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An overview of integration and test plans in organizations with different business drivers[1]

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Abstract

The integration and test plan of a newly developed or manufactured product often has a typical form in a specific organization. This paper describes a number of typical integration and test plans encountered at various organizations with different business drivers. The integration and test plans are described using the same simple notation.

A number of aspects per organization is investigated: a typical integration and test plan, the organization size, product volume, business drivers, number of components in the product and the used technology.

The investigated organizations are grouped according to product complexity and a rough classification of integration and test plans: flexible and regulated integration and test plans. We conclude that flexible integration and test plans are used in time-to-market driven organizations, while regulated plans are used for *non*-time-to-market driven organizations.

Introduction

Planning an integration and test phase is often done by experts in the visited organizations. 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 than 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.

A number of companies has been visited to investigate the influence of the business drivers on the resulting integration and test plans.

The structure of this paper is 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,

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organizational aspects and integration and test plans are discussed in detail followed by a summary and conclusions.

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 (test phases are positioned).

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 phases* 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 and test plan* resulting in a test plan (sequence of test cases) for each test phase.

The elements in an integration plan are: *Develop*, *Assemble*, *Test*, *Disassemble* and *Copy* []. These elements, except *Copy*, are illustrated using an example system: the telephone system depicted in Figure 1. *Copy* is illustrated later in this paper, when two typical software integration plans are discussed.

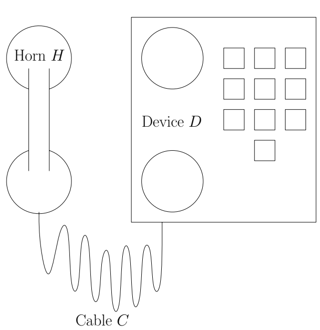

Figure 1 Example telephone system

The three modules in this system, horn (*H*), cable (*C*) and device (*D*), can be integrated using the integration sequence depicted in Figure 2.

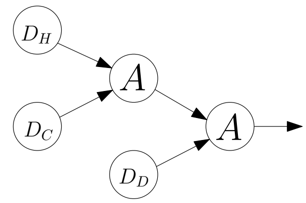

Figure 2 Example integration sequence

The required test phases can now be positioned in between the development (D_H, D_C, D_D) and assembly (*A*) phases. In this quality driven strategy, a test phase is planned for each developed component and after each assembled component. Figure 3 shows the resulting integration and test sequence. Note that a time-to-market driven strategy results in an integration and test sequence where some of the test phases are skipped (not depicted in Figure 3).

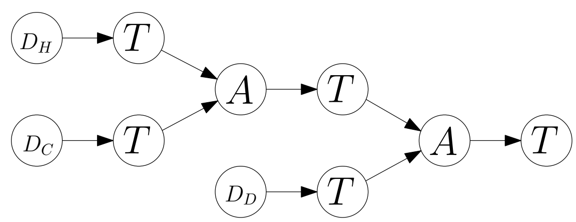

Figure 3 Example integration and test sequence

The horn can now be replaced by a disassemble (DA_{H1}) and an assemble (A_{H2}) action. Figure 4 illustrates the disassembly of Horn 1, followed by the assembly of Horn 2. For this, two horns are developed in D_{H1} and D_{H2}.

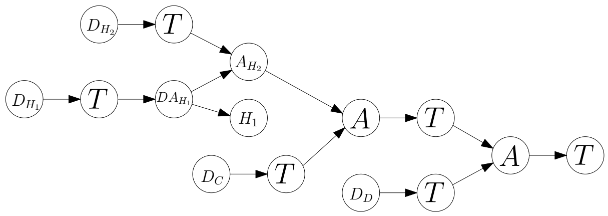

Figure 4 Example integration and test sequence with disassembly and assembly of the horn

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 strategy is as follows:

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

2) Stop criterion: all risk 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.

Business drivers

Business drivers are the requirements that describe the goal of an organization. The business drivers *Time (T)*, *cost (C)* and *product quality (Q)* are known from manufacturing management [Laugen05, Pawar94]. 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 good 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 fast as possible to the market. The first organization develops, manufactures and services these products as cheap 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. The product development, manufacturing of both organizations is different.

Organizational aspects

A number of organizational aspects are of importance for an integration and test plan.

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 usage of complex technology resulting in test cases which are difficult to execute or diagnose. Furthermore, fixing of problems in complex technology can be more difficult.

3) Using many different sub-contractors for the development of components could result in many additional test phases to qualify the delivered components. Organizations with a *cooperating* relation with sub-contractors

have a tight relation based on a mutual goal. Organizations with a *regulated* relation with sub-contractors have a relation based on the regulations and pre-defined agreements.

Investigated organizations

A number of different organizations has 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. Next to that, relevant information like company size, product volume, number of components, technology used and the number of sub-contractors was recorded.

