Expertise
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Zihan Bian

Test Automation Process Assessment

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PREFACE

I have been in the software testing business for nearly 10 years. My enthusiasm for software testing has inspired this thesis project. I am keen to improve the testing process, and I aim to optimize it by combining my working experience and knowledge.

During the past 3 months, I have read some excellent material that strengthened my software testing knowledge. I especially liked the book “Improving the Test Process” by Erik Van Veenendaal and Graham Bath. Through this book, I gained abundant and detailed information on improving the testing process.

All aspects of the project proceeded smoothly. I received tremendous support at work while conducting the survey and interviews. My boss, Tomi Juslin, and Janne Lind (Head of IT) put much trust in me and allowed me sufficient time to complete the project.

Writing was not my forte. Fortunately, by listening to classical music while I was writing, I could concentrate and keep my ideas flowing.

Finally, I want to thank my instructor, Ville Jääskeläinen, for giving me insightful comments and patiently guiding me through the project.

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Test automation (TA) is an important software testing method and is pivotal in software development cycles, especially in agile development. The TA process can directly affect the efficiency and coverage of the testing and the accuracy of the testing results; thus, it can affect the software product quality. By assessing the TA process and identifying the improvement steps, companies can promote high-quality software products.

This thesis concerns TA process assessment at the case company, a Finnish bank that recently established TA to support its digital service transformation. This thesis project aimed to help the case company understand their TA process status and outline the focus areas for improving it. The project outcomes included analysis of the assessment results, improvement suggestions based on assessment results, and planned follow-up checkpoints.

This project initially investigated the overall implementation of TA at the case company and studied the software testing and TA background. Based on the studies, the test automation improvement model (TAIM) [25] was selected as the assessment model for this project. An assessment matrix was defined similarly to the TPI model [23]. A survey and targeted interviews were conducted as the main assessment methods. The survey data was collated to provide insights into providing improvement suggestions and a follow-up plan. Suggestions and follow-up checkpoints were then presented in achievable small steps. Finally, a long-term vision was formed to clarify the direction of continuous improvement.

The assessment found that, at the case company, the maturity levels of key areas (KAs) such as the TA strategy, test tool use, test design, test execution, the overall process, and the verdict are at the initial level, indicating the activities are mostly ad hoc. Thus, a significant team effort is required to improve them. However, KAs such as the test organization, test tool selection, and the software under test have reached a controlled level, indicating the test process activities are performed correctly. The KA of the test environment has reached an efficient level, indicating the test process activities are conducted efficiently.

This thesis project clarified that a clear and solid strategic plan efficiently combining personnel, technologies, and process is key to successful TA.

Keywords	Software quality, Test automation, Testing process, Assessment, Maturity level

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List of Abbreviations

ANSI	American National Standards Institute
ART	Agile release train
CD	Continuous deployment
CI	Continuous integration
CMM	Capability maturity model
CTP	Critical testing process
DM	Defect management
GUI	Graphical user interface
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
ISTQB	International Software Testing Qualifications Board
KA	Key area
PDCA	Plan-do-check-act
PDS	Plan-do-see
PTMM	Personal test maturity matrix
QA	Quality assurance
SAFe	Scaled Agile Framework
SDLC	Software development life cycle
SQA	Software quality assurance
STEP	Systematic test and evaluation process
STLC	Software testing life cycle
SUT	System under test or software under test
TA	Test automation
TAF	Test automation framework
TAIM	Test automation improvement model
TMMi	Test maturity model integration
TO	Test organization
TPI NEXT	Test process improvement NEXT

1 Introduction

Today, many companies have reached almost full test automation (TA) to promote increased test coverage, test efficiency, and effectiveness, and to support DevOps performance. Test automation is indispensable in software testing, software quality, and software development costs. Therefore, continuous improvement of the TA testing process through assessment and follow-ups is imperative and recommended by the testing industry. This thesis focuses on assessing the TA maturity level at the case company.

The case company is a Finnish bank listed on Nasdaq Helsinki. Its strategic focus is to serve individual and corporate customers with asset management services through digital and in-person channels. Digital services represent a general trend leading to increased customer demands for security, quality, and performance in digital banking services. To meet such needs, the IT department continuously improves and optimizes its product development and testing processes, establishing TA to increase the software testing efficiency and coverage. The company has adopted the Scaled Agile Framework (SAFe) [28] software development method, where thirteen agile teams belong to the agile release train (ART) [28]. Among these, eight teams are developing application systems, while one team develops no applications but conducts TA tasks. The preliminary investigation showed that one team is equipped with end-to-end TA capabilities, one or two teams have established some TA, although its completeness is unknown, and the remaining teams mainly use manual testing. To understand the current state in more detail and focus on optimizing testing processes, the IT department required a self-assessment of TA across the SAFe teams, which is the purpose of this thesis project.

This project should enable the IT department to measure the current effectiveness of TA and analyze its fundamental capabilities. It aims to help all IT employees to establish a thorough understanding of the integral status of TA and the impact of the discovered problems on TA, productivity, and software quality. The outcome of this project provides the IT department with a list of improvement suggestions to clarify the direction of continuous improvement activities, gives relevant staff appropriate instructions to take action, and presents suggestions on how the progress can be pursued. It is essential that all staff understand the necessity of active tracking through communication, and that the purpose of tracking is to complete the plan and achieve goals. If the project is properly implemented, establishing a TA maturity assessment can encourage all staff to escape

the constraints of their roles and examine the key points of changes and improvements in TA.

This thesis project was initiated by investigating the overall implementation of TA at the case company, the agile teams that could be selected for evaluation, and the relevant team members who could participate in the survey. This investigation was completed together with the QA lead. The second step was to conduct theoretical studies of software testing and TA and discuss the important role of TA in software testing and the key factors in achieving effective TA. The third step was implementing the assessment project, which included selecting an appropriate assessment model, establishing the assessment matrix, conducting the survey and further interviews, and collating survey data to provide a basis for result analysis. The next step was to analyze the assessment results for each key area (KA) and determine the issues as a basis for improvement suggestions. The final step was to provide first-step improvement suggestions and follow-up plans for high-priority areas based on analysis of the assessment results. The thesis project was concluded at this point.

2 Software Testing

This chapter explains the concepts and methodologies of software testing. It provides an underlying understanding of software quality and testing.

2.1 Software Quality

Software quality as defined in the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) standard [1] is the

> degree to which a software product satisfies stated and implied needs when used under specified conditions.

This definition highlights two aspects: the “explicit need” and the “implied need”. Software quality refers to the degree to which its functions and performance are consistent with the documented requirements and standards, and the indirectly stated functions [1]. Note that quality has distinct meanings for various stakeholders. Quality should likewise reflect stakeholders’ needs. Users’ needs are the basis of software quality evaluation. Software that does not match users’ needs cannot be delivered to customers. The prescribed standards and specifications are common guidelines for software development. If software fails to meet these standards and specifications, this might lead to a poor-quality product. A quality software product should meet specified requirements and comply with regulations and policies.

Quality management is divided into quality assurance (QA) and quality control [8]. Quality control focuses on fulfilling quality requirements, while QA focuses on building confidence in quality [8]. Quality control ensures that each product meets its requirements. A series of reviews and testing is conducted throughout the development cycle to guarantee that the product complies with its specifications. Quality assurance provides management with the required data to determine whether the product quality meets the predetermined goals. If the provided data identifies an issue, management solves it and assigns the required resources. Quality assurance aims to ensure the development of a satisfactory quality product because it focuses on the quality process, quality management system, and consistency audits. It is a management tool that employs plans, systematic activities, and documents to prevent quality-related problems. More details of software QA are explained in Section 2.3.

2.2 Software Quality Attributes

A few existing standards and frameworks describe a taxonomy of software quality characteristics. Here, the discussion is based on the definitions in international standard ISO/IEC 9126-1, which states the six primary characteristics and their sub-characteristics [6]:

- **Functionality** comprises suitability, accuracy, interoperability, functionality compliance, and security. It refers to the software's capabilities to perform tasks according to requirements.
- **Reliability** includes fault tolerance, recoverability, maturity, and reliability compliance. It indicates that a software system will not fail in an environment within a given time.
- **Usability** comprises understandability, learnability, operability, attractiveness, and usability compliance [6]. It refers to the software's ease of use.
- **Efficiency** includes time behavior, computing resource utilization, and efficiency compliance. It refers to the speed of the software and its efficient use of resources.
- **Maintainability** includes testability, analyzability, changeability, modifiability, and maintainability compliance. This indicates that the software product can be changed and improved according to requirements and specifications when needed.
- **Portability** encompasses adaptability, installability, coexistence and replaceability, and portability compliance. It refers to the requirement for software to run with different hardware or environments.

These characteristics refer to the software product quality. They form the external and internal quality models that can be tested with sets of measures. The internal quality concerns the software source code, and the external quality concerns the quality in use [7 pp. 119]. Quality in use is highly contextual: the quality attributes apply to a user's viewpoint when the software product is executed in a specific environment for specific use [7 pp. 119]. It cannot be measured directly.

The ISO's stated characteristics do not include process quality aspects. However, process quality applies to product quality. When a software development process is defined, if the QA personnel find that the work process and results do not meet the established

specifications, it is concluded that the product has defects. Conversely, if the process meets the specifications, it is concluded that the product qualifies.

2.3 Software Quality Assurance

Software has integrated to people's life, from consumer products to business applications. When software does not work as expected, people's life and business operations can be compromised, that lead to accidents, cost of time and money, damage of reputation, and even loss of lives. To avoid these risks from happening, software quality assurance (SQA) is used to offer thorough sequential activities for assuring the quality of software.

According to the Institute of Electrical and Electronics Engineers (IEEE) Standard for Software Quality Assurance Processes (IEEE Std 730-2014), the definition of SQA is

> a set of activities that define and assess the adequacy of software processes to provide evidence that establishes confidence that the software processes are appropriate for and produce software products of suitable quality for their intended purposes. A key attribute of SQA is the objectivity of the SQA function with respect to the project. The SQA function may also be organizationally independent of the project; that is, free from technical, managerial, and financial pressures from the project.

This definition shows that the function of SQA is to supply management with correct visual information to assist process improvement and ensure that the product satisfies the specification. Software quality assurance provides supportive guidance for software testing, including quality standards, testing processes, review methods, tracking, and auditing to discover problems in the software testing and improve testing or the entire development process [2 pp. 16-17]. Hence, the testing work can be inspected, while the testing process can be improved.

The key aim of SQA is to verify and ensure compliance between software products and functional requirements, standards, and time and budget requirements, focusing on defect prevention and decreasing the cost of quality [10]. Software quality assurance personnel notify SQA activities and results to affected groups and individuals promptly [10].

Each member of the development organization is responsible for quality assurance. However, a quality assurance team is often in charge of SQA work. Some pre-requirements must be attained to ensure effective SQA: first, the SQA team should be an independent unit in the organization [7 pp. 130]. The SQA team works as a third party to inspect the execution of software development. It provides developers and management with information on product and process quality based on whether the software project follows defined plans, standards, and procedures, improving project transparency and achieving high-quality software products. Second, top management must understand the importance of software quality and support SQA work [7 pp. 129]. Third, it is important to build an SQA organization with competence in software quality management and technical skills [7 pp. 130].

Software quality assurance methods can be categorized into two types: the technical method and the management method. The technical method is a post-event control that includes debugging, testing, and technical review, with the aim of identifying quality defects [9]. Software testing is one of the most used technical methods and is discussed in Section 2.4. The management method involves prevention that aims to control quality defects through standardization and process management, such as the capability maturity model (CMM) and ISO [9]. Solving problems by technical methods has certain limitations, and standards can only advise what is required and not how to achieve it. Compared to “post-event activities,” prevention is more important in quality assurance. A quality assurance system should also focus on user satisfaction and future problem prevention.

2.4 Software Testing

The evolution of software testing has followed the same path as software development. During early software development, in the 1950s–1970s, although the software was less complex, the software development process was disorganized. Testing was limited. Developers equated testing with “debugging” to correct the software and completed this part of the work themselves [4 pp. 3-5]. The investment in testing was minor, and the testing was often involved too late after the product was completed.

After the 1980s, the software and IT industries made huge strides. Software became more complex, and quality became more important in software development. During this

period, numerous software development processes and frameworks were created and transformed into structured methods of analysis, design, review, and testing [2]. The concept of “quality” was introduced. Software testing became the prime function of SQA [2].

As stated in the American National Standards Institute (ANSI)/IEEE 1059 standard, the definition of software testing is as follows:

> Testing is the process of analyzing a software item to detect the differences between existing and required conditions (that is defects/errors/bugs) and to evaluate the features of the software item.

This definition states that the purpose of software testing is to verify whether the software meets the requirements. It reflects the primary functions of SQA.

Software testing is not a onetime activity during the late stage of development but is integrated with the entire development life cycle, wherein testing is a continuous process to improve the software quality. It involves a series of managed activities, including test planning, test monitoring and control, test analysis, test design, test implementation, test execution, exit criteria evaluation, reporting, and test closure activities [3 pp. 9]. The software testing life cycle (STLC; Section 2.5) is explained in the following text.

Two methods of conducting software testing exist: manual and automated. The automated method involves two aspects: the execution of tests using automation and automatic procedures for managing tests and tracking results [12]. Test automation, continuous integration (CI), and continuous delivery (CD) are becoming increasingly important as the core practices of the agile software development method. More details of TA are explained in Chapter 3.

Different classifications of software testing levels exist [5 pp.30-38]. According to International Software Testing Qualifications Board (ISTQB) foundation syllabus, test levels include component testing, integration testing, system testing, and acceptance testing [5 pp.30-38]. Each level incorporates a group of test activities with its own testing process embedded in the software development life cycle (SDLC). Software test types [5 pp. 39-42] include functional testing, non-functional testing, white box testing, and change-related tests (e.g., confirmation testing and regression testing) [5 pp. 39-42]. Every test

type can be performed at any test level. It is important to choose suitable test types for different test levels.

2.5 Software Testing Life Cycle

A software testing life cycle refers to a series of specific phases being executed in a defined order to ensure that the product quality meets the requirements [3 pp. 8-15]. Each phase involves different entry criteria, activities, and deliverables. During the process, each phase is completed in order. The phases in the STLC usually comprise the phases shown in Table 1.

Table 1. Summary of STLC phases and activities [11], [3 pp. 8-15].

Phases	**Activities**
Requirements	• Prepare a list of requirements and inquiries and obtain solutions from technical managers/responsible persons, system architects, business analysts, and customers. • List the test types to be performed (performance, functional, and security). • List the test environment details, which should include all the tools.
Planning	• Define the test strategy. • Define goals, metrics, and the software testing scope. • Identify test environments, tools, and resources. • Define the test schedule, monitoring, and control procedures. • Determine roles and responsibilities. • List the test deliverables. • Identify risks (if any) and determine mitigations.
Analysis	• Specify the test conditions based on requirements and risks. • Specify the exit criteria.
Design	• List the detailed test conditions and sub-conditions. • Identify test cases and prepare test data. • Set up test environments. • Create traceable metrics.
Implementation	• Create test cases and prioritize them based on the analysis. • Review test cases and sign off. • Ensure test environments and test data are ready. • Define the test execution schedule for manual and automated test runs.
Execution	• Execute test cases according to priority. • Track test results, including metrics. • Report and log defects.

	• Start the control procedure if necessary.
Conclusion	• Review exit criteria. • Report to different stakeholders. • Ensure the risks are mitigated according to plan.
Closure	• Review software completion criteria based on test coverage, quality, time consumption, cost, and key business objectives. • Deliver artifacts. • Conduct lesson-learned sessions.

