Integration and test planning patterns in different organizations

Chapter 3

Integration and test planning patterns in different organizations

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3.1 Introduction

Planning an integration and test phase is often done by experts. These experts have a thorough knowledge about the system, integration and testing, and the business drivers of an organization. An integration and test plan developed for an airplane is different from the integration and test plan for a wafer scanner. Safety (quality) is most important for an airplane, while time-to-market is most important for a wafer scanner. These important aspects are reflected in the integration and test plan. To investigate the influence of the business drivers on the resulting integration and test plans a number of companies has been visited.

An integration and test plan describes the tasks that have to be performed to integrate individual components into a system. Test tasks are performed in between the integration steps. Note that integration is sometimes called assembly. Integration and testing is performed in early development phases and also in a manufacturing environment.

Business drivers describe what the most important drivers for an organization are. Business drivers are defined in terms of time, cost or quality. The hypothesis is that the order in which business drivers are perceived in an organization determine the way of working and therefore also the integration and test plan.

The goal of the investigation into different integration and test plans at different organizations is to determine what the common elements of such an integration and test plan are. Next to that, the differences are investigated. A number of aspects of an organization next to the business drivers are recorded, like: company size, product volume, number of components in the system, technology used and the sub-contractor model. Note that much of the data is obtained directly from the organization or from publicly available resources. A best guess is made by the authors based on the visits to fill in the gaps.

This chapter, which is based on [66] presented at the 2007 Conference on Systems Engineering Research, is structured as follows. First, the elements of an integration and test plan are introduced. Next, the business drivers and organizational aspects which we consider to be of influence are discussed. Then, the different organizations, business drivers, organizational aspects and integration and test plans are discussed in detail followed by a summary and conclusions.

3.2 Integration and test plans

The *integration and test phase* is the phase in product development or product manufacturing, where components are tested and integrated (assembled) into systems. Components can be tested when component development or manufacturing is finished. Furthermore, components can be tested after each integration phase. An *integration and test plan* determines the order of integration and where testing takes place, that is test phases are positioned in between integration steps.

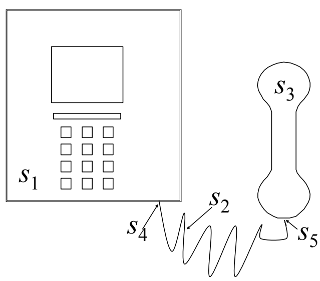

Figure 3.1: Example telephone system.

An integration and test plan is developed before the integration and test phase is started and is often updated when the integration and test phase is executed.

An integration and test plan consists of a sequence of integration and test phases, e.g., the order in which developed components are integrated (assembled) and tested. A test strategy is chosen for each test phase in the integration sequence resulting in a test plan (sequence of test cases) for each test phase.

The elements in an integration and test plan are: Develop DEV, Assemble ASM, Test TST, Disassemble DAS and Copy CPY. These elements, except Copy, are illustrated using an example system: the telephone system depicted in Figure 3.1. CPY is illustrated in Section 3.5.8, when two typical software integration plans are discussed. The three modules in the telephone system, horn (*H*), cable (*C*) and device (*D*), can be integrated using the integration sequence depicted in Figure 3.2.

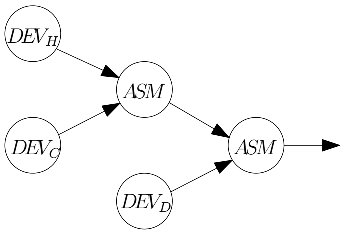

Figure 3.2: Example integration sequence.

The required test phases can now be positioned in between the development (DEV_H, DEV_C, DEV_D) and assembly (ASM) phases. In this quality driven strategy[1], a test phase is planned for each developed component and after each assembled component. Figure 3.3 shows the resulting integration and test sequence. Note that a time-to-market driven strategy[2] may result in an integration and test sequence where some of the test phases are skipped (not depicted in Figure 3.3).