Semi-conductor (ASML and others):

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

A typical semi-conductor equipment integration sequence (Figure 5) consists of development phases (*D*) executed at suppliers, followed by a supplier qualification test and a system assembly phase (*A*). The assembly phase of each system is followed by two test phases: the calibration test T_C and acceptance test T_A. Chuma [Chuma05] investigated the duration of the assembly phase (*A*) and the durations of T_C and T_A for lithographic equipment manufactured at ASML, Canon and Nikon[2]. The average duration of the assembly phase is 9.8 days while the average duration of the calibration and acceptance test are resp. 34.5 and 32.5 days in 2005 according to the report.

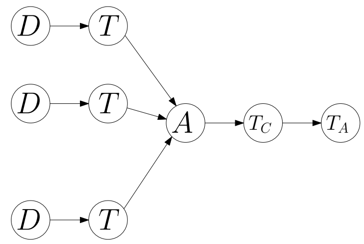

Figure 5 Typical semi-conductor equipment integration and test plan

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 5. New subsystems are developed. The old sub-systems are replaced by the new versions. Figure 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 in by M'_2 Figure 6.

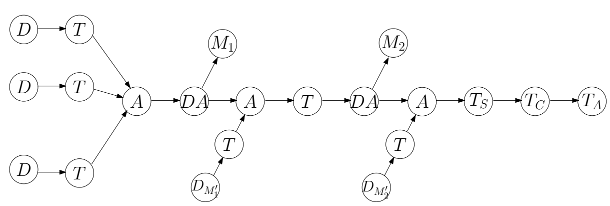

Figure 6 Integration and test plan of a new system type based on a previous system type

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 important than the qualification of sub-systems. Remaining risk in the system is covered in higher level (later) test phases. The

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

final acceptance test is a combination of a thorough system level design qualification T_S and the normal final calibration and acceptance test T_C and T_A. The test cases in the final test phases T_S, T_C, and T_A are often mixed such that an optimal test sequence is obtained.

Automotive (not visited):

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

A typical assembly line (Figure 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 [IEC61508]).

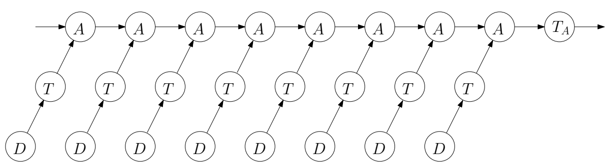

Figure 7 A typical 'assembly-line' for cars

Communication:

Company size	large, 30000 employees
Product volume	120000000 systems/year[3]
Business drivers	Q-C/T
Number of components	Small
Technology used	Proven technology and new software[4]
Sub-contractors	Few/none

A mobile phone communicates with other mobile phones via the (GSM/GPRS/3G) network. The communication protocol between mobile phone and infrastructure is standardized [ETSI]. A single test phase of a few weeks qualifies if a mobile phone operates according 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 8.

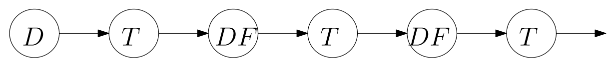

Figure 8 Specific example of a mobile phone test phase

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

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 [Buus97]. 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 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

[3] 120000000 mobile phones have been shipped in the USA only in the year 2005 [Informa06]. The estimated number of shipped units in 2011 is 1.25 billion worldwide.
[4] Relatively proven hardware technology is used in mobile phones. The application (software) is new in this type of products.

an engine is done in a special area and the engine is costly, so it is assembled as late as possible.

Space (satellite manufacturer):

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

Development of a satellite or 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 by [Giordano01]. A planning and scheduling method for a space craft assembly, integration and verification (AIV) is described by [Arentoft92].

Machine builders:

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

A number of machine building organizations have 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 to special customer is done just before the acceptance test T_A. An example of a sequence with a customer specific configuration in the last assembly step is depicted in Figure 9.

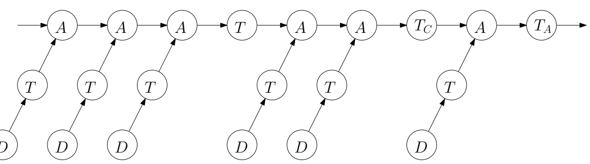

Figure 9 Example manufacturing sequence for machine builders

Drug industry [Rav97,Rav98]:

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

Finally, the drug testing industry is discussed. 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 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 (T_S) is performed to test the potential of the new chemical. The new chemical is then ‘integrated’ into tablets (D_T) or dissolved in liquid (not depicted). What follows next is four test phases in which the new drug is tested (T_A, T_I, T_{II}, T_{III}). The average total duration of the entire plan is 14 years. Test phase T_A is performed on animals to test for toxicity and long term safety. Test phase T_I is performed mainly on healthy volunteers to determine the dose level, drug metabolism and bio-availability[5]. Test phase T_{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 T_{III} is performed to test efficacy and safety on thousands of patients. Test phase T_{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.

