 56, 63–66, 70]. An overview of the solutions is shown in Figure 5.7. Hybrid solution refer to techniques utilizing two or more input models. Interaction diagrams (sequence or collaboration) are the main input model along with another UML model type. The models which are being used as input for integration testing along with the interaction models are: class diagrams, state charts, activity diagrams, use case diagrams, and interaction overview diagrams. Among the investigated techniques there are 19 techniques [7, 11, 19, 22, 24, 26, 30, 32, 33, 36, 37, 41–43, 49, 51, 54, 56] which are using sequence diagram along with some other UML diagram as input model. Four solutions [63–66] use collaboration diagrams along with some other UML model. Figure 5.7 shows the combinations of UML diagrams used as input (e.g. sequence diagrams are combined with class diagrams, state charts, etc.).

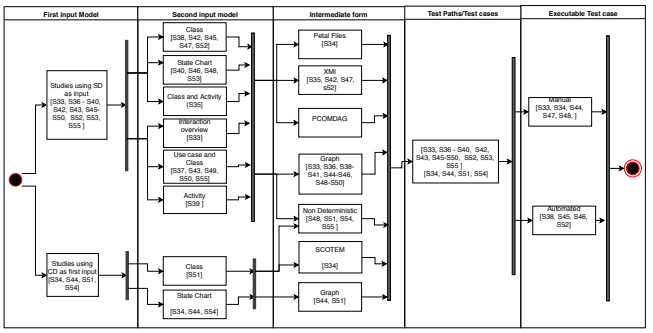


Figure 5.7: Solutions using interaction diagram and some other UML diagram (H) as input

All the hybrid solutions convert each primary input model into some intermediate forms and then convert these intermediate forms into final intermediate form, from which test paths are generated. The final intermediate forms used are XMI [9, 33, 43, 54], Petal files [32], "state collaboration test model" (SCOTEM) [64], "polymorphisms class object method acyclic graph" (PECOMDAG) [37], "system testing graph" [22, 42, 56], sequence diagram graph [24], activity-sequence graph [30], sequence interaction graph [7], test model grap [63], concurrent control flow [49], Extended Variable Assignment Graph (EVAG) [49], structured composite graph [26], and tree [19].

Twenty-two out of twenty-four techniques generate test paths. One technique presented by Wu et al. [66] does not generate test paths. Instead it derives a test adequacy criteria based on input diagrams, that is collaboration and state chart diagrams. Only a subset of techniques used

algorithms for the generation of test paths:

- Depth first search algorithm (DFS) [7, 10, 41]
- Breadth first search algorithm (BFS) [24, 26, 30]
- Traversing algorithms [37, 42, 54]
- Genetic Algorithm (GA) [22]
- Parsers [32, 51]

The techniques function in a similar way to the approaches described in Section 5.4.1. Given the similarity they are not explained in the same detail as the "SD"-based solutions.

Nine techniques [7, 11, 26, 33, 37, 49, 51, 63, 64] provide solutions for generating test data. Four techniques [26, 33, 37, 49] generate test data automatically while five techniques [7, 11, 51, 63, 64] rely on manual test data generation. An overview of the techniques based on hybrid solutions is presented in Figure 5.7.

5.4.2 RQ2: What capabilities and limitations are observed in relation to the approaches?

To respond RQ2 the capabilities and limitations of selected approaches are highlighted. Table 5.7 provides an overview of the capabilities. A subset of approaches (39%) supports the generation of test paths. Only very few studies (6%) also support the automated execution in connection to the generation.

The types of faults possible to detect are interaction, scenario and operational faults. Only for SD the ability of detecting concurrency problems has been highlighted. While test scenarios are generated, only a subset of solutions also provide support to generate test input data, either manually or automatically.