The eight STLC phases are interconnected and mutually reinforced. Each phase is indispensable. The testing process can vary according to the context. As mentioned earlier, software testing connects to software development. Thus, the SDLC can affect the testing process. Other contextual factors, such as test levels, test types and test resources defined by the test strategy, product risks, business domains, operational constraints, and required standards, affect how the testing process is defined [3 pp. 17].

2.6 Testing Process Improvement

Several methods can improve the testing process, including using the Deming cycle or using a test maturity model to assess the testing capability and maturity level. The following sections introduce the two methods.

2.6.1 The Deming Cycle

The Deming cycle, shown in Figure 1, known as plan-do-check-act (PDCA) cycle, originated from the Shewhart cycle created by Walter A. Shewhart, the father of statistical quality control [21]. Shewhart introduced the prototype of plan-do-see (PDS) [22]. Later, William E. Deming further perfected Shewhart's PDS cycle and developed it into PDCA [22]. This model is used for continuous quality improvement.

Figure 1. The Deming cycle [23]

As shown in Figure 1, the Deming cycle is iterative and comprises a four-step process [23]:

- **P (Plan)**—Through collective discussion or individual thinking to analyze the current situation, pinpoint the problems, decide a series of actions as “control points”, and establish objectives for improvement.
- **D (Do)**—Take actions according to the plan and collect data for checking.
- **C (Check)**—Check or study the data collected from execution; for example, compare the actual results to the objectives. Check the control point during the execution of the plan, analyze how the plan was implemented and whether it met expectations, and identify any issues.
- **A (Action)**—The result of the inspection is processed, approved, or denied. Successful actions should be affirmed or standardized; failed lessons should be summarized to avoid their recurrence. The unresolved problems of the current iteration should be moved to the next PDCA cycle.

Implementing improvements should be monitored. The metrics should be analyzed to confirm the effectiveness of the Deming cycle.

2.6.2 Test Maturity Models

A model-based approach is used to assess and improve the testing process. Two categories of test process improvement models exist: process reference models and content reference models [23]. Process reference models include the test maturity model integration (TMMi) model as staged representation and the test process improvement (TPI) NEXT model as continuous representation [23]. Content reference models include the critical testing process (CTP) model and systematic test and evaluation process (STEP) model [23]. These models provide a basis for evaluating the maturity level of the software development organization and further improvements. They promote the improvement of the overall software testing process, software quality management, and product quality. In the following sections, the two most common models are introduced.

The TPI NEXT Model

The TPI NEXT model includes 16 predefined KAs, four maturity levels, and 157 checkpoints [23]. Table 2 shows a high-level summary of the TPI NEXT model and the meaning of each maturity level. The four levels from low to high are initial, controlled, efficient, and optimizing. The initial level indicates no process, and all activities are ad hoc. The controlled level indicates that test process activities are performed correctly. The efficient level indicates that the test process is implemented efficiently. The optimizing level indicates continuous adaptation. All KAs include several checkpoints classified with four maturity levels that form a path of maturity levels for improvements. The checkpoints assess KAs via a scale (i.e., scales 1–5 indicate controlled, 6–10 indicate efficient, and 11–13 indicate optimizing) [23]. A maturity matrix is formed based on assessment results, which visualizes and summarizes the maturity level of each KA.

Table 2. TPI NEXT model [23].

Group	Level	Controlled	Efficient	Optimizing
Stakeholder relations	Stakeholder commitment	• identity of principle stakeholder • budget availability • stakeholder reliability • product risk analysis	• identity of all other stakeholders • level of stakeholder involvement	• line management commitment • stakeholder adaptability

	Degree of involvement (of testing)	• test assignments • involvement in project planning and risk analysis.	• involvement in defect analysis, change requests, and improving test basis.	• standing of the test team within the organization • involvement in lessons learned.
	Test strategy	• agreements with principal stakeholder • relationship of test strategy to risks • retest and regression test strategies.	• agreement with all stakeholders • coverage of test levels and test types • adequacy of test design techniques used.	• process of test strategy creation • effectiveness of test strategy based on production defect metrics.
	Test organization (TO)	• people, tasks, and responsibilities • structure of accountability of TO • TO services and products.	• coordination and delivery of testing activities and services • TO in the overall organization • compliance with test policy.	• optimization of TO services and products • accountability of TO for success/failure of test assignment • benchmarking of TO.
	Communication	• awareness and traceability of decisions, actions, and status • interaction of test team and stakeholders in exchanging information and decision-making.	• specific information flows • meeting participation • adequate means of communication.	• continuous improvement of communications.
	Reporting	• basic information in written reports • frequency and suitability of reporting for stakeholder needs.	• balance of needs and costs • trends and recommendations.	• used for continuous test process improvement • used for continuous software process improvement in organization.
Test management	Test process management	• test plan and contents • agreement between principal stakeholder and other stakeholders • monitoring and controlling.	• handling of test plan deviations • adjustment of test plan and resource reallocation.	• continuous improvement of test process management.
	Estimating and planning	• estimating techniques used • planning information created • agreement with principal stakeholder.	• accuracy of estimating and planning for all test activities • testability of test basis.	• reuse of testware for improved test planning • estimating techniques, principles, and metrics at organization level.

	Metrics	• metrics for estimating and controlling project • systematic recording and storage • accuracy of metrics.	• balance of needs and costs • impact of collection on test process • test process efficiency metrics • interpreting and acting on metrics.	• contribution made by metrics to test process improvement.
	Defect management (DM)	• defect lifecycle and responsibilities • basic defect items recorded • accessibility of DM tool.	• DM tool support for DM life cycle • further defect items recorded • commonality of DM tool • reporting capability of DM tool • use of defect trends.	• availability of DM guidelines for projects • organizational support for DM • root cause analysis and defect prevention.
	Testware management	• identifying by name and version • test case relationship to test basis • accessibility • procedures used.	• referencing by name and version • traceability of test cases to requirements • storage, roles, and responsibilities.	• conservation of testware for reuse.
Test profession	Methodology practice	• documented test method used • applicability to project context • usefulness of test method.	• recorded information • conditional, optional, and mandatory aspects • use of templates.	• continuous improvement of test method.
	Tester professionalism	• training and experience of testing staff • familiarity with test method • availability of all expertise needed • evaluation of testing staff skills.	• available certifications • justification of chosen techniques • performance of tasks • job satisfaction of testing staff.	• participation in skill development activities • career paths for testers • accountability and responsibility for own work • continuous improvement of own work process.
	Test case design	• level at which test cases are recorded • type of test case information.	• understandability of test cases by peers • coverage of test basis • techniques used • use of checklists.	• improvement of test case design using defect analysis • test case validity and maintainability • future use of techniques.
	Test tools	• availability, use, and benefits gained • knowledge levels present.	• selection criteria and creation of business case • integration into the test process.	• consistency of tools policy and test policy

				• reuse of expertise and tools best practices • achievement of business case.
	Test environment	• requirements • supplier agreements • availability change procedures.	• design and acceptance of test environment • service-level agreements.	• ownership • contractual agreements • services provided.

Based on the maturity matrix, a test improvement plan is written. The improvement plan focuses on two objectives: the unachieved checkpoints and the suggestions on the actions to be taken to achieve better maturity levels [23]. The relevant organization should then set priorities for improvements.

The TMMi model

The TMMi model was developed by the Illinois Institute of Technology and is now managed by the TMMi Foundation [24 pp. 6]. The primary aim of this model is to optimize the testing process. As shown in Figure 2, the model comprises five staged maturity levels: initial, managed, defined, measured, and optimization [24 pp. 9]:

- Level 1—Initial indicates that no defined test process exists. The software testing is exploratory or ad hoc.
- Level 2—Managed indicates that test strategies and policy, test plans, test cases, and test environments are formed according to the software-building requirements. The entire test objective is based on risk management. The primary purpose of this level is to develop the product according to the requirements and achieve the creation and compliance of test cases and test plan documents [24 pp. 10].
- Level 3—Defined indicates that the testing process is integrated with the SDLC and standardized across the organization. Testing is conducted independently by a separate organization with monitoring and control. Periodic reviews are conducted. This level's primary aim is to build a clearer image for the organization, helping them achieve the desired quality [24 pp. 10-11].
- Level 4—Measured indicates that the testing process is measurable across the organization. The product quality is tested throughout its lifecycle. Reviews and inspections are integrated with the testing process [24 pp. 11].

- Level 5—Optimization indicates that the organization focuses on defect prevention. Test assets are re-used. The testing process is continuously improved and characterized by quality measurements [24 pp. 11-12].

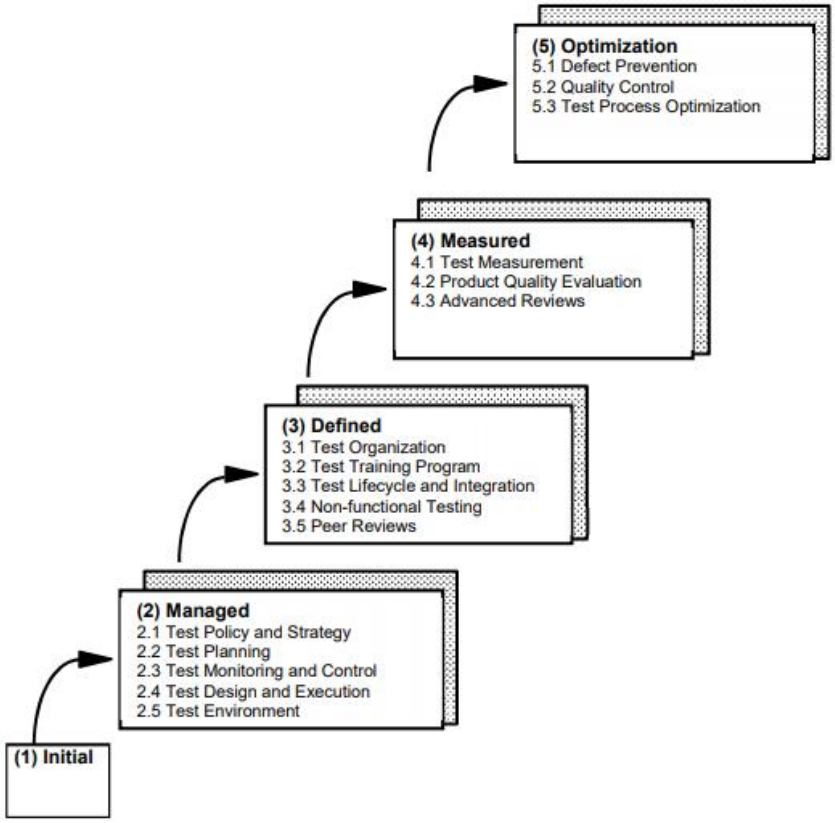


Figure 2. TMMi model [24 pp. 9]

Each level encompasses predefined process areas (PAs) with specific practices (SPs) under specific goals (SGs) and generic practices (GPs) under generic goals (GGs) [23 pp. 14]. Table 3 summarizes PAs and SGs from TMMi level 2 to level 5. Level 1 is an initial level; thus, it has no PAs and SGs.

Table 3. Summary of PAs and SGs for TMMi model levels 2–5 [23 pp. 24-199].

Process Area	**Special Goals**
Level 2—Managed	
2.1 Test Policy and Strategy	• Test policy is established, agreed by stakeholders, and aligned with business. • Organizational test strategy is established. • Test process is measured by test performance indicators.

2.2 Testing Planning	• Critical areas of testing are identified by product risk assessment. • A test approach is established based on product risks. • Test work estimation is structured and maintained for planning testing activities. • A test plan is created for managing testing activities and communicating with stakeholders. • Test plan is reviewed and achieved commitments.
2.3 Test Monitoring and Control	• Testing progress and performance is monitored against defined values. • Product quality is monitored against defined measurements. • Deviations are managed with corrective actions to closure.
2.4 Test Design and Execution	• Test design techniques are used in test conditions and test cases during analysis and design. • Test data is created, execution schedule is defined, and procedures are created. • Test cases are executed based on procedures and schedule, defects are reported, and logs are saved. • Defects or incidents are resolved to closure.
2.5 Test Environment	• Test environment requirements are created based on needs, constraints, and expectations. • Test environments are implemented according to requirements and are usable during test execution. • Test environments are managed and resilient to interruptions.
Level 3—Defined	
3.1 Test Organization	• A test organization supports testing practices. • Test specialist is assigned to test functions according to job descriptions. • Testers career paths are constructed. • Test process is periodically reviewed, and changes are planned and implemented. • Organizational test process is deployed across the organization and incorporate lessons learned.
3.2 Test Training Program	• An organizational test training capability is built and maintained to support test roles. • Testers and others involved in testing are supplied with sufficient trainings.
3.3 Test Lifecycle and Integration	• Organizational test process assets are set and maintained. • Test lifecycle is integrated with development lifecycles, early testing is ensured. • A master test plan is defined, including test approach, test levels and test plan.
3.4 Non-functional Testing	• Critical areas for non-functional testing is identified according to product risk analysis. • Test approach is created and agreed based on non-functional product risks. • Non-functional test conditions and test cases are based on test analysis and design. • Non-functional test data is created, and procedures are defined. • Non-functional tests are executed based on procedures and schedule, incidents are reported, and logs are saved.

3.5 Peer Reviews	• Peer-review approach is defined and agreed. • Peer review is conducted on work products.
Level 4—Measured	
4.1 Test Measurement	• Test measurements are aligned with needs and objectives. • Test measurement results are supplied and reviewed against needs and objectives.
4.2 Product Quality Evaluation	• Project goal for product quality is measurable and is established and maintained. • Product quality goals are monitored, quantified, and managed with corrective actions.
4.3 Advanced Reviews	• Peer-review approach is aligned with dynamic testing. • Product quality is measured by peer reviews early in the lifecycle. • Test approach is adjusted based on early peer-review results.
Level 5—Optimization	
5.1 Defect Prevention	• Common and root causes of defects are determined. • Common and root causes of defects are prioritized and systematically eliminated.
5.2 Quality Control	• Test process is controlled, and performance is as expected based on quantitative objectives. • Statistical methods are used in test design and executions.
5.3 Test Process Optimization	• Test process improvements support quality and process performance. • New testing technologies are identified and tested to determine their value to the testing process. • Test improvements are supported by new testing technologies and deployed across the organization. The benefits are measurable and shared with the organization. • High-quality test process components and testware are reused across the organization.

The assessment is conducted based on the “TMMi Assessment Method Application Requirements” (TAMAR) [23]. Rules and requirements must be followed to gain consistency. A sufficient quantity and depth of assessment evidence must be available to conclude the maturity level. Each piece of evidence must prove that a goal (SG or GG) of a PA is achieved. A PA is scored by a four-level scale: N (not achieved), P (partially achieved), L (largely achieved), and F (fully achieved) [23]. Here, N indicates that 0%–15% of the goals are fulfilled; P that 15%–50% are fulfilled; L that 50%–85% are fulfilled; and F that over 85% are fulfilled. The maturity level is then determined according to the lowest classified PA [23]. Future improvements are referenced from the TMMi’s framework.

Besides the above two most used models, other models such as the test management approach (TMap) and personal test maturity matrix (PTMM) are also used for assessment. It is noteworthy that these models do not focus on the TA process.

3 Test Automation

This chapter describes the purpose of TA, its value, and the key factors for achieving successful TA.

3.1 Definition and Usage of Test Automation

No authoritative definition of TA exists. Based on the author's experience, TA is the automation of software testing. It replaces test scripts with codes, manual test steps with code execution, and manual result comparison with automatic predefined assertions. It is an automated process involving compilation, deployment, execution, and report generation. It covers unit testing, functional testing, performance testing, graphical user interface (GUI) testing, security testing, and database testing.