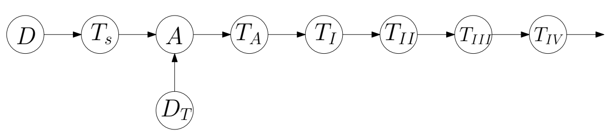

Figure 10 Integration and test plan for medical drugs

Product development in general:

Company size	>50
Product volume	>50
Business drivers	Any
Number of components	>25
Technology used	any
Sub-contractors	productdependent

Not specific for any type of organization is the integration and test plan for newly developed products. This type of integration and test plan is specific for the system. The general approach is that the integration sequence is planned as concurrently as possible. Test phases can be planned in between the development and assembly phases. Where and if test phases are planned depends on the business drivers of the developing organization. The integration and test plan for product development leads to the first functional system and is specific for that system.

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 [Cusumano97].

The first example plan, depicted in Figure 11, contains a periodic test phase which is executed. Integration continues when the test phase passes.

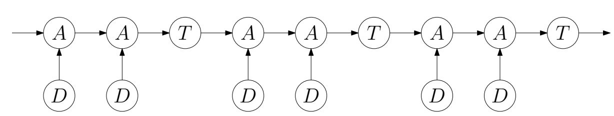

Figure 11 Software integration with periodic test phases

The second example plan, depicted in Figure 12, contains a periodic test in parallel with integrations of new code. A copy (*C*) of the software is made and used to test the software.

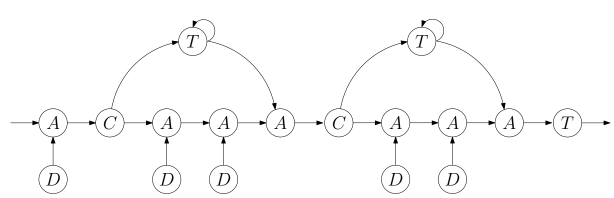

Figure 12 Software integration with parallel test phases

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,

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

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 12 with an explicit 'self-loop' on the test process and an explicit assembly of solutions into the baseline.

Summary

The integration and test plans of seven organization types, product development and software development are discussed. The sequence itself can differ between organizations. This is also the case for the test positioning strategy, which dictates where test phases are placed in the sequence.

Some organizations require a test phase after each development and assembly phase, while others use a more flexible approach. Another difference in the integration and test sequence between organizations is the test strategy of each test phase.

A distinction is made between a regulated approach and a flexible approach. The strategy of a *regulated approach* is focussed 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 focussed 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 usage of a regulated or flexible test approach.

Overview of integration and test plans and organizations

An overview of the organizational types and their influence on an integration and test plan is depicted in Figure 13. Each circle indicates an organization which is visited or otherwise investigated. The size of the circle indicates the size of the organization (large circles correspond with large organizations). The grey 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 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. The legend of organizational types can be found in Table 1. In some cases, multiple organizations of the same organizational type have been investigated. All investigated organizations are depicted in Figure 13.

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

Table 1 Legend of organizational types

The flexible and regulated test approaches correspond with two different business drivers. The time-to-market driven organizations use a flexible test approach, characterized by a loose test positioning strategy and test strategies for each test phase with a fixed (limited) duration and the goal to minimize as much risk as possible within the limited duration. The investigated quality-driven organizations use a regulated test approach (test all and completely).

The integration and test plan for product development (not depicted in Figure 13) is drivers of an organization can be characterised 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 any other organization. The business drivers of both organizations should match.