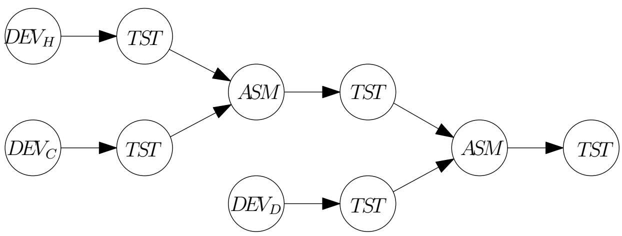

Figure 3.3: Example integration and test sequence.

A replacement of the horn can now be modeled by a disassembly of horn 1 (DAS_{H_1}) and an assembly of horn 2 (ASM_{H_2}). Figure 3.4 illustrates the disassembly of Horn 1, followed by the assembly of Horn 2. For this, two horns are developed in DEV_{H_1} and DEV_{H_2}.

[1] A quality driven strategy is a strategy that reduces the risk after every development or assembly step as much as possible by performing test phases. The probability that the final quality is less than expected is minimal by removing risk as early as possible.

[2] The goal of a time-to-market-driven strategy is to integrate and test the product as fast as possible with as less quality loss as possible. Some testing is performed in between assembly steps, but not everything is tested. Priority lies with the progress of integration.

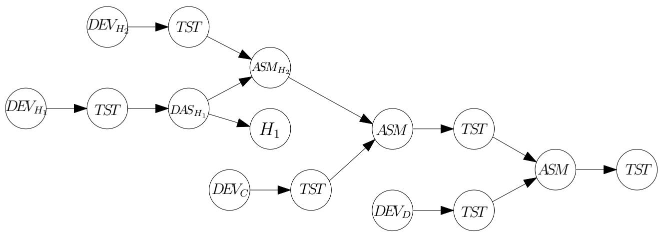

Figure 3.4: Example integration and test sequence with disassembly and assembly of the horn.

The test strategy for each of the test phases can now be chosen, resulting in a test plan for each test phase T. A single test strategy for all test phases could also be chosen.

A quality driven integration and test plan requires that all test phases are executed with a quality driven strategy. The selected elements of the strategy are:

1. Test sequence: execute all test cases, fix the detected faults and re-execute the test cases;

2. Stop criterion: all risks must be removed in each test phase;

3. Test process configuration: execute test cases first, followed by diagnosis and fixing the detected faults.

Many different integration and test plans can be obtained for a single system by varying integration sequences, test strategies and test phase positioning strategies. Different organizations often use a specific integration and test planning *method* resulting in similar integration and test plans for similar products.

3.3 Business drivers

Business drivers are the requirements that describe the goal of an organization. The business drivers *Time*, *cost*, and *product quality* are known from manufacturing management [76, 97]. We will use these business drivers to characterize the investigated organizations.

An organization with time as the key business driver is focused on delivering products as quickly as possible to the market. An organization with cost as key business driver is focused on delivering products as cheaply as possible to the market. Finally, an organization with product quality as key business driver is focused on delivering products to the market which satisfy the customer as much as possible.

The order of importance determines the way of working in the organization. For example, an organization with T-C-Q (Time first, cost second and quality least important) as business drivers delivers products of different quality and production cost than an organization operating with T-Q-C as business drivers. Both deliver products as quickly as possible to the market. The first organization develops, manufactures and services these products as cheaply as possible. Product quality is least important. The focus of the second organization is on product quality (next to fast delivery). Cost is least important.

3.4 Organizational aspects

The integration and test plans of very different organizations were investigated. Sometimes a specific department was visited. The observed integration and test plan was probably only one of the forms in that organization, while the business drivers are for the entire organization. Therefore, additional aspects of the organization are also recorded to determine the possible effect of these aspects. A number of organizational aspects that are recorded are:

1. The number of products shipped per year or number of end-users influences the required product quality and maintenance cost.
2. More complex products result in more complex integration and test plans. Complexity can be the result of many components, resulting in many integrations and possible test phases. Complexity can also be the result of the use of complex technology resulting in complex test cases.
3. Using many different sub-contractors for the development of components could result in many additional test phases to qualify the delivered components. Next to that, political aspects could result in additional test phases. For instance, subcontractor test cases could be repeated to accept the delivered products, resulting in additional test phases. The other way around is also possible.