An important feature of the approaches proposed in the literature is the degree to which they were evaluated. The most commonly stated methods used for the evaluation are case studies and experiments. Furthermore, to demonstrate the merits of the approaches proof of concepts have been used, though they represent the weakest form of evaluation. Overall, 26 papers stated that they present evaluations either using case studies or experiments. In the following section presenting RQ3, the completeness of reporting with regard to rigor and relevance is assessed using the rubric by Ivarsson and Gorschek [67].

Coverage criteria were defined for the approaches, and the most commonly targeted criterion was path coverage, 43% of the selected studies are using this criterion. Among the other criteria, condition coverage was used by 13%, message coverage was used by 19%, and model coverage was used by 7% of the selected primary studies. While 18% of the studies are either using other criteria or they did not mention any.

The limitations are summarized in Table 5.8. The lack of tool support, test data generation, and test case execution are commonly highlighted. Furthermore, high complexity has been stressed as an issue. Every technique has to follow some specified step to generate test cases. A technique has high complexity if it is manual, semi-automated (with a number of different steps) and no tool support.

Table 5.7: Capabilities in relation to MBT approaches

Capabilities		SD	CD	H
Testing	Static, dynamic testing		[62]	[9]
	Test paths (scenario) generation	[10, 18, 34, 68, 69, 71, 72]	[60]	[22, 26, 30, 32, 36, 41, 42, 54, 56, 63–65, 70]
	Test case execution			[51, 63, 64]
Detection of faults	Interaction, scenario, operational	[10, 23, 27–29, 31, 40, 52, 57, 68, 69]	[60, 61]	[7, 22, 24, 33, 36, 42, 51, 54, 64, 70]
	Concurrency (e.g. deadlock)	[13, 18, 53, 58]		
Test input generation	Manual	[10, 52, 57]		[7, 49, 51, 63, 64]
	Automated (Efficient)	[20, 21, 31, 38]	[61]	[26], [33], [36]
Stated method	Experiment	[21, 28, 34, 57, 58]	[60]	[24]
	Case Study	[10, 27–29, 31, 40, 68, 69]	[59]	[7, 22, 30, 32, 36, 37, 49, 51, 54, 64, 65, 70]
	Proof of Concept	[13, 18, 20, 23, 35, 38, 52, 53, 72, 73]	[61, 62]	[9, 19, 26, 33, 41, 42, 56, 63]
Coverage criteria	Path	[23, 28, 29, 34, 37, 40, 52, 68, 69, 71, 72]	[59, 61]	[7, 22, 24, 30, 41, 56, 63, 64, 70]
	Predicates/ conditions	[20, 31]	[59]	[19, 26, 36, 37]
	Messages	[10, 57, 58]	[62]	[33, 42, 43, 51, 54, 66]
	Transitions	[35]		
	Model	[38]		[9, 32, 65]

5.4.3 RQ3: How strong the evidence with respect to rigor and relevance to support the outcome of various test case generation techniques?

The main objective of this section is to provide the score of individual selected publication according to rigor and relevance. The complete results of each publication containing an empirical study (i.e. case study or experiment) with respect to rigor and relevance are summarized in Tables 5.9 to 5.11. The tables show the studies that either stated that a case study or experiment, i.e. an empirical study has been conducted. It is evident that a high number of studies in all categories scored only the rating "0" according to the rubric by Ivarsson and Gorschek. The reason for the assessment can be found in the article by Wohlin [6], who highlights that *"case study is often a misused research method. In many papers, the authors actually mean example or illustration and not a case study in the way it is defined"*. In particular, Wohlin highlights the references by Yin and Runeson and Höst [4] as a guide to follow. Similarly, experiment was frequently used as a means to present results from operations on an example system. Though, many important parts of experimental research have not been documented. In particular the guidelines by Basili [3], Wohlin et al. [2] and Juristo [1] are to be highlighted here. None of the case studies referred to a