Although TA has become the dominant software testing method, it can never completely replace manual testing because it cannot achieve the manual testing coverage. Not every test case is suitable for automation [18 pp.13]. For example, if a test engineer needs to advise whether a page layout is correct, they can find more defects within a brief time with manual testing than by using TA.

Test automation is more suitable for situations [18 pp.12] when the software development period is long, the software version is constantly updated, and the requirements are not often changed. When repeated testing is required, such as reliability testing and regression testing, this may require frequent executions, such as daily or even hourly or when new changes are committed to the source code. If the software version is unstable, the functionalities may be changed often, and TA is unsuitable. When the TA plan, measures, or most objects are unrecognizable and test script maintenance is frequent or difficult, TA implementation fails.

Although companies value the reusability of automated testing, this attribute can be sometimes seen as a disadvantage. When the repeated test execution cannot detect errors that exceed its framework, manual testing is a better choice. This ambiguity indicates that the decision to implement TA should be made according to the product requirements and particularities of the project.

3.2 The Significance of Test Automation

An example is the quality inspection in a manufacturing plant. Quality assurance staff check the quality of the product manually. As the production scale expands and the production becomes faster, the manual quality inspection becomes the bottleneck of efficiency because the production speed far exceeds the speed of manual quality inspection and testing. The rate of human error increases because of the increased workload, resulting in personnel fatigue or inertial thinking. Increasing the number of quality inspection staff to maintain efficiency increases the labor cost. Automated quality inspection solves the above three key problems. When the workload increases, the labor force cannot always rotate; thus, it is necessary to increase the labor force to work in three shifts. However, the automation system can run continuously.

As in the above example, TA addresses the same problems in SQA. In the context of agile development, where software development is fast-paced, time-to-market pressure is high. The execution efficiency of the TA system far exceeds the manual efficiency. It provides rapid feedback to the development team. It does not make mistakes because of continuous operation or become fatigued or lazy. With the characteristics of repeatability, the automated test scripts can be fully reused in multiple environments. Test automation can run cumbersome tests efficiently and run tests that are impossible for manual testing to achieve.

The value of TA is not limited to the technical level; it also balances the software development costs in the long term. When a feature is added to existing software, it increases its complexity. Over time, especially under the pressure of rapid delivery, it becomes more difficult for developers and testers to maintain the quality of software. Whether it is inherent or accidental [13 pp. 6], increased complexity accompanies added features. This inevitably increases the total software development costs because of the extended effort and time developers and testers spend on testing and fixing bugs. Test automation makes running regression test suites more convenient, reliable, and cost-effective. Besides TA, regular refactoring can control the complexity to stabilize the cost [13 pp. 9-10].

Test automation not only relates to software quality and software development productivity but also interconnects many aspects of software development, such as architecture, business structure, working practices, business culture, and documentation [13 pp. 10-

11]. These aspects impact TA, which can reflect the associated problems; thus, the organization can address these problems.

When implementing TA, many important factors need to be considered in advance. The key factors of achieving successful TA are discussed in the following sections.

3.3 Test Automation Strategy

Although TA can improve test efficiency, it requires substantial investment, including maintaining the test environment and test cases and developing test scripts. Therefore, a good TA strategy should be established before implementation. This strategic decision should consider the following aspects.

3.3.1 The Tests Should be Automated

The tests can be divided into prefunctional and cross-functional tests [14 pp. 50]. The former verify different output data corresponding to specific input data of an operation, including customer tests on the business level, component tests, and unit tests, which can be fully automated [14 pp. 51-52]. The latter verify various aspects of the software system characteristics, including exploratory testing, usability tests, and property testing, which are mainly manual testing [14 pp. 52-53].

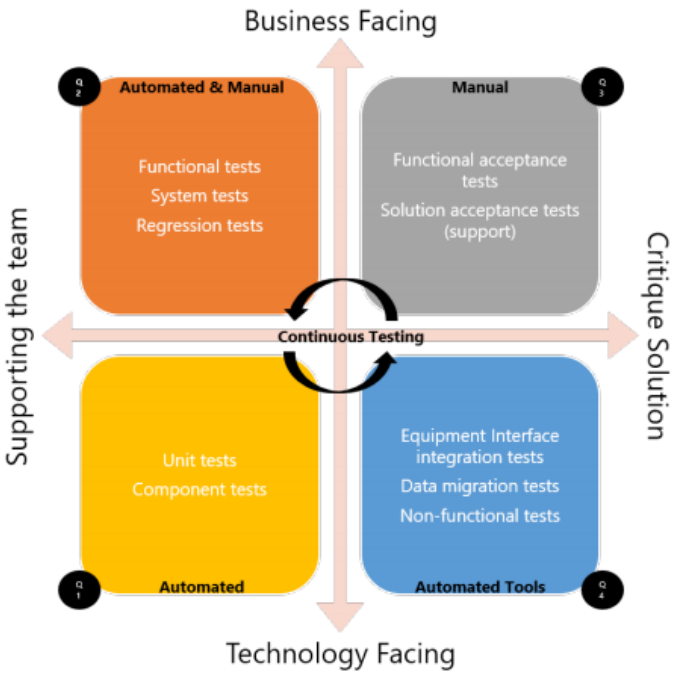


Figure 3. Testing quadrants [15 pp. 98]

The testing quadrants adopted from Brian Marick and Lisa Crispin (shown in Figure 3) suggest considering testing types from a broader perspective.

- Quadrant 1 (Q1) [15 pp. 99] lists technology-facing tests that support the team and are associated with TA. The primary goal is to use development practices enabling continuous development; Q1 comprises unit and component tests.
- Quadrant 2 (Q2) [15 pp. 99] lists business-facing tests that support the team and are associated with automated and manual testing. The primary goal is to ensure that testing is aligned with the business needs and enables iterative development; Q2 comprises functional, system, and regression tests.
- Quadrant 3 (Q3) [15 pp. 101-102] lists business-facing tests that critique the product and are associated with manual testing. The key goal is to evaluate the solution to be delivered and its use from the user's perspective; Q3 comprises functional acceptance tests and solution acceptance test support.
- Quadrant 4 (Q4) [15 pp. 102-103] lists technology-facing tests that critique the product and are associated with automated tools. The primary aim is to cover integration and non-functional testing, such as performance, monitoring, and security; Q4 comprises equipment and interface integration tests, data migration tests (if any), and non-functional tests.

3.3.2 Test Automation Pyramid

Testing must be layered. A TA pyramid can help define how each level of tests can be automated. The TA pyramid was first introduced by Mike Cohn in 2009. When it was first proposed, it was a three-tiered pyramid, with user interface (UI), service, and unit tests from top to bottom [17]. Lisa Crispin later added the manual test to the pyramid [15 pp.277] in her book "Agile Testing." The test pyramid shifts from focusing on the number of tests to focusing on the quality of tests. It recommends increasing the bottom-level test investment.

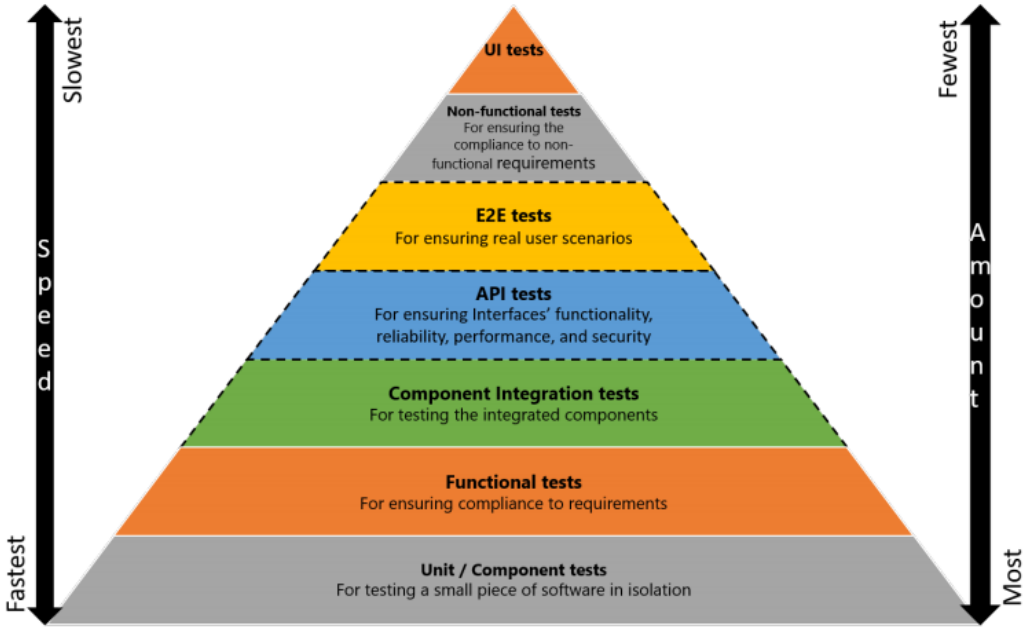


Figure 4. Test automation pyramid [17]

The paper adapted Figure 4 from Mike Cohn's TA pyramid. It aims to illustrate how the effort can be divided between different types and levels of automated tests. This pyramid structure with a wide base and narrow top represents the automation allocation for each layer. The higher the level, the lower the execution efficiency, which delays the feedback cycle of continuous integration. The higher the level, the higher the development of complexity. If the team has limited capacity, this affects the delivery schedule. The lower the level, the stronger the unit isolation, and the easier it is to locate and analyze problems. Thus, at the bottom, unit and component tests should be automated. Functional and system tests, application programming interface (API) tests, and end-to-end tests are decided case by case and automated if workable. The non-functional and UI tests should use automation tools as much as possible but might not be fully automated. Automated test cases from previous test cycles form the automated regression test suite.

3.4 Test Automation Tools and Selection

Two types of TA tools are available on the market: recording and script tools [14 pp. 53]. The advantage of the recording tool is that it does not require testers to write code, but the recorded script is fragile and difficult to maintain; thus, the maintenance cost is high. The opposite is true for the scripting tool. The corresponding threshold for programming

skill is high, while the maintenance cost is relatively low. However, this does not indicate that only one tool can be used; this depends on the test level and test types defined in the test strategy, from which the requirements for the tool can be identified.

Many automation tools support free software frameworks, such as Selenium and Appium. Framework integration reduces the testing workload and increases collaboration between teams.

Most of the automated testing tools offer flexible scripting options. This allows the test team to write test scripts in the preferred language. Good TA tools improve the reusability of test components and provide flexible scripts that can be reused between projects. Integration of the tools can form an ecosystem of collaborative efforts that can assist object identification, support for CI and CD tools such as Jenkins, error logging, test case management, report sharing, and shared repositories. These attributes [16] are usually considered before choosing a tool.

The testing team should adopt the tools easily. The ease of adoption can be measured based on the skills and learning curve required to use the tool. Tutorial resources are an advantage. Additionally, community support should be checked. An active user forum is an advantage of understanding the complexity of the tool.

When investing in TA, the cost of tools is a key point. Test automation tools can be costly. In the long-term, TA can be cost-effective, especially in regression testing. Test automation reduces the effort associated with manual testing; however, development and maintenance of automated scripts and review of test results require manual participation.

Open-source tools are recommended; however, not every open-source automation tool has every feature that might be required. A commercially licensed tool can provide additional value; for example, some companies offer real-time support and training for premium programs. Besides the cost of tools and their infrastructures, labor costs should be considered, including guidance on using and maintaining the tools.

3.5 Test Automation Framework

The TA framework (TAF) plays an important role in TA. It sets the guidelines for TA that help test engineers to maintain tests consistently, improve the test structure, standardize the code style, reduce code maintenance, increase reusability, involve non-technical testers in participating in coding activities, reduce the training time for using the tool, and use data reasonably [19]. The TAF should be established to be user-friendly, comprehensive, and maintainable [18 pp.14]. The following considerations can help to build such a TAF. The more aspects are ensured, the better the outcome of TA [18 pp. 14]:

- Detailed statistical information about quality should be facilitated.
- Besides logging, easy access for troubleshooting failed tests should be enabled.
- Dedicated test environments should be configured according to requirements and used only for TA.
- Each step in the test script should be traceable.
- The test script should be constructed for easy scalability and maintenance.
- The test script should be regularly updated and amended.
- The test script should be easily omitted when needed.
- The system under test (SUT) should be monitored and recovered when fatal errors occur.
- Test scripts that are subject to interface and data change, or where the input data depends on other tests' output, should be avoided.
- The test environment should avoid being dependent on context.

3.6 Test Automation Organization

A new era of software development methods, such as agile and DevOps, has replaced the old waterfall model, and the demand for software testing continues to grow in the industry. Testing organizations are now working together with development organizations. As TA has gradually replaced manual testing, the TA organization is of fundamental importance to TA success.

Test automation testers must not only understand the basic testing theory and have basic testing ability [3 pp. 71]; they must also have software programming capabilities because automated test scripts are often written in code. When the script is executed, the source

code generates output based on the assertions in it. Some TA tools allow test engineers to write scripts with keywords rather than code. Soft skills are important besides technical skills (e.g., communication, learning, observation ability, concentration, and test thinking) in supporting the team's communications [3 pp. 73].

The team must comprise skilled TA testers, have efficient communications with all stakeholders, and have problem-solving abilities. Team members should be motivated to perform automation tasks [3 pp. 75].

3.7 Test Automation Process

Test automation, as part of software testing, incorporates similar phases to the STLC. Its phases and activities are shown in Table 4.

Table 4. Summary of phases and activities of TA process [20].

Phases	**Activities**
Requirements	• Analyze the test requirements and testability of the SUT. • Design the test requirement tree according to the test plan, requirements, and specification.
Planning	• Define the test strategy for TA. • Clarify the TA objects. • Define the TA scope, including the content, test method, test schedule, and test environment. • Ensure that the workforce, hardware, test data, and other resources required for the test are fully prepared. • Select the TA tools. • Define the deliverables.
Design	• Design the TA framework. • Design the TA test cases that can cover all the required points. • Define the test data.
Implementation	• Set up a test environment. • Generate test data. • Write the test scripts. • Comply with management standards for unified test management and maintenance.

Execution and Reporting	• Execute the test scripts. • Track the test results, including metrics. • Report and log defects. • Start the control procedure if necessary.
Maintenance	• Analyze the test requirements and testability of the SUT. • Design the test requirement tree according to the test plan, requirements, and specification.

A good TA process may initially appear cumbersome; however, it will be highly efficient once implemented. No matter how complete the testing process is, it will inevitably have shortcomings. Testers should follow the PDCA cycle to find, report, and correct shortcomings. This should be part of a continuous improvement process.

Besides the above-mentioned factors, such as knowledge transfer, the SUT and TA metrics also affect the overall success of TA.

4 Implementation of Assessment

This chapter reports the implementation of the assessment including the utilization of TA assessment model, the construction of the survey questionnaire, the aggregation of survey answers, and the analysis of the assessment results.

4.1 Assessment Model

This study examined the requirements for assessment model from the following aspects [23]:

- The model content should be easy to use, well-researched, give sufficient details and support improvement suggestion process. For this assessment project, the model must support in-depth evaluation of TA.
- The model design should support end-to-end self-assessment, suggest improvement in small and manageable manner, assist improvement prioritization and flexible adoption to various projects or organizations.

Other formal considerations include conditions [23], such as

- The model is publicly recognized and supported.
- The integrity and quality of the model is accepted by software testing industry.
- The model is not biased.
- It may issue an organization formal certificate of its assessed level.

Based on the research in the background part of the study, TPI NEXT model and TMMi model have good content and design, but they concentrate only on general testing process assessment and improvement. Although they are used by testing industry, they do not supply sufficient descriptions of needed improvements for TA.