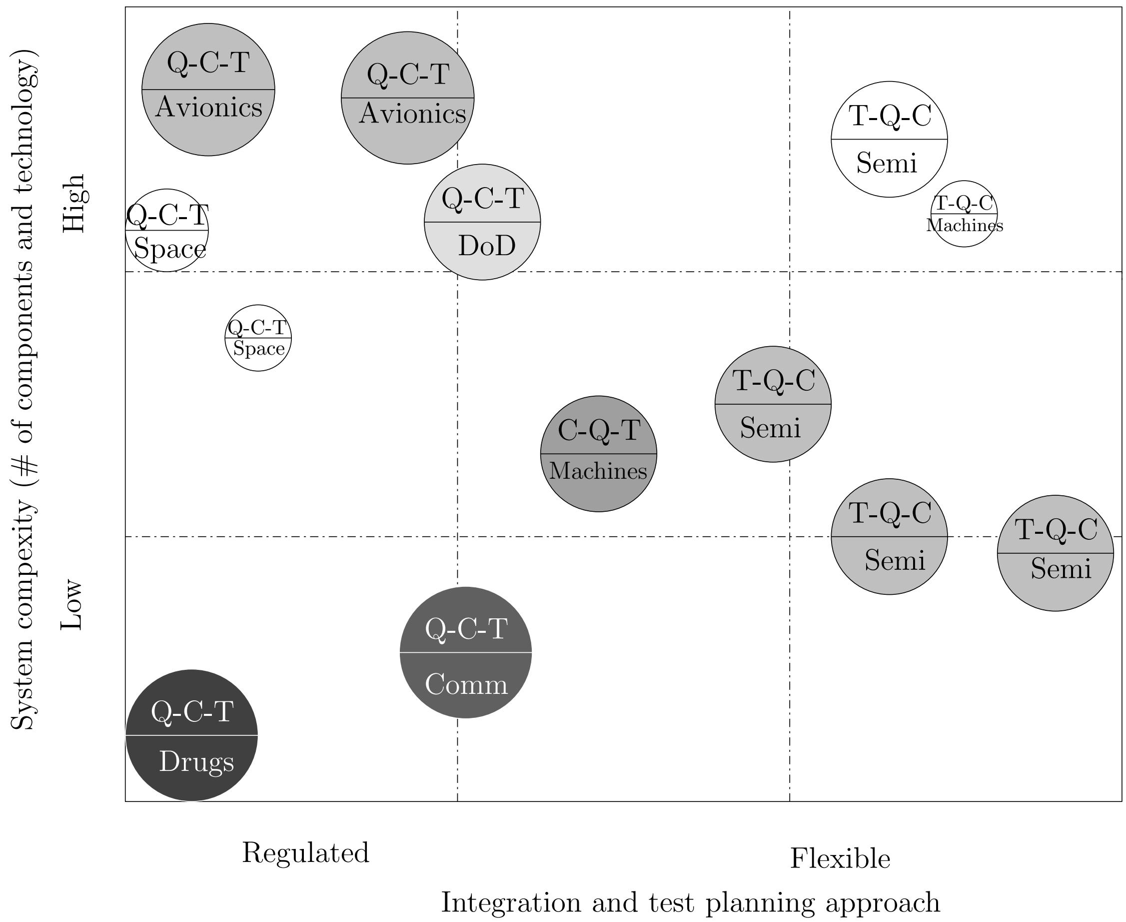

Figure 13 Overview of the visited organizations by system complexity and test

executed as concurrently as possible. At ASML, the test approach for product development is tailored to the business drivers for the specific product under development.

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

Two types of test approaches are distinguished: regulated and flexible plans. Flexible integration and test plans are used in time-to-market driven organizations, while regulated integration and test plans are used for non-time-to-market driven organizations. The main difference 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.

A regulated test approach consists of many test phases which reduce all the risk just after it is introduced in the system. The test strategy of each test phase is focused on reducing all possible risk in the test phase.

A flexible test approach consists of less test phases and these test phases are executed partly. Testing is stopped when a certain time limit is reached to ensure maximal progress in the overall integration and test plan. The test strategy of each test phase is focused on reducing as much risk as possible in the available time.

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 integration sequence, test sequencing methods, 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 are that these plans are easier to plan and control. All parties involved know on forehand 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 obtain a better plan. The cost of this flexibility is the organizational effort which is involved in the continuous optimization cycle.

A combination of a regulated integration and test plans with known 'control' points in the plan and flexibility in the intermediate phases could be a good combination.

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Biography

I.S.M. de Jong has a B.Sc. in Laboratory Informatics and Automation from Breda Polytechnic. He has been a software engineer in various companies in the USA and The Netherlands. Since 1996 he has worked with ASML in systems testing, integration, releasing and reliability projects. His specialization is in the field of integration and test strategies. Since 2003 he is a Ph.D. student at the Eindhoven University of Technology in the TANGRAM project. His research concerns integration and test strategies.

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J.M. van de Mortel-Fronczak graduated in computer science at the AGH University of Science and Technology of Cracow, Poland, in 1982. In 1993, she received the Ph.D. degree in computer science from the Eindhoven University of Technology, the Netherlands. Since 1997 she has worked as assistant professor at the Department of Mechanical Engineering, Eindhoven University of Technology. Her research interests include specification, design, analysis and verification of machine control systems.

J.E. Rooda received the M.S. degree from Wageningen University of Agriculture Engineering and the Ph.D. degree from Twente University of Technology, The Netherlands. Since 1985 he is Professor of (Manufacturing) Systems Engineering at the Department of Mechanical Engineering of Eindhoven University of Technology, The Netherlands. His research fields of interest are modelling and analysis of manufacturing systems. His interest is especially in control of manufacturing lines and in supervisory control of manufacturing machines.