Table 5.8: Limitations

Limitations	SD	CD	H
No tool support	[10, 13, 18, 23, 27, 28, 34, 35, 40, 50, 53, 57, 58, 68, 69, 71–73]	[59, 61, 62]	[7, 19, 22, 24, 26, 30, 41–43, 63, 65, 66, 70]
No test data generation	[13, 18, 23, 27–29, 34, 35, 40, 53, 58]	[59, 60, 62]	[9, 19, 22, 24, 30, 32, 37, 42, 43, 54, 56, 65, 66]
High complexity	[10, 13, 18, 20, 28, 31, 34, 35, 50, 53, 68, 69, 71]	[59, 60]	[19, 22, 26, 41, 42, 56, 63]
No test case execution	[10, 13, 18, 23, 27, 28, 34, 35, 40, 50, 53, 57, 58, 68, 69, 72]	[59, 61, 62]	[7, 9, 19, 22, 30, 32, 36, 41–43, 54, 56, 70]
More test case generation	[18, 27]		[37]
Issues in transforming model into intermediate form	[10, 23, 29, 34, 35, 53]		[19, 24, 26]
Restriction in proposed methods	[38]	[61, 62]	[37, 49]

guide for the research method. Hence, a key area for improvement is to utilize guidelines and to correctly label the research method used. In many cases, the correct label (example or proof of concept) was used. In Table 5.11 we can see some good scores in the rigor column. Similarly, the relevance score is comparatively better for the studies presented during recent years. In Table 5.9 we can see the presence of rigor score for the years 2016 and 2017. So we can infer two facts, 1) quality of the recent studies regarding rigor score is slightly better, 2) hybrid solutions have better relevance score. These facts indicate that from an industry perspective hybrid solution (i.e., test case generation techniques using a combination of interaction diagrams along with some other model) are more relevant. However, regarding the overall results, it is visible that no clear trend of scores with respect to years can be seen in Tables 5.9 to 5.11 as we found papers with high and low scores for both new and old papers (see Figure 5.8).

RQ3.1: How primary studies refer to each other?

Another interesting factor is to see how the studies are related to each other. Of the 54 primary studies, only 26 studies are referred by the other primary studies. Generally, studies are said to be related with each other if authors are referring the other studies while defining their methodology. We found only two studies ([37] is citing [38], and [59] is citing [60]) in their methodology directly and explicitly drawing ideas from them. Other studies are referring each other mainly in the related work section or in the introduction section. Furthermore, it is of interest to see whether studies conduct a comparative analysis. Again, we found only two studies in which authors compared their work with already existing studies ([54] compared with [43] and [36] compared with [26]). A complete mapping of the references of the primary studies with each other are presented in Table 5.12.

Table 5.9: Rigor and relevance scores: Sequence Diagrams

Ref	Rigor				Relevance				Year
	C	D	V	C+D+V	U	C	S	U+C+S	
[73]	0.5	0	0	0.5	0	0	0	0	2017
[68]	0.5	0	0	0.5	0	0	0	0	2017
[69]	0.5	0.5	0	1	0	0	0	0	2016
[71]	0.5	0.5	0	1	0	0	0	0	2016
[72]	0.5	0	0	0.5	0	0	0	0	2016
[10]	0	0	0	0	0	0	0	0	2015
[29]	0	0	0	0	0	0.5	0	0.5	2014
[23]	0	0	0	0	0	0	0	0	2014
[13]	0	0.5	0	0.5	0	0	0	0	2014
[58]	0	0	0	0	0	0	0	0	2013
[28]	0	0	0	0	0	0	0	0	2013
[31]	0	0	0	0	0	0	0	0	2013
[27]	0	0	0	0	0	0	0	0	2012
[50]	0	0	0	0	0	0	0	0	2012
[53]	0	0	0	0	0	0	0	0	2011
[18]	0.5	0.5	0	1	0	0	0	0	2011
[55]	1	1	0	2	0.5	0	0.5	1	2010
[35]	0.5	0.5	0	1	0	0	0	0	2008
[52]	0	0	0	0	0	0	0	0	2008
[40]	0	0	0	0	0	0	0	0	2007
[21]	0	0	0	2	0	0	0	0	2007
[34]	0	0	0	0	0	0	0	0	2006
[57]	1	1	0.5	2.5	0.5	0	0	0.5	2005
[20]	0	0	0	0	0	0	0	0	2005
[38]	1	0.5	0	1.5	0	0	0	0	2002

Rigor– C: Context, D: Study Design, V: Validity threats
Relevance– U: User/Subjects, C: Context (industry), S: Scale

5.5 Discussion

This section thoroughly presents the analysis of results that are synthesized during review of literature with respect to research questions specified. Furthermore, relationships between the included papers are explored.