In 2014, a group of experts developed a maturity model for TA assessment — Test Automation Improvement Model (TAIM) [25]. It is by far the finest model for test automation improvement that covers end-to-end view of test automation testing process with holistic approach. The work was published in 2014 that introduced one general area and ten

Key Improvement Areas (KIA) in TAIM: test management, test requirements, test specifications, test code, test automation process, test execution, test verdicts, measurement, test environment, and test tools [25]. A recent study [26] has developed 15 KAs into TAIM after further revisions. All KAs correspond to several assessment practice items. Although this model is still under research, and the maturity levels have yet published, its overall design and composition provide complete details for TA assessment. With its existing content, one can still find deficiencies in TA process by utilizing TAIM as the assessment model.

4.2 Assessment Key Areas

There are 15 KAs included in the assessment [26]:

- Test automation strategy (see Section 3.3).
- Resources refer to TA workforce, time, and budget.
- Test organization (TO) (see Section 3.6).
- Knowledge transfer refers to the relevant information and knowledge is shared and maintained within a company.
- Test tool selection (see Section 3.4)
- Test tool use refers to the use of tool.
- Test environment refers to the setups including hardware, software, data (see Section 3.5).
- Test requirement (see Section 3.7)
- Test design (see Section 3.7)
- Test execution (see Section 3.7)
- Verdicts refers to the collected result of test executions on which test report shall be based.
- Test automation process (see Section 3.7)
- Software under test (SUT) refers to testability and maturity of the software to be tested by TA.
- Measurements refer to the quantified measures to determine the quality and performance of TA.
- Quality attributes (see Section 2.2) refer to the testware's quality attributes.

Several practices are defined for each KA. Table 5 summarizes each KA and its included practices, highlighting the aspects that must be considered in the assessment.

Table 5. Summary of TAIM KAs [26 pp. 149-151].

Key Area	Practices
1. Test Automation Strategy	• The TA strategy is created. • The TA goals are set. • A cost-effectiveness analysis of TA is conducted. • Risk analysis is established. • The test scope and degree of TA are defined. • Overlaps between automated and manual testing are examined. • The gaps and overlap between test types and levels are examined. • Resources to perform TA tasks are identified. • Roles and responsibilities for TA tasks are identified. • The effort estimation for TA tasks is calculated. • Stakeholders' feedback on changing the TA strategy is collected.
2. Resources	• Enough skilled staff are assembled to perform TA tasks. • The budget suffices to fund TA. • Sufficient time is available for TA tasks. • Enough test tools are available to support testing activities. • All required software, hardware, and test data are available in the test environment.
3. Test Organization	• Members of the TO are motivated. • The TO members have defined roles and responsibilities. • The TO has an effective communication and problem-solving mechanism. • Organizational and management support for TA is available. • The TO has sufficient professional knowledge and technical skills to perform TA tasks. • The TO can maintain test tools in use.
4. Knowledge Transfer	• The expertise, good practices, and good test tools are retained. • Time for training and the learning curve is supported.
5. Test Tool Selection	• The required features of the test tools are described. • The attributes of the test tools are listed. • Constraints are analyzed.
6. Test Tool Use	• Preconditions to tool use are clarified. • Business cases are set to analyze the return on investment of each tool. • New test tools are formally introduced to the organization. • New test tools are experimentalized in pilot projects.

	• Regular evaluations of test tools are conducted based on the goals. • The rules and principles for using test tools are defined.
7. Test Environment	• The requirements of the test environment are thoroughly understood. • The configuration of the test environment is managed. • The test environment and test data are tested before use. • Support for the test environment is supplied. • Test environment failure or dependencies are identified. • Test data is used in compliance with regulations and legislation. • Test data is managed correctly. • The test environment matches the production environment.
8. Test Requirements	• TA requirements are collected in a defined manner. • A controlled change process applies to TA requirements.
9. Test Design	• Test design techniques are used. • The test design patterns are recorded and reused. • Test suites are structured for different purposes. • Test design guidelines are defined. • The test code is examined by static and dynamic measurements.
10. Test Execution	• TA is used for prioritized test cases to meet the schedule. • Automatic pre-processing tasks are executed before test execution. • Automatic post-processing tasks are executed after test execution. • Parallel executions for complex system. • Critical failures of test execution are alerted.
11. Verdicts	• The test oracles used to determine whether the system passes or fails the test are reliable and certain. • The test result can be understood by monitoring the test status and progress. • The test results summary is integrated from different sources. • Test result insights are received by relevant stakeholders. • Every stakeholder can see useful information from the dashboard.
12. Test Automation Process	• As part of the testing process, the TA process is structured and stable. • The TA and development cycle are conducted in parallel. • The TA process supports other processes. • TA development has fast feedback cycles.
13. Software Under Test	• The SUT has sufficient maturity to perform TA. • The SUT has sufficient testability to perform TA. • The SUT has sufficient speed to execute TA.
14. Measurements	• TA is measured by appropriate metrics. • Important attributes of TA are defined.

	• Areas of improvement are recognized by using measurements. • Regular feedback is given on each TO member's performance. • Measurements are visible in the test report and dashboard.
15. Quality Attributes	• Portability • Maintainability • Efficiency • Reliability • (Re)usability • Functionality

As classified in the above table, 76 practice items are the basis for assessment surveys.

4.3 Assessment Matrix

An assessment matrix was applied to illustrate the current maturity level of each practice item in each KA. This study adopted a similar representation of the TPI NEXT model to construct the scales and matrix.

The priority for each KA was agreed by both stakeholders and the QA organization, as illustrated in Figure 5. The KA's priority influenced the improvement priority. The improvement should draw further attention to the higher priority areas, such as the TA strategy, TO, test tool selection, test tool use, and the verdicts.

	Prioriry		
Key Area	**L**	**N**	**H**
Test Automation Strategy			x
Resources		x	
Test Organization			x
Knowledge Transfer		x	
Test Tool Selection			x
Test Tool Use			x
Test Environment	x		
Test Requirements		x	
Test Design		x	
Test Execution		x	
Verdicts		x +	
Test Automation Process		x	
Software Under Test		x	
Measurements	x		
Quality Attributes		x	

Figure 5. Defined KA priorities

As shown in Figure 6, L is low priority, H is high priority, and N is neutral priority. This example explains the relationship between improvement priorities and maturity levels. Here, KA1 and KA2 are marked as level B–Controlled; however, since the KA1 TA strategy (H–high priority) has higher priority than KA2 resources (N–neutral priority), improvement should first be focused on KA1.

	Prioriry			Level			
Key Area	**L**	**N**	**H**	**Initial**	**Controlled**	**Efficient**	**Optimizing**
Test Automation Strategy			x	X			
Resources		x		X			

Figure 6. Example of a KA assessment priority matrix

Each practice item was scored by survey respondents using a progressive scale from low to high, including seven items: totally disagree, disagree, slightly disagree, neutral, slightly agree, agree, and totally agree. These levels were mapped onto a numeric scale (0–6) from low to high.

	Scale	Totally Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Totally Agree
	Level	Initial		Controlled		Efficient		Optimizing
	Category	A		B		C		D
	Scale	0	1	2	3	4	5	6
ID	KA1. Test Automation Strategy							
P1	The TA strategy is created.	10	1	1	1	1	1	1
P2	The TA goals are set.	0	1	1	0	14	0	0
P3	A cost-effectiveness analysis of TA is conducted.	5	1	5	0	5	0	0
P4	Risk analysis is established.	1	1	10	1	1	1	1
P5	The test scope and degree of TA are defined.	0	0	0	15	1	0	0
P6	Overlaps between automated and manual testing are examined.	0	1	10	2	3	0	0
P7	The gaps and overlap between test types and levels are examined.	1	10	1	1	1	1	1
P8	Resources to perform TA tasks are identified.	1	0	0	0	0	15	0
P9	Roles and responsibilities for TA tasks are identified.	0	0	0	0	0	0	16
P10	The effort estimation for TA tasks is calculated.	0	1	9	2	4	0	0
P11	Stakeholders' feedback on changing the TA strategy is collected.	1	0	7	7	0	0	1

Figure 7. Example of assessment matrix mapping

As an example, in Figure 7, the maturity level scale is divided into four categories from low to high:

- Scale 0–1 marked with red is categorized as A: Initial.
- Scales 2–3 marked with yellow are categorized as B: Controlled.
- Scales 4–5 marked with green are categorized as C: Efficient.
- Scale 6 marked with blue is categorized as D: Optimizing.

The color marks provide a visual aid to locate the KA deficiencies and determine which items require further improvement.

A practice item's maturity level is determined according to the category with the most frequent score. For example, in Figure 7, 10 occurrences of scale 1 for P1 fall into category A, which is the most recurrent compared to other categories. Thus, the level of P1 is recorded as Initial.

If multiple categories have the same number of occurrences, the lower level is chosen. For example (in Figure 7), for P3, categories A (scale 0), B (scale 2), and C (scale 4) all contain 5 occurrences; thus, the level of P3 is marked as Initial.

4.4 Assessment Survey

A survey and interviews were the primary methods of assessment.

A survey questionnaire was constructed with closed-ended questions. The closed-ended questions [31] required respondents to select the answers from a list of responses to determine their degree of approving the statement.

A total of 80 questions covering 15 KAs (including 76 practice items) were asked. This study used original questions from TAIM 77 instruments [27] as much as possible to ensure the authenticity of each instrument. The original instruments were well constructed and concise. They have been revised many times by experts. Only a few questions were improved by this study to enhance the comprehensibility, for example, by adding further examples and explanations of professional terms. To prepare for the data entry and analysis, the numerical order of the questions corresponded to each practice item, and the answers corresponded to the defined scale number specified in the assessment matrix (see Section 4.3). The average completion time for the survey was 50 minutes.

This study chose respondents based on their job responsibilities and business relevance, to reach a good effective rate. The survey was conducted among the nine SAFe teams. At least one member of each team who was directly involved in the development or testing process was invited to complete the survey. Twenty respondents were selected and completed the survey, of which 20% were TA specialists, 50% were software developers and technical specialists, 10% were testers, and 20% were business-relevant staff, such as product owners and scrum masters.

Microsoft Forms were used for online survey. The online survey method overcame time and location limitations and was convenient for conducting quantitative research on survey results. However, it was troublesome to conduct in-depth investigations. For self-completed questionnaires, it was challenging to determine whether the respondents completed them carefully and objectively, and whether they understood the questions and the answering method.

To mitigate the negative impact on the survey result, individuals or groups of respondents were asked further questions via web meetings or chats (e.g., using Microsoft Teams and Flowdock) that required respondents to provide a further description of the subject and consider a more precise condition of it, such as the SUT, product risks, team composition, and job descriptions. Further questions were asked based on survey responses, for example, when respondents assigned a practice item a better or worse score than

average. The answers were recorded for data abstraction. The collected data helped to support the assessment matrix for the analysis and improvement plans.

4.5 Assessment Survey Raw Data Mapping

Raw data were exported from Microsoft Forms as an Excel file. Figure 8 shows a piece of raw data, where the column ID contains practice items, and the respondent columns contain the scores given to each practice item by each respondent.

The scores were then converted into numerical scales according to the assessment matrix (see Section 4.3): totally disagree was converted to scale 0, disagree to scale 1, slightly disagree to scale 2, neutral to scale 3, slightly agree to scale 4, agree to scale 5, and totally agree to scale 6. Figure 9 shows a sample of transformed data.

ID	respondent 1	respondent 2	respondent 3	respondent 4
P1.We have defined a test automation strategy for test automation.	Totally agree-6	Neutral-3	Totally disagree-0	Disagree-1
P2.We understand goals for our test automation.	Totally agree-6	Agree-5	Totally disagree-0	Totally disagree-0
P3.We create a business case to conduct cost-benefit analysis of our test automation.	Slightly agree-4	Slightly disagree-2	Totally disagree-0	Totally disagree-0
P4.We identify and analyze the risks of test automation.	Totally agree-6	Slightly disagree-2	Totally disagree-0	Totally disagree-0
P5.We define the scope of test automation, e.g. what should be automated and to what deg	Agree-5	Agree-5	Totally disagree-0	Disagree-1
P6.We acknowledge the overlap between automated testing and manual testing.	Totally agree-6	Neutral-3	Totally disagree-0	Totally agree-6
P7.We periodically review our automation strategy and update it depending on our present	Totally agree-6	Disagree-1	Totally disagree-0	Totally disagree-0
P8.We identify necessary resources to implement test automation, e.g., test tools, test data	Agree-5	Slightly disagree-2	Totally disagree-0	Slightly disagree-2
P9.We identify roles and responsibilities for test automation tasks.	Totally agree-6	Slightly disagree-2	Totally disagree-0	Agree-5
P10.We estimate the effort for test automation tasks.	Agree-5	Slightly agree-4	Totally disagree-0	Totally disagree-0
P11.We communicate with stakeholders the changes of test automation strategy and collect	Totally agree-6	Slightly disagree-2	Totally disagree-0	Totally disagree-0

Figure 8. Sample of raw data

The next task was to sum the number of times each scale was rated for each practice item based on the transformed data shown in Figure 9. The aggregate number was counted using the following Excel formula:

“COUNTIF (range, criteria)”

The range refers to the cells to count, that is, respondents’ scores for each practice item in a row, and criteria refer to the condition that cells should be counted. For example, COUNTIF(B4:T4; “1”) counts the number of times that scale 1 has appeared between cells B4–T4, the row for practice item P1 in Figure 9, in which P1 was rated scale 1 by respondents for 8 occurrences.

ID	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20
P1.We	6	3	0	1	2	1	5	1	4	1	1	5	1	2	0	1	1	4	2	5
P2.We	6	5	0	0	2	5	5	4	5	1	1	5	1	3	0	1	4	5	5	6
P3.We	4	2	0	0	1	1	3	1	3	1	1	4	1	0	0	1	0	3	1	3
P4.We	6	2	0	0	2	1	4	1	4	1	1	4	1	1	0	1	0	1	1	3
P5.We	5	5	0	1	3	5	5	5	5	1	1	5	1	1	0	1	2	2	5	6
P6.We	6	3	0	6	4	6	6	5	5	3	1	4	1	1	0	1	4	4	3	5
P7.We	6	1	0	0	1	2	5	0	3	1	1	5	1	0	0	1	2	2	1	5
P8.We	5	2	0	2	2	3	5	4	5	1	1	5	3	4	0	1	4	4	2	6
P9.We	6	2	0	5	1	3	5	5	5	1	1	5	1	1	0	1	4	4	1	6
P10.We	5	4	0	0	1	5	5	5	5	1	1	4	1	1	0	1	3	4	1	6
P11.We	6	2	0	0	1	3	4	1	3	2	1	5	1	0	0	1	1	3	1	3

Figure 9. Sample of transformed data

As shown in Figure 10, the numbers listed in each scale column are the aggregate counts.

Level		Initial		Controlled		Efficient		Optimizing
Category		A		B		C		D
Practice Item	Scale	0	1	2	3	4	5	6
P1.We have defined a test automation strategy for test automation.		2	8	3	1	2	3	1
P2.We understand goals for our test automation.		3	4	1	1	2	7	2
P3.We create a business case to conduct cost-benefit analysis of ou		5	8	1	4	2	0	0
P4.We identify and analyze the risks of test automation.		4	9	2	1	3	0	1
P5.We define the scope of test automation, e.g. what should be aut		2	6	2	1	0	8	1
P6.We acknowledge the overlap between automated testing and m		2	4	0	3	4	3	4
P7.We periodically review our automation strategy and update it de		5	7	3	1	0	3	1

Figure 10. Sample of aggregate data

Base on the occurrences of each scale in each category, the level of each practice item was determined by that with the greatest number of occurrences. However, after the data were aggregated, the occurrences of several practice items appeared to be the same in various categories. Here, it was agreed (see Section 4.3) that the lower category would determine the level. For example, as highlighted in Figure 10, the same numbers appeared in categories A (4 times scale 1), C (4 times scale 4) and D (4 times scale 6) for item P6; since category A was the lowest level, P6 was classified as level Initial.