3.5 Investigated organizations

A number of different organizations have been visited to investigate the influence of business drivers on integration and test plans.

A summary is given for each of the investigated organizations. The order of business drivers indicates the relative importance of the business driver, i.e., T-Q-C means that time-to-market is most important followed by quality and least important is cost. T-Q/C means that quality and cost are equally important. The order of the business drivers is determined by the authors after the visit or investigation. Next to that, relevant information like company size, product volume, number of components, technology used and the number of sub-contractors was recorded.

3.5.1 Semi-conductor (ASML and others)

A typical semi-conductor equipment integration and test sequence (Figure 3.5) consists of development phases (DEV) executed at suppliers, followed by a supplier qualifica-

Company size	Medium, 5000 employees
Product volume	200-300 systems/year
Business drivers	T-Q-C
Number of components	large / very large
Technology used	New technology
Sub-contractors	Many, cooperating

Table 3.1: Semi-conductor equipment manufacturer characteristics.

tion test and a system assembly phase (ASM). The assembly phase of each system is followed by two test phases: the calibration test TST_C[3] and acceptance test TST_A[4]. Chuma [38] investigated the duration of the assembly phase (ASM) and the durations of TST_C and TST_A for lithographic equipment manufactured at ASML, Canon and Nikon[5]. The average duration of the assembly phase is 9.8 days while the average duration of the calibration and acceptance tests in 2005 are 34.5 and 32.5 days, respectively, according to the report.

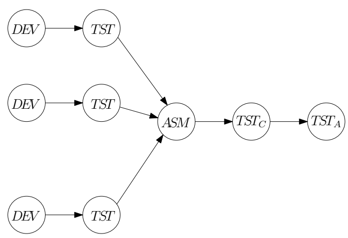

Figure 3.5: Typical semi-conductor manufacturing integration and test plan.

ASML develops semi-conductor equipment using platforms. The integration and test plan of a new system-type of a new platform is developed specifically for this system (See product development later). Subsequent system types in a new platform are integrated and tested based on a previous system type. First, a previous system type is manufactured as in Figure 3.5. New subsystems are developed. The old sub-systems are replaced by the new versions. Figure 3.6 depicts this integration and test plan. The previous system type is assembled after the first assembly step. Modules, like M_1, are disassembled (and re-used) and a newly developed module M_1' is assembled. Module M_2 is replaced similarly by M_2'.
A typical aspect in this time-to-market driven organization is that the newly developed sub-systems M_1' and M_2' are not tested thoroughly. Integration progress is more impor-

[3] A calibration test phase is a test phase where test cases and calibration tasks are interchanged. Test cases are executed on the system to determine the performance of the system. If the system is 'out of specification', calibrations are performed and testing continues.

[4] An acceptance test is the test executed to determine if the customer accepts the system.

[5] ASML, Canon and Nikon are the main suppliers of lithographic equipment to the semi-conductor market.

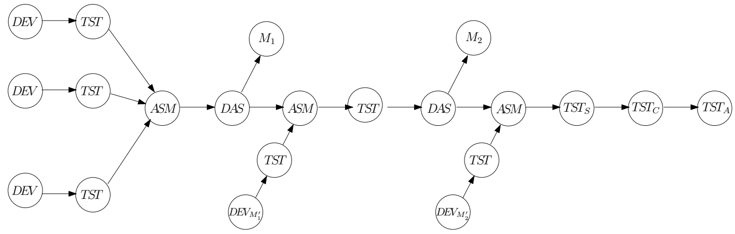

Figure 3.6: Semi-conductor development integration and test plan.

tant than the qualification of sub-systems. Remaining risk in the system is covered in higher level (later) test phases. The final acceptance test is a combination of a thorough system level design qualification TST_S and the normal final calibration and acceptance test phases TST_C and TST_A. The test cases in the final test phases TST_S, TST_C, and TST_A are often mixed such that a faster test sequence is obtained.