5.5.1 Analysis of research questions

With regard to **RQ1** (*What are various proposed MBT test case generation approaches based on UML interaction diagrams?*), we were interested to see to publication trends and classification of the techniques. Regarding publication trends, we found that the authors who published their articles in the journals, few of them targeted the good publication venues. On the other hand regarding conferences, we have found the majority of papers are from the conferences who have published their proceedings in IEEE, ACM, and Springer. One reason for not considering the good publication venues could be that the studies are not conducted rigorously, results of RQ3 support this analogy.

Table 5.10: Rigor and relevance scores: Collaboration Diagrams

Ref	Rigor				Relevance				Year
	C	D	V	C+D+V	U	C	S	U+C+S	
[59]	0	0	0	0	0	0	0	0	2013
[60]	0.5	1	0	1.5	0.5	0	0	0.5	2011
[61]	1	1	0	2	0	0	0	0	2006
[62]	0.5	0	0	0.5	0	0	0	0	2000

Rigor– C: Context, D: Study Design, V: Validity threats
Relevance– U: User/Subjects, C: Context (industry), S: Scale

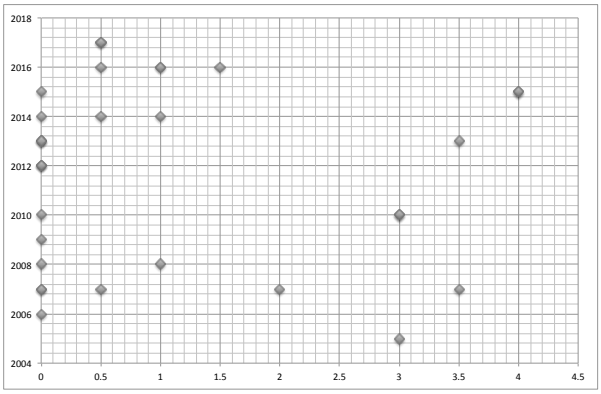


Figure 5.8: Sum of Rigor and Relevance Scores (X-Axis) and Year Published (Y-Axis)

Regarding the classification of the techniques, we found that majority (48%) of the proposed test case generation approaches belong to category "SD" transforming UML sequence diagrams into intermediate forms such as control flow graph, sequence dependency graph, or sequence diagram graph. The integration level testing has been the main focus of the approaches. The main objective for which techniques have been proposed includes, detection of faults such as interaction, operational, scenario [10, 20, 23, 27, 28] to address concurrency issues such as deadlock detection and synchronization [13, 18, 53, 58], and test paths generation with high coverage [31, 34, 35]. To generate a Markov chain model [39], the testing of web pages [55], to the test object oriented application [20, 38] were also achieved through these approaches. Commonly used traversing algorithms are depth first search [10, 18, 23, 27, 29, 31, 52] heuristic algorithm used in [28, 34, 34, 40, 40], breadth first search [18] and other algorithms that are proposed [13, 20, 35, 50, 53, 58].