Key Areas	ID	Practice Items	Category	Level
KA1. Test Automation Strategy	P1	The TA strategy is created.	A	Initial
	P2	The TA goals are set.	C	Efficient
	P3	A cost-effectiveness analysis of TA is conducted.	A	Initial
	P4	Risk analysis is established.	A	Initial
	P5	The test scope and degree of TA are defined.	C	Efficient
	P6	Overlaps between automated and manual testing are examined.	A	Initial
	P7	The gaps and overlap between test types and levels are examined.	A	Initial
	P8	Resources to perform TA tasks are identified.	B	Controlled
	P9	Roles and responsibilities for TA tasks are identified.	A	Initial
	P10	The effort estimation for TA tasks is calculated.	A	Initial
	P11	Stakeholders' feedback on changing the TA strategy is collected.	A	Initial

Figure 11. Sample of classification based on aggregate data

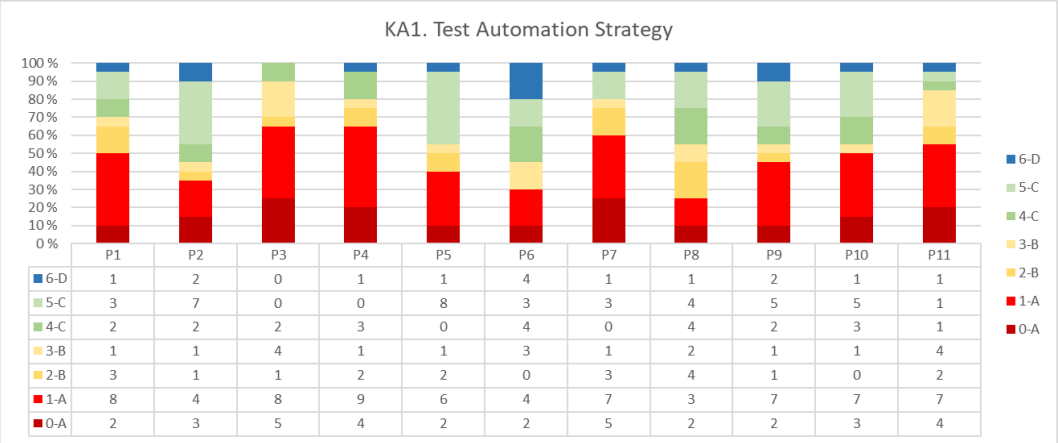
Figure 11 shows the sample classification results for each practice item. Here, the data mapping was complete, and the results are shown in Appendix 1. The next step was analysis of results.

5 Analysis of Assessment Results

This chapter studies the assessment results for each KA (see Section 4.2) as the basis for prioritizing necessary improvements. The following sections discuss one or two KAs.

5.1 Test Automation Strategy

Although TA exists company-wise, not all staff were aware of the TA strategies (P1); this is reflected in Figure 12, which shows that most of the respondents scored it as 1. This suggested that the TA strategy was not defined or broadly implemented. Correspondingly, the scoring of a regular review and update of the TA strategy (P7) and communication with stakeholders over changes in the strategy (P11) were also poor. Contradicting P1 and P7, most respondents acknowledged that they understood the goals for TA (P2) even without a defined TA strategy.



	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
6-D	1	2	0	1	1	4	1	1	2	1	1
5-C	3	7	0	0	8	3	3	4	5	5	1
4-C	2	2	2	3	0	4	0	4	2	3	1
3-B	1	1	4	1	1	3	1	2	1	1	4
2-B	3	1	1	2	2	0	3	4	1	0	2
1-A	8	4	8	9	6	4	7	3	7	7	7
0-A	2	3	5	4	2	2	5	2	2	3	4

Figure 12. Results distribution for KA1

More than half the respondents believed that the team had neither launched a cost-benefit analysis of TA (P3), nor analyzed and identified its risks (P4). If the teams regularly conducted evaluations, the low score may originate from insufficient transparency or lack of familiarity of employees with the internal decision-making process.

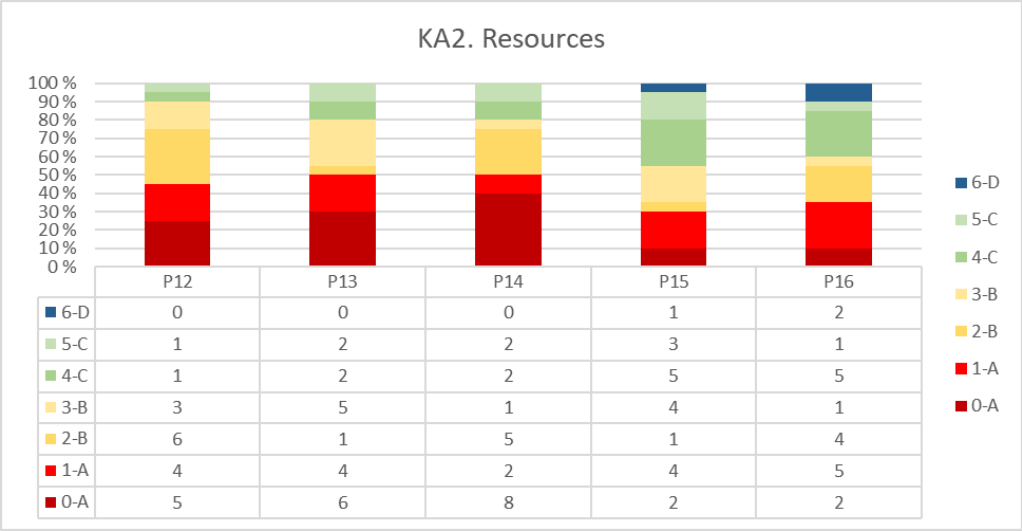
About 50% of the respondents thought their team performed appropriately in determining the scope and depth of TA (P5), but others did not. An unclear test scope can be an unintended consequence of an unclear test strategy. Regarding recognizing the overlap

between manual testing and TA (P6), the scoring results were divided into, low, medium, and high scores.

Resources, including budget, tooling, roles, and responsibilities, were among the significant issues mentioned during additional interviews. This was why the respondents gave low scores for P8, P9, and P10. Section 5.2 surveys the resource issues.

5.2 Resources

During further interviews, when the respondents were asked what could help their teams improve or establish TA, most of the answers related to the resource issue.



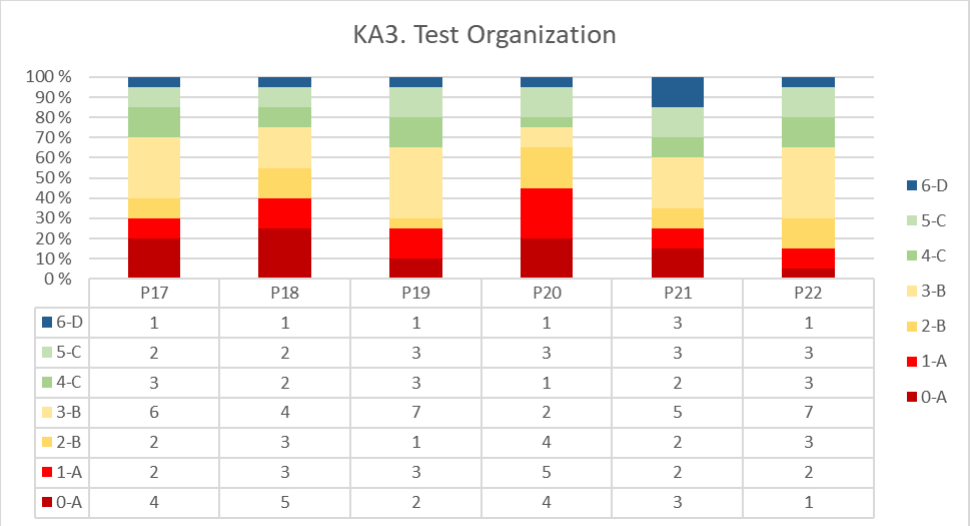
	P12	P13	P14	P15	P16
6-D	0	0	0	1	2
5-C	1	2	2	3	1
4-C	1	2	2	5	5
3-B	3	5	1	4	1
2-B	6	1	5	1	4
1-A	4	4	2	4	5
0-A	5	6	8	2	2

Figure 13. Results distribution for KA2

The teams that did not have TA stated that they needed more skilled people to conduct TA (e.g., experienced testers and automation experts) (P12), corresponding training, and effective tools (P15). A large majority highlighted a lack of time and effort allocated to perform TA tasks (P14) and a budget to fund TA (P13). One team that manages multiple systems has an extremely long regression testing cycle. Here, manual testing is the only available method, and this is conducted by a business unit because no competent testers are available. As shown in Figure 13, the teams gave low scores for these practice items. Although test environment management (P16) was not highlighted by any teams, 75% of the respondents saw room for improvement in areas such as environment consistency, data management, and supported software.

5.3 Test Organization and Knowledge Transfer

The case company has a QA unit, and its testers are assigned to SAFe teams. This assessment was for the testing groups in each SAFe team. It is noteworthy that some development teams do not have testers, and developers have assumed the role of testing.

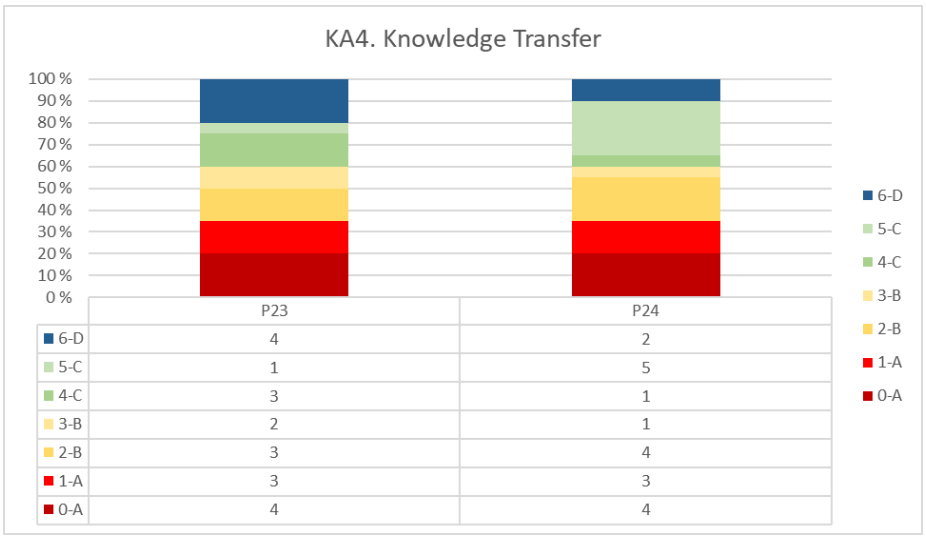


	P17	P18	P19	P20	P21	P22
6-D	1	1	1	1	3	1
5-C	2	2	3	3	3	3
4-C	3	2	3	1	2	3
3-B	6	4	7	2	5	7
2-B	2	3	1	4	2	3
1-A	2	3	3	5	2	2
0-A	4	5	2	4	3	1

Figure 14. Results distribution for KA3

Two major groups of opinions existed on the motivation (P17) of testers, as shown in Figure 14. While 30% of the respondents believed that the testers were motivated, 20% believed they were not. Interestingly, these negative answers originated from those belonging to the development team without TA testers, where developers or other team members often assume the role of testers. Under such circumstances, while employees are saturated with work, their enthusiasm for undertaking lengthy testing tasks is inevitably affected. The results for defining the roles and responsibilities of test organization (P18) and organizational support and management support for TA (P20) were scored extremely low. Many respondents expressed their frustration that management did not provide timely support (e.g., labor force and tools) to help them complete their tasks more effectively. Some respondents suggested that because the realization of TA often required significant investment in the early stages, the team leaders believed that the return on the investment was insignificant.

In assessing TO's abilities, such as effective communication and problem-solving mechanisms (P19), expertise and technical skills (P21), and ability to maintain testing tools (P22), relatively more positive comments were offered, as shown by the corresponding scores.



	P23	P24
6-D	4	2
5-C	1	5
4-C	3	1
3-B	2	1
2-B	3	4
1-A	3	3
0-A	4	4

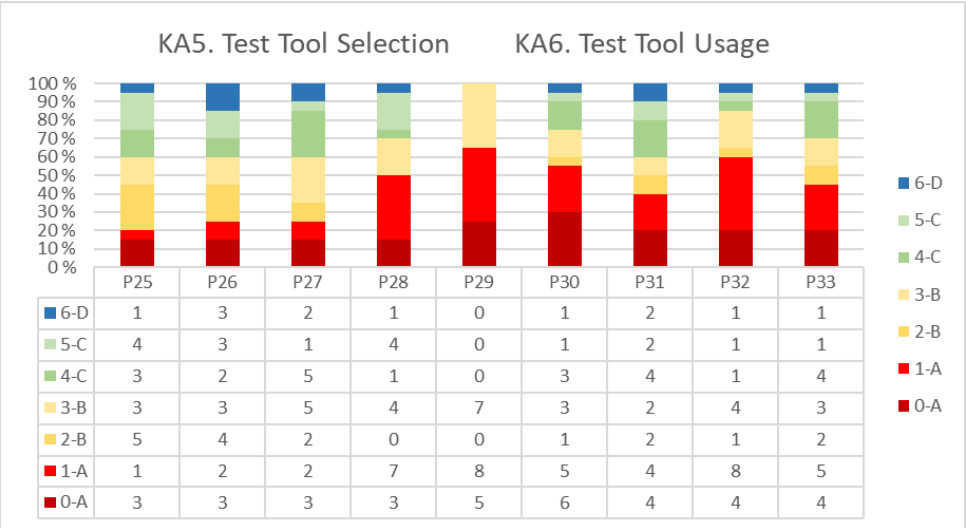
Figure 15. Results distribution for KA4

Knowledge transfer is an important measure to enhance the competence and capability of the TO. Regarding the evaluation of this KA, the opinions were again extremely scattered, with mixed reviews. However, most of the opinions on sharing knowledge, practices, and good test tools (P23) were concentrated in the middle and lower scores, as shown in Figure 15. This may be due to the lack of a sharing platform or atmosphere in some teams.

Although over 25% of the respondents indicate that they would value time for training and the learning curve (P24), 50% gave low scores for this aspect. As with the previous item, the operational style and atmosphere of each team can directly affect how team members learn or master new skills during their work.

5.4 Test Tool Selection and Use

The feedback on test tool selection was good for identifying the required features (P25), attributes (P26), and constraints (P27), as shown in Figure 16.