3.5.2 Automotive

Company size	large, 30000 employees
Product volume	100000 systems/year
Business drivers	C-T/Q
Number of components	Medium
Technology used	Proven technology
Sub-contractors	Many, cooperating

Table 3.2: Automotive manufacturer characteristics.

A typical assembly line (Figure 3.7) for cars consists of a number of assembly steps (A) followed by a short final acceptance test phase T_A. Suppliers develop (manufacture) and test the parts which are assembled into a car. Testing is standardized and focused on quality (for instance measurement techniques for electrical systems are described in IEC 61508 Part 7 [64]).

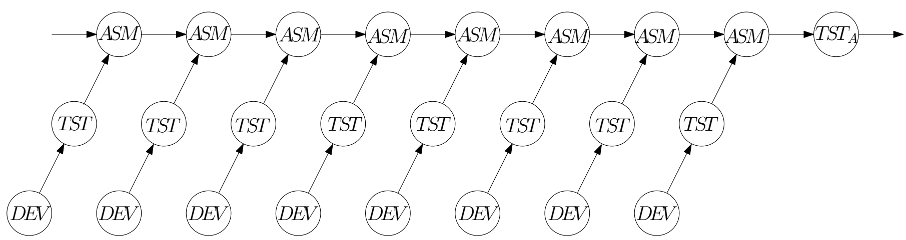

Figure 3.7: A typical ’assembly-line’ for cars.

3.5.3 Communication

Company size	large, 30000 employees
Product volume	120000000 systems/year
Business drivers	Q-C/T
Number of components	Small
Technology used	Proven technology and new software
Sub-contractor	Few/none

Table 3.3: Communication equipment manufacturer characteristics.

A mobile phone communicates with other mobile phones via the (GSM/GPRS/3G) network. An estimated 120000000 mobile phones have been shipped in the USA only in the year 2005 [63]. The estimated number of shipped units in 2011 is 1.25 billion worldwide. The communication protocol between a mobile phone and the infrastructure is standardized [43]. A single test phase of a few weeks qualifies if a mobile phone operates according to the standard. The visited organization developed such a standard test set, which is used by different mobile phone developers. This test phase is repeated if problems are found and fixed until the phone operates according to the standard. A specific example of this re-test phase with three test phases and two diagnose and fix phases (DF) is depicted in Figure 3.8.

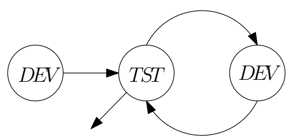

Figure 3.8: Specific example of a mobile phone test phase.

3.5.4 Avionics/DoD

Company size	large, 30000 employees
Product volume	300 systems/year
Business drivers	Q-C-T
Number of components	High
Technology used	Proven technology
Sub-contractors	Many, regulated

Table 3.4: Avionics/DoD manufacturer characteristics.

Airplanes and systems developed for the department of defense (DoD) are integrated and tested using a strict process, like for example the integration and test process for the

777 flight controls [35]. All sub-systems are tested in the supply chain to ensure a short final test phase. To accommodate this, interfaces between sub-systems are thoroughly described and do not introduce new problems. An integration and test plan for an airplane or DoD system is similar to the plan depicted in Figure 3.5. Sub-systems are tested completely before integration. The duration of the final calibration test phase T_C for an airplane, like an Airbus A320, is only a few days, including a test flight. Assemblies are performed in between the final calibration test phase and acceptance test phase. For instance, the engine of an airplane is assembled when all other parts have been assembled and calibrated. The reason for this is safety and cost. Assembling an engine is done in a special area and the engine is costly, so it is assembled as late as possible.

3.5.5 Space (satellites)

Company size	medium, 5000 employees
Product volume	10 systems/year
Business drivers	Q-C-T
Number of components	Medium
Technology used	Proven technology
Sub-contractors	Few, cooperating

Table 3.5: Space/satellite manufacturer characteristics.