During Review of literature, it has been noted that a few techniques (only 7%) have been identified in which input model is a UML collaboration model. The main objective of these techniques is to increase reliability and detection of faults (interaction). The intermediate repre-

Table 5.11: Rigor and relevance scores: Hybrid

Ref	Rigor				Relevance				Year
	C	D	V	C+D+V	U	C	S	U+C+S	
[70]	0	1	0.5	1.5	0	0	0	0	2016
[7]	1	1	0	2	0.5	0.5	0	2	2015
[64]	1	1	0.5	2.5	0.5	0	1	1.5	2015
[9]	0	0	0	0	0	0	0	0	2015
[24]	0	0	0	0	0	0	0	0	2014
[19]	0	0	0	0	0	0	0	0	2014
[37]	0.5	0	0	0.5	0	0	0.5	0.5	2014
[56]	0	0.5	0	0.5	0	0	0	0	2013
[22]	0	0	0	0	0	0	0	0	2012
[30]	0	0	0	0	0	0	0	0	2010
[54]	1	1	0.5	2.5	0.5	0	0	0.5	2010
[32]	0	0	0	0	0	0	0	0	2009
[63]	0.5	0.5	0	1	0	0	0	0	2009
[26]	05	1	0	1.5	0	0	0	0	2009
[49]	0.5	0.5	0	1	0	0	0	0	2008
[51]	0	0	0	0	0	0	0	0	2008
[11]	1	1	1	3	0.5	0	0	0.5	2007
[36]	0	0.5	0	0.5	0	0	0	0	2007
[42]	0	0.5	0	0.5	0	0	0	0	2007
[65]	0	0	0	0	0	0	0	0	2007
[33]	0.5	0	0	0.5	0	0	0	0	2007
[43]	0	0	0	0	0	0	0	0	2006
[41]	0.5	1	0	1.5	0	0	0	0	2001

Rigor– C: Context, D: Study Design, V: Validity threats
Relevance– U: User/Subjects, C: Context (industry), S: Scale

sentations that are generated include trees and weighted graphs. These intermediate forms are traversed to generate test paths. The traversing algorithms are Prims and Dijkstra for weighted graph.

The hybrid techniques for test case generation are also proposed, 45% of the selected primary studies belong to this category. The UML interaction models (sequence, collaboration) are used with combination of other diagram (Class, Activity, State chart and use case). The main objectives of these proposed technique is to detect interaction, scenario and operational faults [22, 24, 42], test cases generation from analysis artefacts [33, 36]. These inputs models are transformed into intermediate representations. The most common intermediate representation includes sequence interaction graph [10], structured composite graph [26], system testing graphs [42], activity sequence graph [30] and system graph [56]. This intermediate representation has been traversed to formulate the test paths. These test paths are then leads towards test cases generation.

With regard to RQ2 (*"What capabilities and limitations are observed in relation to the approaches?"*) the most common merits that are achieved in the proposed techniques includes detection of specific fault types, test input generation (few technique generates automated test input), and coverage criteria achieved (paths, messages, transition). The most commonly high-

Table 5.12: Primary Studies referring to each other

Referred to	**Referring Primary Studies**			
Primary Study	Introduction	Related Work	Methodology	Comparison
[62]	[7, 21, 59, 63]	[23, 24, 31, 40, 49, 61, 64]		
[64]	[10, 63],	[60]		
[54]		[18, 34, 36, 40]		
[49]	[27, 57]			
[39]		[29, 35]		
[41]	[43]	[23, 36, 49, 64]		
[29]	[36, 60]	[18, 57, 58]		
[38]	[31]	[22, 24, 29, 35–37, 40, 50, 52, 57, 61, 64]	[37]	
[45]	[64]	[33, 35, 61]		
[11]	[27, 57]			
[18]	[34]	[58]		
[21]		[18, 32, 40, 60]		
[50]		[35]		
[13]		[9]		
[26]				[36]
[31]	[34]	[32]		
[60]	[27]		[59]	
[27]	[9]			
[35]		[18, 34]		
[61]		[52]		
[42]		[7, 18, 36, 59, 60]		
[28]	[27, 59]	[32]		
[43]		[27, 35, 54]		[54]
[30]	[27]			
[36]		[7, 18, 23, 60]		
[56]		[22]		

lighted drawback was the lack of support for test data generation, no tool support, complexity of test generation steps, no support for test case execution. Furthermore, issues while converting input models into intermediate representations have been highlighted. In particular, high complexity and lack of tool support have been highlighted as hinders for a transfer of research results to industry practice [21]. Thus, this is an important focus of future research to address.