	P25	P26	P27	P28	P29	P30	P31	P32	P33
6-D	1	3	2	1	0	1	2	1	1
5-C	4	3	1	4	0	1	2	1	1
4-C	3	2	5	1	0	3	4	1	4
3-B	3	3	5	4	7	3	2	4	3
2-B	5	4	2	0	0	1	2	1	2
1-A	1	2	2	7	8	5	4	8	5
0-A	3	3	3	3	5	6	4	4	4

Figure 16. Results distribution for KA5 and KA6

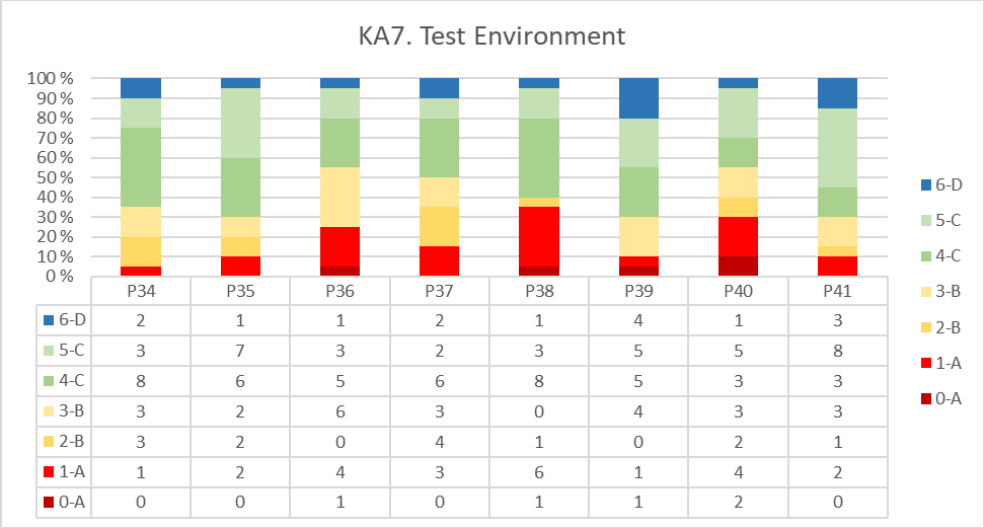
Contrary to tool selection, the tool use scores leaned toward low scores, as shown in Figure 16. The general opinions were that no formal process of introducing new tools (P30) existed within the group. Thus, regarding elaboration of the preconditions for the tool (P28), many negative reviews were offered on gaining management commitment, understanding the test tools, and maintaining the documents. This may imply that the entire department has not yet sufficiently promoted unified standard test tools for different purposes, resulting in the majority being confused about the new tools while dissatisfied with the tools in use.

For whether ROI analysis of test tools was conducted (P29), the grouped scores were medium and low. It could be argued that teams have overlooked the financial perspective of using TA tools. Some teams have used some new test tools in pilot projects (P31) and announced the piloting results to the remainder of the organization. However, the goals of using test tools (P32) were not widespread and lacked periodic reviews. Some teams have written guidelines for the use of test tools (P33); however, since many teams have no TA, it was difficult to judge the establishment of guidelines.

5.5 Test Environment

A good software testing environment enables testers to do their jobs. The suitability of the test environment seriously affects the authenticity and correctness of the test results. The assessment results for this KA were good, as shown in Figure 17.

During the stage of designing the test environment, teams believed that they designed the environment according to the requirements (P34). The test environments were also close to the production environments (P41), where defects were found earlier than in production. However, due to various resource limitations, they could only perform the tests in an approximate simulation environment. Most of the respondents considered that teams performed well in managing the configuration of test environments (P35) and identifying faults or dependencies (P38).



	P34	P35	P36	P37	P38	P39	P40	P41
6-D	2	1	1	2	1	4	1	3
5-C	3	7	3	2	3	5	5	8
4-C	8	6	5	6	8	5	3	3
3-B	3	2	6	3	0	4	3	3
2-B	3	2	0	4	1	0	2	1
1-A	1	2	4	3	6	1	4	2
0-A	0	0	1	0	1	1	2	0

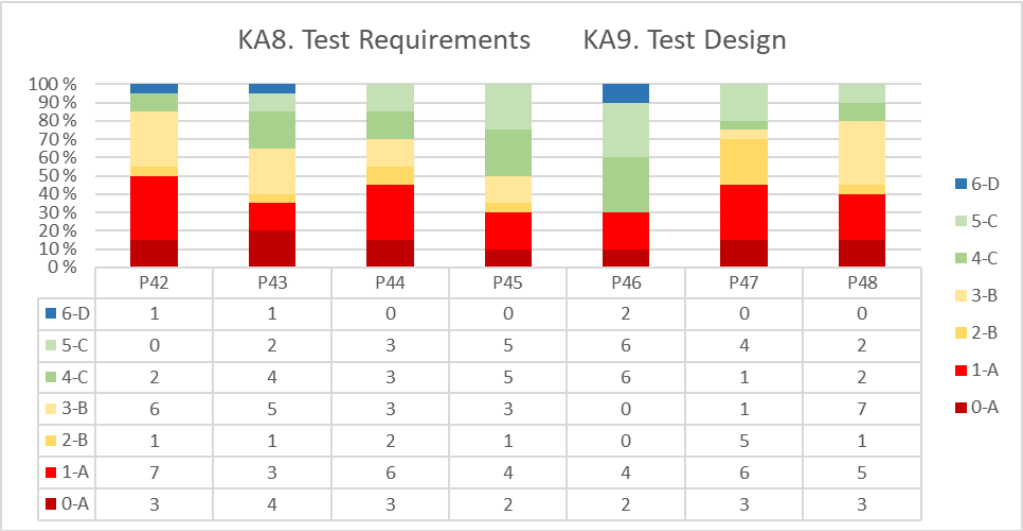
Figure 17. Results distribution for KA7

Conversely, the inadequacy of the test environment support (P37) and ineffectiveness of verifying the environment and data before use (P36) were reported by the respondents. A few respondents believed that stable test environments not only rely on configuration personnel but also require all staff to cooperate to minimize negative environmental factors in the testing.

The test data should be as realistic as possible for software testing. For banking systems, customer and test data are highly sensitive. Of the respondents, 90% agreed that they used the test data in compliance with regulations and legislation (P39). However, most respondents did not consider that they managed test data correctly (P40) regarding creation, reuse, maintenance, and destruction.

5.6 Test Requirements and Test Design

Test requirements are the foundation of the test process and determine the test objects, scope, test coverage, roles, scheduling, and test design. They must be observable and evaluable. A defined method of deriving TA requirements (P42) is thus crucial. As shown in Figure 18, 85% of the respondents disapproved of the current method of obtaining test requirements, including the required clarity, details, and coverage. Only 35% of the respondents thought the effects of the changing TA requirements (P43) were under control. The most mentioned issue was unmanaged requirement changes during a later stage of TA development.



	P42	P43	P44	P45	P46	P47	P48
6-D	1	1	0	0	2	0	0
5-C	0	2	3	5	6	4	2
4-C	2	4	3	5	6	1	2
3-B	6	5	3	3	0	1	7
2-B	1	1	2	1	0	5	1
1-A	7	3	6	4	4	6	5
0-A	3	4	3	2	2	3	3

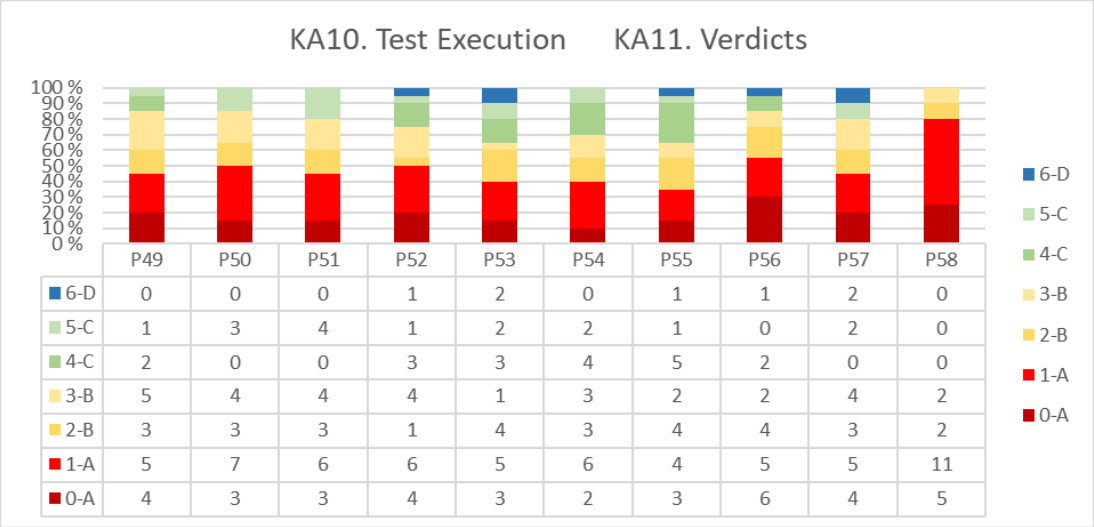
Figure 18. Results distribution for KA8 and KA9

Testing techniques, such as boundary value analysis, equivalence partitioning, decision tables, state transitions, and structure-based techniques [5 pp. 55-61], involve specialized logical thinking ability that requires testers to understand a certain technique and apply it during test design. The scores for using specific test design techniques (P44) were low to medium. This implies potential problems: either the testers were unfamiliar with the testing techniques, or they ignored their application. Both alarming reasons can lead to imperfect test capability. However, unexpectedly, half of the respondents claimed that their teams captured and reused the patterns in using test design techniques (P45) while they were troubled by applying techniques.

Teams appeared to perform better on grouping test cases into test suites for different purposes (P46). They achieved this by setting up the test executions in the Jenkins CI environment. Excellent test codes and test cases are inseparable from the code standard and guidelines. The scores showed that more standardized guidelines are needed on designing test cases (P47) across the organization together with broader static and dynamic measurements on test codes (P48).

5.7 Test Execution and Verdicts

The test execution involves deciding how to execute the tests and what tests to use. From the recorded test execution, the execution results can be obtained, the test steps can be examined, and defects for the test execution can be created (or linked). As shown in Figure 19, 95% of the respondents thought they did not sufficiently prioritize the automated test cases to meet the test execution schedule (P49). Poor test execution management could cause this. Test execution management should be defined in the test plan and test strategy, where the scope, purpose, method, resources, and risks of the test execution are described.



	P49	P50	P51	P52	P53	P54	P55	P56	P57	P58
6-D	0	0	0	1	2	0	1	1	2	0
5-C	1	3	4	1	2	2	1	0	2	0
4-C	2	0	0	3	3	4	5	2	0	0
3-B	5	4	4	4	1	3	2	2	4	2
2-B	3	3	3	1	4	3	4	4	3	2
1-A	5	7	6	6	5	6	4	5	5	11
0-A	4	3	3	4	3	2	3	6	4	5

Figure 19. Results distribution for KA10 and KA11

Automatic preprocessing (P50) before the test execution and automatic post-processing tasks (P51) are part of the TA execution process. Most respondents gave low scores on

these two items. They further highlighted the issues, such as a lack of routes to automatically create testing data in certain systems, missing scheduled test executions against CI, and Jenkins pipelines still being triggered manually.

Based on the score distribution shown in Figure 19, many teams did not implement parallel test executions for complex systems (P52). This may be because the test environments do not support multiple simultaneous executions, or the teams did not thoroughly consider the possibilities and advantages of their implementation. Parallel executions must be designed from the level of TA architecture and TAF. If the framework or architecture is immature or not created, minimal opportunities exist for parallel executions.

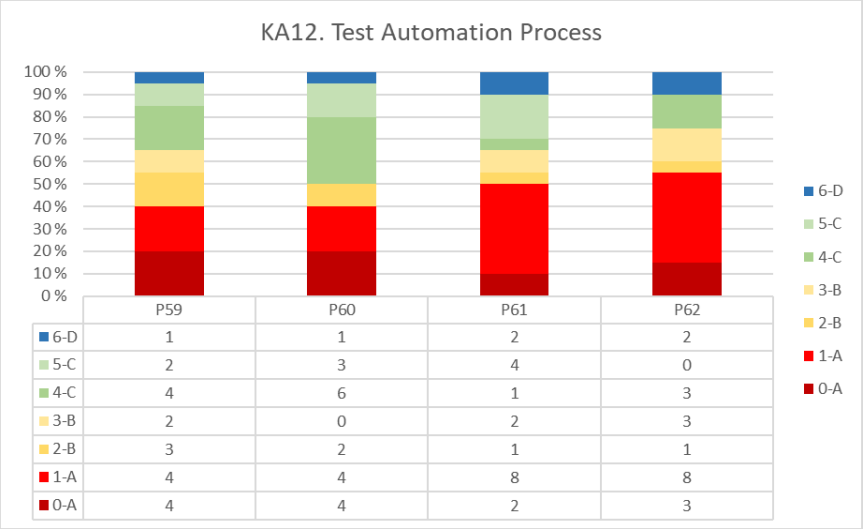
Test execution must involve a conclusion for each tested item, that is, whether the test passes. A mechanism should exist to alert relevant people when critical failures occur, such as a crash caused by the program, a deadlock in the database, or a data communication error (P53). The evaluation result implied that such an alert mechanism has not been used or was used at a minimum level.

A verdict should be given based on the reliable facts of a situation, for example, whether a SUT behaves as expected based on testing results. Test oracles must reliably conclude whether a system behaves correctly when it passes or fails a test (P54). The assessment result shown in Figure 19 implied that several teams had no confidence in their test oracles. Some reported that while defects in the test object did not cause inconsistency or failures of test results, but errors in the test environment, test oracles, and test framework did. According to the comments, most of the teams agreed that they monitored the status and progress of testing regarding test results (P55).

However, the teams were not optimistic regarding test reporting, especially on presenting comprehensive test reports with test results collected from original sources (P56), sharing useful results with relevant stakeholders (P57), and using dashboards with stakeholders (P58). The content, format, depth, and details of the reports were not targeted to different stakeholders. Two key issues may require resolution: first, whether the teams have identified the targeted contents and shared them with different stakeholders. Theoretical learning and communicating with stakeholders can help teams create useful reports. Second, a common platform may be required to display dashboards to stakeholders.

5.8 Test Automation Process

Evaluating the TA process as a separate KA, rather than via separate stages and steps, can increase understanding of how the teams view the status of TA holistically. As shown in Figure 20, most respondents did not positively review the overall TA process. More than half the teams disagreed that they conducted TA via a stable and controllable test process (P59). The TA process is an independent cycle; however, it still depends on the overall testing and software development processes. An uncontrollable and unstable process can show the instability of the overall testing process and its separation from the development process.



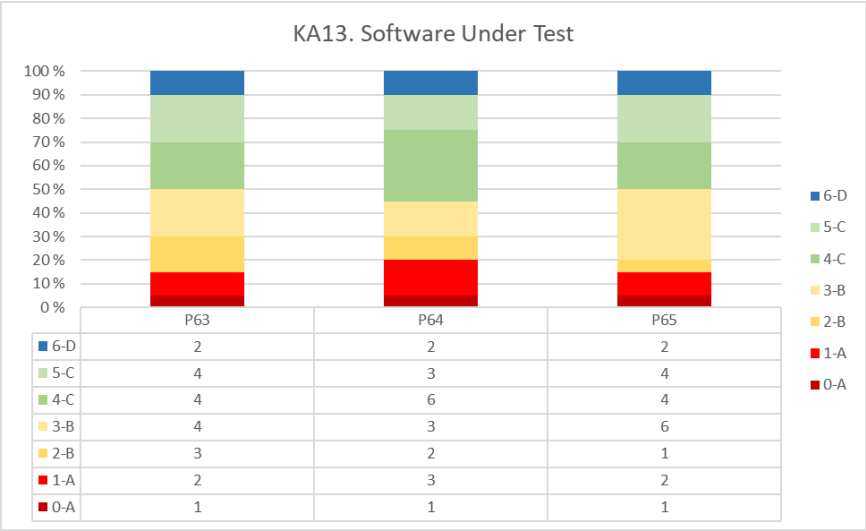
	P59	P60	P61	P62
6-D	1	1	2	2
5-C	2	3	4	0
4-C	4	6	1	3
3-B	2	0	2	3
2-B	3	2	1	1
1-A	4	4	8	8
0-A	4	4	2	3

Figure 20. Results distribution for KA12

Half the respondents thought they conducted the TA in parallel with development cycles (P60); however, the other half did not. This may be because TA code development has shifted to the early stage of software development in some teams rather than the late stage when the product code is completed. Most respondents argued that the TA process was not built to support other processes (P61). They focused on building the tests but ignored the importance of integrating TA into the testing processes, and the rapid feedback cycles (P62) of TA development.