Development of a satellite or another space vehicle results in a single system which is delivered to the customer. Each system is unique. The integration and test plan is very similar to an integration and test plan of a newly developed system. The assembly phases are executed as concurrently as possible. Test phases are planned after each development and each assembly phase such that the risk in the system is minimal at all times. An overview of international verification and validation standards for space vehicles, including the main differences between standards, is described in [52]. A planning and scheduling method for space craft assembly, integration and verification (AIV) is described in [3].

3.5.6 Machine builders

A number of machine building organizations has been visited. The developed systems varied from manufacturing equipment to large office equipment. A variety of integration and test plans has been observed in the different organizations. Most of the organizations use an integration plan which is similar to the plan used in the automotive industry. Some use a fix-rate assembly, e.g., each assembly step is performed in a fixed 20 minute time slot by a single operator. Some calibration tests are performed in between assembly steps. Configuring the system for a customer is done just before the

Company size	Medium, 5000 employees
Product volume	1000 systems/year
Business drivers	C-Q-T
Number of components	Medium
Technology used	Proven technology
Sub-contractors	Many, cooperating

Table 3.6: Machine manufacturer characteristics.

acceptance test T_A. An example of a sequence with a customer specific configuration in the last assembly step is depicted in Figure 3.9.

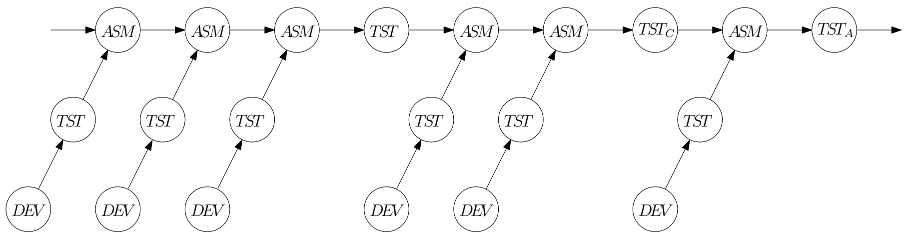

Figure 3.9: Example manufacturing sequence for machine builders.

3.5.7 Drug industry

Company size	large, 20000 employees
Product volume	Millions of tablets/year
Business drivers	Q-C-T
Number of components	Small
Technology used	New technology
Sub-contractors	None

Table 3.7: Drug developing company characteristics.

The drug testing industry is discussed based on [105, 106]. The type of products in this industry is different compared to the technical products as discussed before. Testing of medical drugs is also quite different. Figure 3.10 depicts an integration and test plan for medical drugs.

The development of a potential new drug is a combination of chemical design and a structured search. The integration and test plan starts if a new chemical entity (NCE) is discovered. A screening test (TST_S) is performed to test the potential of the new chemical. The new chemical is then 'integrated' into tablets (DEV_T) or dissolved in liquid (not depicted). What follows next are four test phases in which the new drug is tested (TST_A, TST_I, $TST\,II$, TST_{III}). The average total duration of the entire plan is 14 years. Test phase TST is performed on animals to test for toxicity and long term safety. Test phase TST_I is performed mainly on healthy volunteers to determine the dose level, drug metabolism and bio-availability[6]. Test phase TST_{II} is a test phase on a few hundred patients to test the efficacy of the dose and the absence of side effects. Test phase TST_{III} is performed to test efficacy and safety on thousands of patients. Test phase TST_{IV} is performed after the new drug has received a product license to test for rare adverse events and to gain experience with untested groups of patients.

The conclusion of every test phase can be that testing will not be continued. The new drug will not be further developed and released, in contrary to the (technical) products of the other organizations which can be fixed.

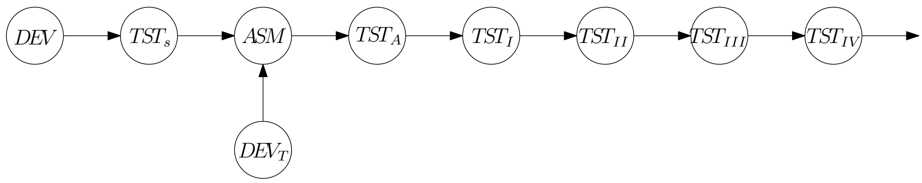

Figure 3.10: Integration and test plan for medical drugs.