The rigor and relevance of studies has been assessed to answer RQ3 (*"What is the rigor and relevance of the included primary studies according to the rigor and relevance scoring rubric proposed by Ivarsson and Gorschek?"*) With regard to rigor of the primary studies only few studies received scores higher than "0". The main reason may be that no research guideline has been followed, and the research method has been wrongly labeled. As mentioned earlier, Wohlin [6] pointed out that in many cases illustrations or examples are presented instead of studies following the methodological guidelines. Hence, the clear need for empirical studies following the guidelines for experimentation [1–3] and case studies [4, 5] should be highlighted. In particular, empirical comparisons between different approaches presented here are of interest. For future work we propose to compare studies within the categories shown in Table 5.6. With

regard to relevance, given that examples have been used, no real users or industrial systems have been used as the system under test (SUT). Hence, seeking collaboration with industry is an important future endeavor encouraged for future work on MBT with collaboration diagrams.

Furthermore, our results reveal that the proposed techniques are not related to each other. We define the relatedness as if the authors are referring to the other techniques in their methodology or they are comparing their technique(s) with the existing techniques. We found only four studies that are referred by the other authors in this regard. The least relatedness is considered if the authors are referring to other techniques in their related work section. In this regard 14 studies are there that are referred by the other authors in the related work of their studies. This shows that test case generation using interaction diagrams is not a well researched and mature area.

5.6 Conclusion

This paper presents a mapping of model based testing techniques based on UML interaction diagrams. It has been explored that UML interaction diagrams are being used mostly for integration testing. It is also discovered that interaction diagrams are being used as standalone model to generate test cases, at the same time there are some techniques which are combining interaction models with some other UML model (class, state chart, etc.). The proposed solutions have various capabilities claimed in the papers. Approaches from all investigated categories (SD, CD and H) are capable of generating test paths, though the needed inputs (test data) are only generated by a few approaches. The techniques also support detecting different types of defects, such as interaction and concurrency problems. It is also important to point out that solutions from sequence diagrams are applicable to collaboration diagrams if the collaboration diagrams include temporal information (numbering of messages).

The study shows that the practical usefulness of the proposed solutions still needs to be demonstrated. Key issues highlighted by the authors were the lack of tool support and the complexity of the approaches proposed. Thus, the transfer of the approaches to industry would be facilitated through developing tools that can be integrated into existing development frameworks. Furthermore, studies did not follow guidelines when conducting and reporting case studies or experiments. The systematic use of guidelines will aid in further improving the rigor of studies.

In summary, the following work should be focused on in the future:

- Provide tool support to enable practitioners to integrate the solutions into their development processes and development tools.
- Within an academic environment, empirically compare different types of solutions (such as different intermediate models) with respect to ease of use, efficiency (number of tests run in a specific time frame) and effectiveness (defect detection ability) through experimentation. The results provide preliminary insights of which solutions have potential for practical use.
- Empirically compare and study the solutions in real industrial contexts through case studies and action research.

With these steps taken, different forums may be targeted, such as Empirical Software Engineering primarily focusing on empirical studies.

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Appendix B

Treatment of databases

Databases often provide different settings ans possibilities for searches. In the following we specify how the different databases have been used to retrieve the articles. Google Scholar has been used as an index database. The university library only provided access to these databases, other databases (such as Scopus) were not available to the authors.