5.9 Software Under Test

The software under test mentioned here refers not only to the software but also the system context. This includes all stakeholders, development cycles, related documents (process documents, technical documents), deployment, related technologies, business knowledge, and legal affairs.



	P63	P64	P65
6-D	2	2	2
5-C	4	3	4
4-C	4	6	4
3-B	4	3	6
2-B	3	2	1
1-A	2	3	2
0-A	1	1	1

Figure 21. Results distribution for KA13

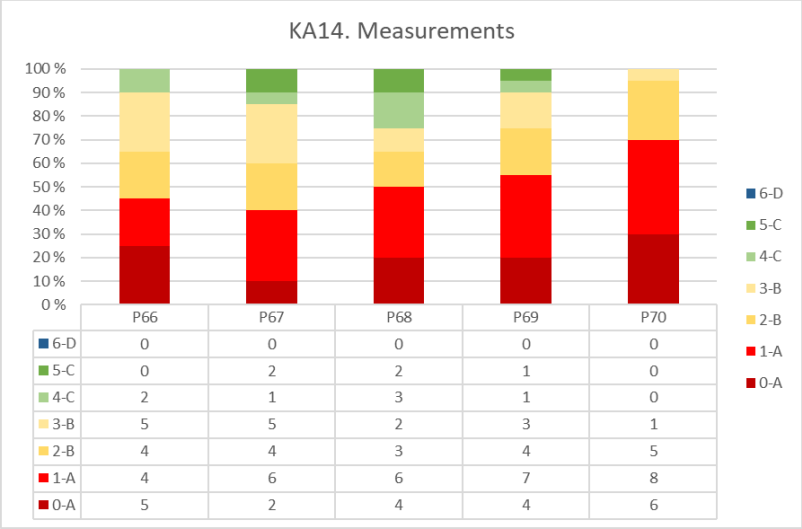
Based on Figure 21, approximately half the respondents gave positive feedback on the SUT; however, the testability (P64) of the SUT by TA was a major concern because some technology stacks do not support TA. The maturity (P63) of the SUT also affected the realization of TA. This created a situation where end-to-end testing is challenging to achieve as part of system testing. The execution speed of the SUT (P65) can affect the execution speed of automated test cases. Delays sometimes made the test results unpredictable because the SUT execution speed was unduly slow.

5.10 Measurements

As many organizations use certain measurements to judge effectiveness, the effectiveness of TA must also be measured. Unlike the usual measurements, TA development is also code development; thus, additional measurements are required, such as the false

alarm rate, coverage rate, code maintainability, automation process rate, and cost-efficiency.

As shown in Figure 22, the assessment results for this KA were poor. Almost 90% of the respondents disagreed that TA was measured by appropriate metrics (P66). Most of them stated that they had never weighed the crucial attributes of TA (P67) as measurements. As no appropriate measurements existed, it was difficult for the team to identify improvement areas through measurements (P68). However, some respondents mentioned that they found problems through code reviews, which improved their TA code quality. Regarding whether the TO members received feedback about their performance (P69) regularly, most responses revealed that the feedback circuits were insufficiently engaged, particularly the communication between developers and testers.



	P66	P67	P68	P69	P70
6-D	0	0	0	0	0
5-C	0	2	2	1	0
4-C	2	1	3	1	0
3-B	5	5	2	3	1
2-B	4	4	3	4	5
1-A	4	6	6	7	8
0-A	5	2	4	4	6

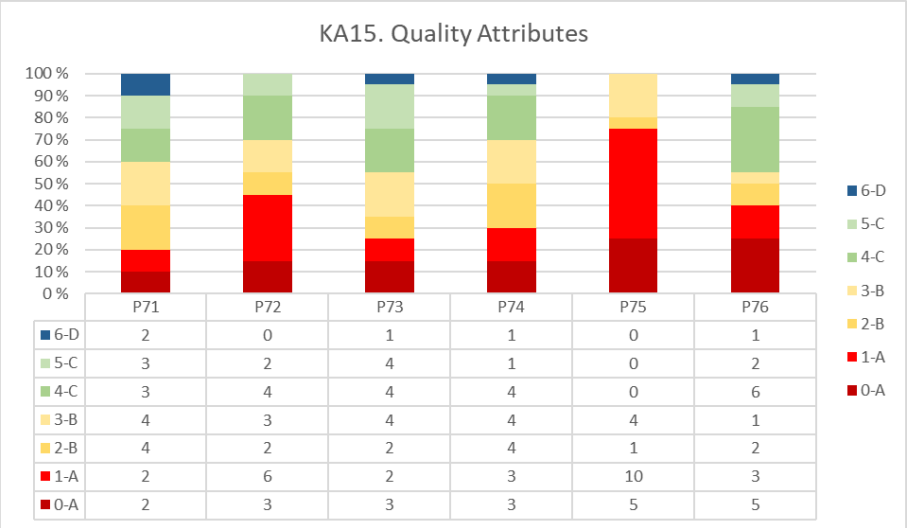
Figure 22. Results distribution for KA14

Reporting measurements appeared to be a significant problem for each team, particularly the measurement of TA. Teams admitted that the appropriate measurements were missing and were not visible in any format, neither test reports nor dashboards (P70). Software testing activities must be monitored through measurements and metrics that provide insight into teams' testing progress, productivity, and performance and the quality of the software under test.

5.11 Quality Attributes

This section considers the quality attributes, including portability, maintainability, efficiency, reliability, usability, and functionality. The details of each attribute are given in Section 2.2.

Regarding portability (P71), 40% of the respondents thought that their automated tests could be implemented in new environments easily, despite potential differences in the hardware and software environments and the configurations.



	P71	P72	P73	P74	P75	P76
6-D	2	0	1	1	0	1
5-C	3	2	4	1	0	2
4-C	3	4	4	4	0	6
3-B	4	3	4	4	4	1
2-B	4	2	2	4	1	2
1-A	2	6	2	3	10	3
0-A	2	3	3	3	5	5

Figure 23. Results distribution for KA15

Three aspects were included in the maintainability (P72): the testware, test environment, and automated tests. Of the respondents, 70% suggested that the TA testware, such as test data, test cases, and test reports, were not organized in convenient architecture, as shown in Figure 23. Most of the teams considered that they managed the setups and configuration of the test environment effectively. Only half the respondents thought the test environments were complex to maintain and update in terms of deployment and development. More than half the teams said that as the number of automated test cases increased, the workload of the testers increased, and it was difficult to maintain automated tests to keep them operational. Developers paid minimal attention to whether new codes would break existing tests, and the testers did not communicate with developers regarding code changes. For the traditional waterfall model, the quality team maintains test scripts, and the development team is not involved. However, the agile framework

blurs the boundaries between the responsibilities of the two units. The agile method includes cross-functional development teams and agile testers. Thus, both units should maintain the TA.

Efficiency (P73) implies quality and speed. The results showed that half the respondents had little confidence in their automated tests to produce reliable and fast results (P75). This could imply instability of current automated test cases, causing test results to oscillate and creating excessive maintenance work.

Reliability (P74) covers two aspects: automated tests and the test environment. Most of the opinions further proved that the automated tests were not resistant to inconsequential changes, such as SUT and requirement changes and unexpected test execution events. However, more than half the respondents thought the test environments had high accessibility when automated tests were running but required appropriate restoration and a recovery mechanism to revert to the preceding status.

Almost all teams agreed that the usability (P75) of their automated tests was poor and not useful to other users except for testers. Some teams have been using a keyword-driven TA framework to write automated test cases; however, the test case construction was complex and thus difficult even for testers to understand.

Most of the opinions confirmed that TA met the given test purposes and fulfilled the functionality (P76) attribute in terms of increased defect detection efficiency and test coverage, shortened test cycles, and better product quality.

6 Recommendations and Conclusion

This chapter establishes a general practice method, defines the areas for improvement based on pre-defined priorities, proposes the initial steps for changes, sets the initial objectives for the follow-up, and outlines a long-term vision.

To achieve effective improvements, the general practice should be goal-oriented to avoid aimless actions; a consensus should be reached, and building management commitment ensured. The TA process improvements must be led and promoted through an effective TA process improvement task force. This task force shall clarify periodic goals of improvements, including setting step-by-step action points, conducting regular reassessments, organizing regular follow-up meetings, and promoting continuous improvement. Achieving consensus on the issues and optimization schemes by all participants during the entire process is the basis for implementing subsequent actions.

The improvement procedures involve three stages; each one is further refined based on the consensus of the previous ones. Key milestones should be set separately to control the progress.

- The first stage involves summarizing the current state of the TA process, clarifying organizational level responsibilities, including the role of the management sponsorship, defining high-level goals. A consensus must be formed between the stakeholders and task force.
- The second stage involves setting achievable short-term goals on a team level based on the operational reality and stakeholders' acceptance. A consensus must be formed among the relevant teams.
- The third stage involves entering the specific improvement cycle, where the Deming cycle should be adopted in each team.

During the entire improvement process, periodic follow-up meetings should be held. Every meeting must achieve an effective outcome, including the following points:

- Resolutions to the issues must be addressed, such as the responsibilities, blockers, and alternative plans for the next step

- A consensus of all relevant parties, such as stakeholders and team leaders, must be achieved. A decision-maker can determine the eventual plan if multiple parties cannot agree.
- Meetings must be guided to avoid deviation from the theme. Meeting minutes must be recorded.

6.1 Improvement Suggestions

As shown in Figure 24, the KAs are ranked top-down based on, firstly, their pre-defined priority and, secondly, their assessed maturity levels. The KAs with the higher priority and lower maturity level must be addressed first: the IT department should prioritize improving the TA strategy, test tool use, verdicts, resources, knowledge transfer, test requirements, test design, and test execution.

	Prioriry			Level			
Key Area	**L**	**N**	**H**	**Initial**	**Controlled**	**Efficient**	**Optimizing**
Test Automation Strategy			✓	✓			
Test Tool Use			✓	✓			
Test Organization			✓		✓		
Test Tool Selection			✓		✓		
Verdicts		✓+		✓			
Resources		✓		✓			
Knowledge Transfer		✓		✓			
Test Requirements		✓		✓			
Test Design		✓		✓			
Test Execution		✓		✓			
Test Automation Process		✓		✓			
Software Under Test		✓			✓		
Quality Attributes		✓			✓		
Measurements	✓			✓			
Test Environment	✓					✓	

Figure 24. Improvements based on priority

The following suggestions and follow-up checks focus on the above KAs. The follow-up period may be 3–6 months after the first-step improvement is started.

Test Automation Strategy

The major finding for the TA strategy was the lack of high-level and low-level strategic plans. The recommended initial steps for improving the TA strategy are described in Table 6.

Table 6. Improvement suggestions and follow-up for test automation strategy

Level	First-step	Follow-up Checkpoints
IT department	➢ QA leadership creates a high-level TA strategy that supports an organization's business goals and aligns with the architectural model. They review the content with teams: - general guidance on testing methodologies (e.g., keyword-driven, data-driven), TA tools, testing levels, testing coverage, checklist of requirement analysis ➢ The strategic plan must be reviewed regularly. It can be reviewed yearly.	✓ A high-level TA strategy is created and reviewed with the teams. ✓ The TA strategy is aligned with business goals and the architectural model.
Teams	➢ Each team adopts the high-level strategy and creates a team-level TA strategy that should be agreed with the team and stakeholders without contradicting the team's goals. - The team-level strategy should define the test levels according to the TA pyramid while considering the application's characteristics and resources. - The strategy should also clarify the test types to be automated and the estimated effort for the TA task.	✓ A team-level TA strategy is created and agreed by the team and stakeholders. ✓ The TA strategy adopts the high-level plan, clarifying all the necessary aspects. ✓ Teams and stakeholders have agreed on the strategy and approach to managing changes.

	- It is recommended that the risks and mitigating methods are identified in the strategic plan. ➢ Teams communicate with relevant stakeholders to agree on the strategic approach and future changes.	

Test Tool Use

Regarding the tool use, the major issue was the lack of a tool-specific ROI analysis business case. Other major issues include inadequate new tool introduction and unified test tool guidelines. Minor issues were found, such as unclear preconditions for tool use and a lack of periodic reviews of the tools. The actions addressing the major issues are listed in Table 7.

Table 7. Improvement suggestions and follow-up for test tool use

Level	First-step	Follow-up Checkpoints
IT department	➢ QA team defines and manages guidelines for using the TA tools and introducing the goals and purposes of the tools to teams ➢ IT management builds business cases to analyze cost-effectiveness of tools.	✓ Guidelines are defined and introduced to teams. ✓ Cost-effectiveness analysis is conducted for at least one existing tool.
Teams	➢ teams acquire knowledge and preconditions of using tools from QA team ➢ teams follow the guidance and use the tools independently.	✓ Teams adopted the tools and used them according to guidelines.

Verdicts

For the verdicts, three major findings were identified: the test oracle was overlooked, the test results were not integrated, and the test results were not effective for stakeholders. The required changes and checkpoints for improvement are specified in Table 8.

Table 8. Improvement suggestions and follow-up for verdicts

Level	First-step	Follow-up Checkpoints
IT department	➢ The correct behavior of the system or component must be specified in the specifications. ➢ stakeholders set the criteria for TA results reporting and dashboard.	✓ specifications contain accurate descriptions of correct system behaviors ✓ criteria for results reporting and dashboard are supplied to teams.
Teams	➢ teams refactor existing tests to improve and/or add test oracles ➢ teams integrate (all) test results - construct reporting templates - build dashboards.	✓ Test oracles are examined and improved, and code commits can be traced. ✓ Test reports show integrated results to stakeholders. ✓ Dashboards are configured according to criteria provided by stakeholders.

Resources

This KA was not the most poorly scored area but was the most mentioned topic during assessment interviews. The major issues were concentrated in the following three aspects: insufficient funds for TA, insufficient time allocation to perform TA tasks, and lack of TA experts or capabilities in many teams. Table 9 lists achievable actions for improvement.

Table 9. Improvement suggestions and follow-up for resources

Level	First-step	Follow-up Checkpoints
IT department	➢ consider budget to fund TA infrastructure-building for the teams that do not have TA. ➢ consider budget to fund TA skill learning program to increase TA capabilities	✓ a visible budget plan to fund TA.

	➢ consider budget to hire more TA experts for the teams that do not have TA testers.	
Teams	➢ Include TA tasks as part of the feature story; estimate the effort as part of the story points during sprint planning. ➢ Proactively gain TA skills through individual learning.	✓ traceable record of TA task estimation in stories, visible on teams' scrum boards.

Knowledge Transfer

The existence of knowledge sources, such as expertise and good TA practices, is a necessary condition for the realization of knowledge transfer. Extensively mining internal and external knowledge sources, stimulating the willingness of internal knowledge sources to share knowledge, and improving their ability to interpret and express knowledge help enterprises to sustain good knowledge transfer results. The assessment results showed that TA knowledge was not properly collected, maintained, and shared. Table 10 provides suggestions on how knowledge transfer can be improved.

Table 10. Improvement suggestions and follow-up for knowledge transfer

Level	First-step	Follow-up Checkpoints
IT department	➢ Use enterprise knowledge management (EKM) models and methods [29] to promote knowledge transfer.	✓ a rational plan for managing TA-related knowledge.
Teams	➢ Aim to capture all forms of knowledge and information about TA. ➢ Aim to manage this knowledge and information in concrete sustainable formats. ➢ Share the managed TA knowledge and information within the team or organization.	✓ visible contents of TA knowledge sharing and transferring.