3.5.8 Integration and testing of software baselines

A special case of an integration and test plan for product development is an integration and test plan for software developments which are delivered into a single code base. All code ends up in a configuration management system. Testing is done on the code before delivery and on the 'release', a specific baseline in the configuration management system. Two example integration and test plans are discussed. These types of integration and test plans have been encountered at several visited companies, including ASML. Next to that, Cusumano describes a similar integration and test plan as used by Microsoft [39]. The first example plan, depicted in Figure 3.11, contains a periodic test phase. Integration continues when the test phase passes.

The second example plan, depicted in Figure 3.12, contains a periodic test in parallel with integrations of new code. A copy (CPY) of the software is made and used to test the (copied) software.

The test phase in the periodic case is on the critical path, while the test phase in the parallel case is not. On the other hand, problems found in the periodic case are solved before new integrations are performed. Problem solving in the parallel case is more complex, because two baselines are to be maintained at any point in time. This is depicted in Figure 3.12 with an explicit 'self-loop' on the test process and an explicit assembly of solutions into the baseline.

[6]How (and how fast) is the product entered in the body, bloodstream and excreted from the body.

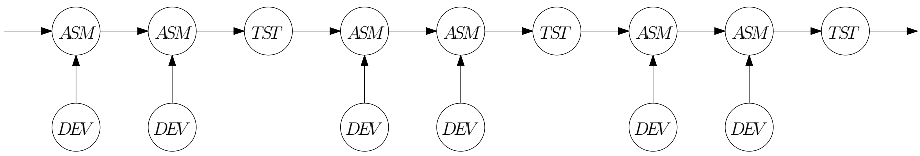

Figure 3.11: Software integration with periodic test phases.

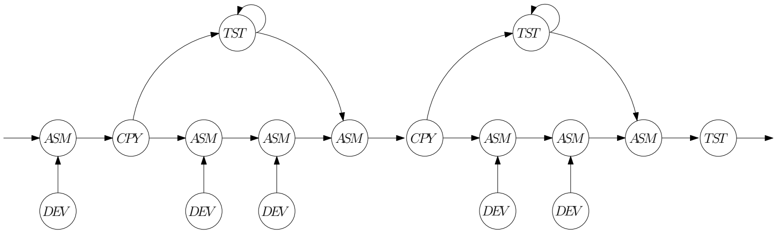

Figure 3.12: Software integration with parallel test phases.

3.6 System complexity versus planning approach

An overview of the organizational types and their influence on an integration and test plan is depicted in Figure 3.13. The organizational types can be found in Table 3.8. Each circle indicates an organization which has been visited or otherwise investigated. The size of the circle indicates the size of the organization (large circles correspond with large organizations). The gray tone of the circle indicates the number of delivered end-products. A darker circle indicates more shipments. Each circle contains the key business drivers (in order) for the visited organization. The organizations are placed in the graph in Figure 3.13 according to the integration and test planning approach on the x-axis (regulated or flexible) and the system complexity on the y-axis. The complexity is a combination of number of components and technology used. The type of organization is described in the bottom half of the circle. In some cases, multiple organizations of the same organizational type have been investigated. All investigated organizations are depicted in Figure 3.13.

A distinction is made between a regulated approach and a flexible approach. The strategy of a *regulated approach* is focused on removing all risk as soon as possible. Consequently, test phases are planned after each development and assembly action. The focus of each test phase is on removing all possible risk. The *flexible approach*, on the other hand, is focused on maximal integration progress. Test phases are planned after some of the development and assembly actions. These test phases are partially executed and the remaining risk is covered by a later test phase.

The flexible approach allows the optimization of test phases by moving test cases from one phase to another phase. The regulated approach prescribes that specific test cases need to be performed in a specific test phase. Optimization of a test phase can only be done within the test phase itself. The organizations which are visited are grouped according to the complexity of the product and the use of a regulated or flexible test approach.