- *IEEE Search Criteria:* The default search option is used to search the related publications. No advanced options are used such as the researcher do not set at specific criteria to search only title, key words and abstract etc.
- *Science Direct:* The advance search option is used to identify the related publications. The database did not include options for conferences, but rather only for books and journals. Reference works (secondary studies) have been excluded.
- *ACM:* The advance search option is used to identify the related publications from ACM digital library. The filter is also applied during executing the search string and only title is selected to match with search sting. Moreover, we search the publications from ACM full text selection.
- *Google scholar:* The advance search option is used to identify the related publications from Google scholar. The first filter that is applied is search only "in the title of the article". From the "find article" option "with the exact phrase" and "with at least one word" has been selected. More specifically, the search string is (test case generation) AND (Model based testing), and thereafter test case generation were searched with exact phrase and model based testing with at least one word in the phrase.

Appendix C

Publication Venues

Table C.1: Publication types (J = Journal, C = Conference, S = Symposium, W = Workshop) and publication venues of the primary studies

Ref#	Type	Venue	Year
[68]	J	International Refereed Journal of Engineeering & Technology	2017
[73]	J	Journal of Engineering Science and Technology	2017
[69]	J	British Journal of Mathematics & Computer Science	2016
[71]	J	Chinese Journal of Electronics	2016
[70]	J	Journal of Software	2016
[7]	J	Computational Intelligence in Data Mining	2015
[22]	J	Procedia Computer Science	2015
[9]	J	International Journal for Innovative Research in Science and Technology	2015
[13]	J	International Journal of Computer Science and Engineering	2014
[32]	J	International Journal of Innovations in Engineering and Technology	2014
[59]	J	World Journal of Science and Technology	2013
[27]	J	International Journal of Advanced Research in Computer Science and Software Engineering	2013
[40]	J	International Journal of Computer Applications	2013
[25]	J	IET Software	2013
[30]	J	The International Journal of Computer Science & Applications (TIJCSA)	2012
[58]	J	ACM SIGSOFT Software Engineering Notes	2012
[60]	J	IETE Journal of research	2011
[53]	J	International Journal of Computer Science and Information Technologies	2011
[26]	J	Journal of Object Technology	2010
[36]	J	International Journal of Software Engineering	2010
[63]	J	Information Technology and Control	2009
[61]	J	Information and Software Technology	2007
[64]	J	Information and Software Technology	2007
[45]	J	ACM SIGSOFT Software Engineering Notes	2000
[72]	C	International Conference on Computer and Information Science	2016
[10]	C	Intelligent Computing, Communication and Devices	2015
[23]	C	International Conference on Intelligent Computing Applications (ICICA)	2014
[19]	C	International Conference on Computer Science & Education	2014
[31, 56]	C	International Conference on Advances in Computing	2013
[28]	C	International Conference on Software and Computer Applications	2012
[18]	C	International Conference on Electronics Computer Technology (ICECT)	2011
[54, 57]	C	International Conference on Contemporary Computing	2010
[49]	C	International Conference on Software Testing Verification and Validation	2009
[37]	C	International Conference for Young Computer Scientists	2008
[35]	C	International Conference on Software Engineering, Articial Intelligence, Networking, and Parallel/Distributed Computing	2008
[29]	C	International Conference on Systems, Man and Cybernetics	2007
[21]	C	International Conference on Computational Intelligence and Security	2007
[33]	C	International Conference on Quality Software	2007
[51]	C	Conference of the center for advanced studies on Collaborative research	2007
[24]	C	International Conference on Advanced Computing and Communications	2007
[42]	C	International Conference on Information Technology	2007
[43]	C	GI Jahrestagung	2006
[55]	C	International Conference on Computational Science and Its Applications	2005
[20]	C	Annual IEEE India Conference-Indicon	2005
[39]	C	Asian Test Symposium, ATS 2003	2003
[66]	C	International Conference on COTS-Based Software Systems	2003
[41]	C	International conference on the Unified modeling Language	2003
[38]	C	International Conference on Automated Software Engineering, ASE	2002
[62]	C	International conference on the Unified modeling Language	2000
[34]	S	International Symposium on Telecommunications (IST)	2014
[65]	S	Annual Midwest Instruction and Computing Symposium	2014
[52]	S	International Computer Symposium	2008
[50]	W	International workshop on software test	2006