	➢ Aim to search for more TA knowledge and information from internal and external sources.	

Test Requirements

The test requirements determine what must be tested, describe the conditions, and cover business rules, functionalities, and non-functional requirements. The test design and execution depend on the test requirement. The assessment results indicated that no defined methods of obtaining TA requirements existed. Table 11 indicates actions for minimizing the issues mentioned.

Table 11. Improvement suggestions and follow-up for test requirements

Level	First-step	Follow-up Checkpoints
IT department	➢ Stakeholders define use cases, business rules, functionalities, and non-functional requirements.	✓ Use cases, business rules, functionalities, and non-functional requirements are visible, at least at Epic [32] or feature level.
Teams	➢ Test manager or QA personnel writes TA test requirements based on the information collected from stakeholders and risk analysis.	✓ TA test requirements are defined and visible in the test management system.

Test Design

Test design is an essential and practical step in the testing process. A lack of test design techniques and test case design guidelines was the main finding for this KA. Table 12 proposes improvement steps for these two aspects.

Table 12. Improvement suggestions and follow-up for test design

Level	First-step	Follow-up Checkpoints
IT department	➢ The QA team creates TA test case design guidelines: - The reliability, reusability, and maintainability of the script should be the top priority. - rigorous code standards.	✓ TA Test case design guidelines are visible to teams.
Teams	➢ TA test case design guidelines and code standards are adopted as part of the code review. ➢ Test case design must be conducted before implementation. - Test requirements are matched. - Design techniques are applied.	✓ Guidelines and code standards are used in the pull request code review process.

Test Execution

Regarding test execution, three key issues were found: prioritization, fault alarm, and automated pre- and post-processing tasks. As listed in Table 13, this study suggests improving the first two aspects.

Table 13. Improvement suggestions and follow-up for test execution

Level	First-step	Follow-up Checkpoints
Teams	➢ Clarify and prioritize TA test executions based on specific needs: - Scheduled execution: Monitor the quality of the code version. - Automatic trigger: The smoke test execution time is controlled within 10 minutes and is automatically triggered when the submitted codes are merged into the master branch. The	✓ Test executions are prioritized and configured according to needs in CI/CD pipelines. ✓ An alert mechanism is set for critical failures. ✓ The alert mechanism involves the team and relevant stakeholders.

	corresponding personnel are notified by email if a problem occurs. - Manually trigger regression testing. For example, a full execution is triggered twice in a cycle (a week or a sprint); it must be triggered manually in the actual situation. ➢ Set the alert mechanism for critical failures of test executions.	

The above suggestions are for improvement in high-priority areas. The given executable first-steps are intended for a short-term period; they are not planned for a completed long-term period. These suggestions still require management support. The QA organization and SAFe teams must determine the most suitable methods via further discussions.

6.2 Potential Threats to Validity

The TAIM study paper [26] specifies two potential threats to the internal validity [30] related to this project. The first is criterion validity: the study states that the instruments they built were the first independent instruments that assess the maturity level of TA [26 pp. 150]. Thus, the effectiveness must be checked after further inspections with more pilots. The second is construct validity, which the study indicates must be further studied and tested with the support of other validity evidence.

Based on the assessment results of this thesis project, two factors may affect the validity of the results: the first is the motivational factor. Answering the survey is time-consuming and requires additional effort outside working hours; participants may lose their motivation and thorough judgment during the process, affecting the scores they give. The second is the generalization factor. Despite a few teams having good TA, most of the assessed SAFe teams do not have TA ready; their scores may significantly affect the outcome.

6.3 Long-term Vision

The TA testing process involves the interaction of three elements: process, personnel, and technology. The efficient integration of the three elements can improve the quality of software products and increase customer satisfaction (internal and external) while reducing costs and increasing corporate profits. This study's long-term visions of the three elements are as follows.

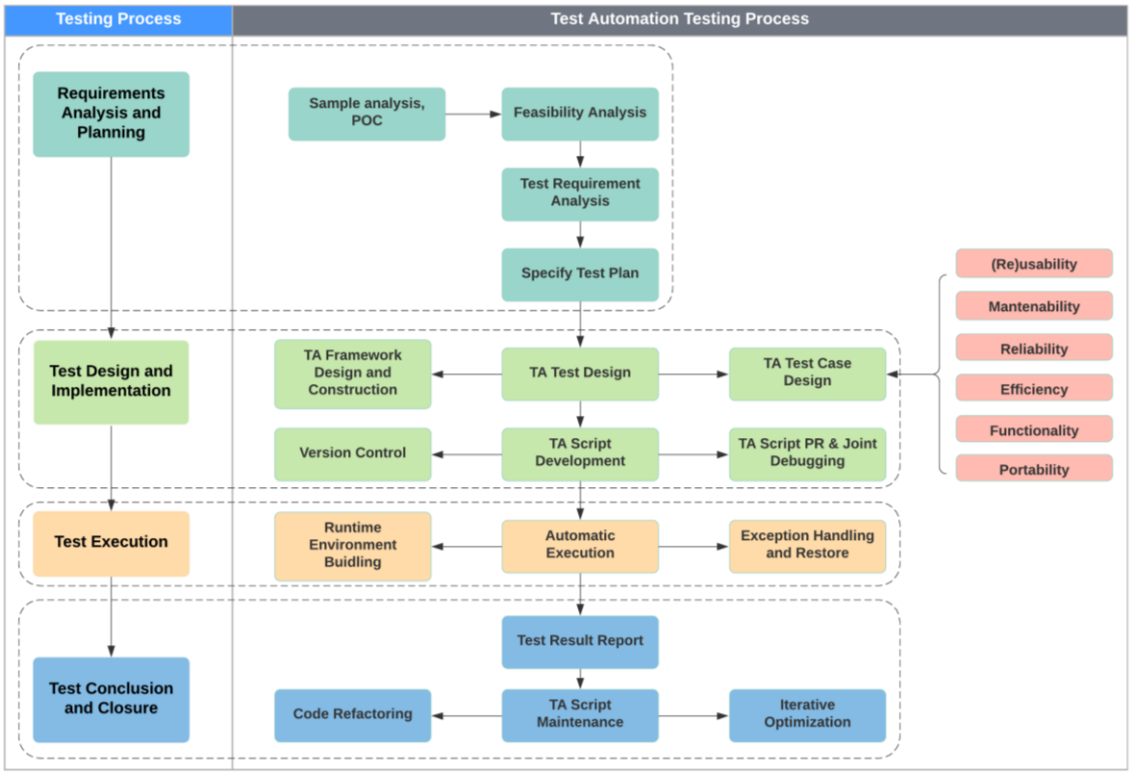


Figure 25. Proposal for TA process

Process

The TA process should ultimately establish a system that embraces testing policy, testing strategy, testing process, testing plans, and risk management. It is not only part of the overall testing process but is also an independent process that aligns with the phases of the overall testing process.

The current TA process at the case company is ineffective. A long-term goal to make the TA process efficient and effective is proposed by this study, as illustrated in Figure 25,

which shows a concise model based on combining the theoretical study and analysis of the assessment results. The SAFe teams should follow the process model during each program increment (PI). Improvement suggestions for each TA process phase include the following:

- In the first phase of the testing process, requirement analysis and planning, the feasibility of TA should be analyzed accordingly by using the proof of concept (POC) method, and the test plan should then be written according to the obtained testing requirements by the testers or test managers.
- During the second phase of the testing process, test design and implementation, the TA is designed according to the test plan. The test design includes the design of the TA infrastructure, runtime environment, and TA test cases. When designing the runtime environment, the team or TA specialist must consult DevOps personnel and stakeholders to gain precise information on CI, monitoring, and reporting. When designing the TA test case, the TA test case design guidelines should be followed, and the quality attributes, including portability, maintainability, efficiency, reliability, (re)usability, and functionality, must be considered. Regarding implementation, the TA script development must combine two aspects: the version control of the scripts and the code review based on the TA code standard defined by the QA team and debugging.
- In the third phase of the testing process, test execution, TA test executions should be triggered automatically. This step also includes two important parts. One is the construction of the runtime environment. If all necessary factors are considered during the test design stage, setting up the environment should be simple. The other part is handling exceptions and errors. Besides providing timely alerts and generating necessary logs, the entire operation must automatically restore and resume unfinished executions.
- In the final phase of the testing process, test conclusion and test closure activities, the results report should be generated automatically after the test execution. A more optimal solution is to automatically integrate the generated reports into the test management system so that the results can be further converted into useful data for reporting to stakeholders. After a testing cycle is completed, the scripts enter the maintenance phase, where code refactoring and iterative improvements must be conducted.

This is only a preliminary proposal for improving the TA process; it aims to provide an implementable process framework.

Personnel

To stabilize the QA team (testing organization), team members require room for growth. The TO members should be divided into roles based on responsibilities, such as test engineers, senior QA engineers, and test managers. Regarding skills, these can be divided into functional test engineers, TA specialists, and security test specialists. The TO recruitment plan should match business needs. Regular training must be provided to build TO skills, such as testing foundation training (e.g., test case design methods), industry knowledge training (e.g., banking, bonds, and loans), and testing skills training (TA, performance testing, and security testing). Career plans should be provided for TO members: for example, a senior manual tester becomes a business analyst or a test manager, and a TA engineer becomes a test architect.

Technology

Technology includes TA testing tools, TA infrastructure, and CI and CD tools. The technologies ultimately aim to support efficient testing cycles and accurate testing results. A choice of testing tools must be available, as a single tool or TA framework may not apply to all testing levels and test types. The QA team should continue to use the infrastructure as code (IaC) method, container technology, and a deployment tool to build a TA infrastructure that supports fully automatic pre- and post-processing and test execution and is fully integrated with CI and CD pipelines.

6.4 Conclusion

The assessment found that, at the case company, the maturity levels of KAs such as TA strategy, test tool use, test design, test execution, TA process, and the verdict are at the initial level, indicating the activities are mostly ad hoc. Thus, a significant team effort is required to improve them if the improvement suggestions are accepted and implemented. However, KAs such as the test organization, test tool selection, and the software under test have reached a controlled level, indicating the test process activities are performed correctly. The KA of the test environment has reached an efficient level, indicating

the test process activities are conducted efficiently. The case company should continue to maintain its operational efficiency for these KAs. Additionally, it should conscientiously refine the current TA strategic plan to efficiently combine personnel, technologies, and process with solid and clear goals to achieve successful TA.

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Appendix 1: Assessment Results

The following table lists the results of TA process assessment where each KA and its included practice items are classified with maturity levels.

Key Areas	ID	Practice Items	Category	Level
KA1. Test Automation Strategy	P1	The TA strategy is created.	A	Initial
	P2	The TA goals are set.	C	Efficient
	P3	A cost-effectiveness analysis of TA is conducted.	A	Initial
	P4	Risk analysis is established.	A	Initial
	P5	The test scope and degree of TA are defined.	C	Efficient
	P6	Overlaps between automated and manual testing are examined.	A	Initial
	P7	The gaps and overlap between test types and levels are examined.	A	Initial
	P8	Resources to perform TA tasks are identified.	B	Controlled
	P9	Roles and responsibilities for TA tasks are identified.	A	Initial
	P10	The effort estimation for TA tasks is calculated.	A	Initial
	P11	Stakeholders' feedback on changing the TA strategy is collected.	A	Initial
KA2. Resources	P12	Enough skilled staff are assembled to perform TA tasks.	B	Controlled
	P13	The budget suffices to fund TA.	A	Initial
	P14	Sufficient time is available for TA tasks.	A	Initial
	P15	Enough test tools are available to support testing activities.	C	Efficient
	P16	All required software, hardware, and test data are available in the test environment.	B	Controlled
KA3. Test Organization	P17	Members of the TO are motivated.	B	Controlled
	P18	The TO members have defined roles and responsibilities.	A	Initial

	P19	The TO has an effective communication and problem-solving mechanism.	B	Controlled
	P20	Organizational and management support for TA is available.	A	Initial
	P21	The TO has sufficient professional knowledge and technical skills to perform TA tasks.	B	Controlled
	P22	The TO can maintain test tools in use.	B	Controlled
KA4. Knowledge Transfer	P23	The expertise, good practices, and good test tools are retained.	A	Initial
	P24	Time for training and the learning curve is supported.	C	Efficient
KA5. Test Tool Selection	P25	The required features of the test tools are described.	B	Controlled
	P26	The attributes of the test tools are listed.	B	Controlled
	P27	Constraints are analyzed.	B	Controlled
KA6. Test Tool Use	P28	Preconditions to tool use are clarified.	A	Initial
	P29	Business cases are set to analyze the return on investment of each tool.	A	Initial
	P30	New test tools are formally introduced to the organization.	A	Initial
	P31	New test tools are experimentalized in pilot projects.	A	Initial
	P32	Regular evaluations of test tools are conducted based on the goals.	A	Initial
	P33	The rules and principles for using test tools are defined.	A	Initial
KA7. Test Environment	P34	The requirements of the test environment are thoroughly understood.	C	Efficient
	P35	The configuration of the test environment is managed.	C	Efficient
	P36	The test environment and test data are tested before use.	B	Controlled
	P37	Support for the test environment is supplied.	C	Efficient
	P38	Test environment failure or dependencies are identified.	C	Efficient
	P39	Test data is used in compliance with regulations and legislation.	C	Efficient
	P40	Test data is managed correctly.	C	Efficient

	P41	The test environment matches the production environment.	C	Efficient
KA8. Test Requirements	P42	TA requirements are collected in a defined manner.	A	Initial
	P43	A controlled change process applies to TA requirements.	B	Controlled
KA9. Test Design	P44	Test design techniques are used.	A	Initial
	P45	The test design patterns are recorded and reused.	C	Efficient
	P46	Test suites are structured for different purposes.	C	Efficient
	P47	Test design guidelines are defined.	A	Initial
	P48	The test code is examined by static and dynamic measurements.	B	Controlled
KA10. Test Execution	P49	TA is used for prioritized test cases to meet the schedule.	A	Initial
	P50	Automatic pre-processing tasks are executed before test execution.	A	Initial
	P51	Automatic post-processing tasks are executed after test execution.	A	Initial
	P52	Parallel executions for complex system.	A	Initial
	P53	Critical failures of test execution are alerted.	A	Initial
KA11. Verdicts	P54	The test oracles used to determine whether the system passes or fails the test are reliable and certain.	A	Initial
	P55	The test result can be understood by monitoring the test status and progress.	C	Efficient
	P56	The test results summary is integrated from different sources.	A	Initial
	P57	Test result insights are received by relevant stakeholders.	A	Initial
	P58	Every stakeholder can see useful information from the dashboard.	A	Initial
KA12. Test Automation Process	P59	As part of the testing process, the TA process is structured and stable.	A	Initial
	P60	The TA and development cycle are conducted in parallel.	C	Efficient
	P61	The TA process supports other processes.	A	Initial
	P62	TA development has fast feedback cycles.	A	Initial

KA13. Software Under Test	P63	The SUT has sufficient maturity to perform TA.	B	Controlled
	P64	The SUT has sufficient testability to perform TA.	C	Efficient
	P65	The SUT has sufficient speed to execute TA.	B	Controlled
KA14. Measurements	P66	TA is measured by appropriate metrics.	A	Initial
	P67	Important attributes of TA are defined.	A	Initial
	P68	Areas of improvement are recognized by using measurements.	A	Initial
	P69	Regular feedback is given on each TO member's performance.	A	Initial
	P70	Measurements are visible in the test report and dashboard.	A	Initial
KA15. Quality Attributes	P71	Portability	B	Controlled
	P72	Maintainability	A	Initial
	P73	Efficiency	B	Controlled
	P74	Reliability	B	Controlled
	P75	(Re)usability	A	Initial
	P76	Functionality	C	Efficient