Semi	Semi-conductor equipment
Avionics	Airplanes
Space	Satellites
DoD	Department of defense systems
Drugs	Medical drugs
Comm	Communication equipment
Machines	Machine equipment

Table 3.8: Legend of organizational types.

3.7 Conclusions and discussion

Different organizations use different integration and test plans to develop or manufacture their products. The elements of an integration and test plan are the same for all investigated organizations. The key business drivers of an organization can be characterized by Time, Cost and Quality. An integration and test plan is specific to an organization, the product and the business drivers.

As a result, it can be concluded that a strategy to obtain an integration and test plan for a specific organization cannot be copied to another organization just like that. The business drivers of both organizations should match.

Two types of test approaches are distinguished: regulated and flexible plans. Flexible integration and test plans are used in time-to-market driven organizations, whereas regulated integration and test plans are used for other organizations. The main differences between a regulated and flexible integration and test plan are 1) the positioning of test phases and 2) the type of test strategy which is used for each of the test phases.

Optimizing an integration and test plan could be beneficial in terms of time, cost and quality. A flexible integration and test plan allows many optimization opportunities. Among these are the selection of an integration sequence, a test sequence, the selection of a test positioning strategy, and the selection of a test strategy per test phase.

A regulated (fixed) integration and test plan consists of a regulated integration sequence. Selecting a different (better) sequence is difficult. The cost of changing the regulations should be taken into account. This is also the case for the test positioning strategy and the chosen strategies for specific test phases.

The benefit of a regulated integration and test plan is that these plans are easier to plan and control. All parties involved know from the start what to expect and what to do. The test content is known in advance for all test phases. The benefit of a flexible integration and test plan is that the plan allows for more optimization techniques to

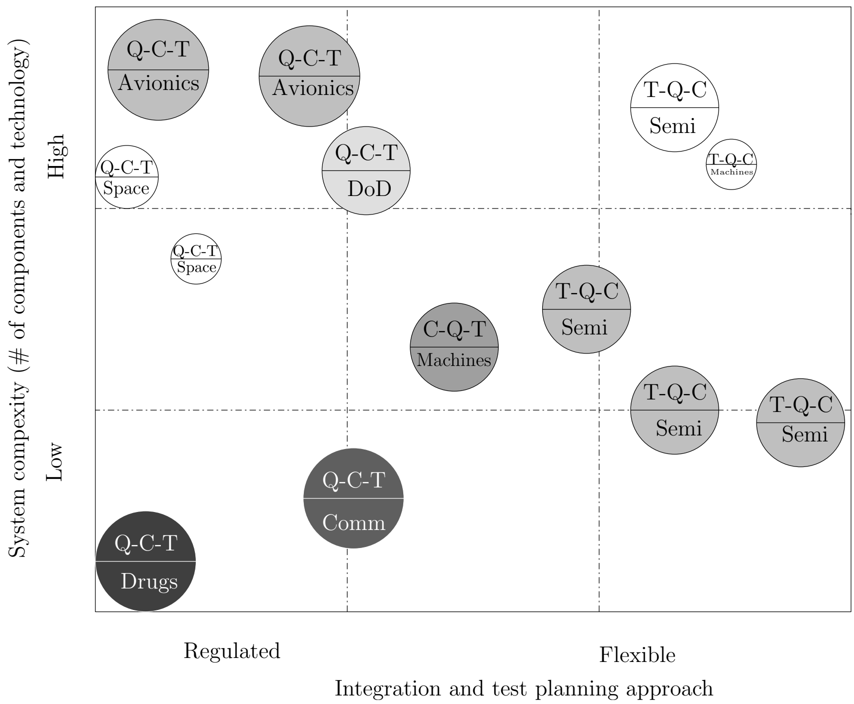

Figure 3.13: Overview of the visited organizations by system complexity and test strategy.

obtain a better plan. The cost of this flexibility is the organizational effort which is involved in the optimization cycle.

A combination of a regulated integration and test plan with known 'control' points in the plan and flexibility in the intermediate phases could be a good solution for organizations that either try to increase the quality levels and maintain the short time-to-market or organizations that try to reduce the time-to-market while maintaining the product quality.