Integrating virtual and physical testing to accelerate the engineering product development process

ABSTRACT: Testing is essential in developing a successful complex engineering product. System level integration and testing can use between 35% and 50% of development resources. External factors such as legislation and customer requirements drive essential testing whilst internal factors such company experience, affordability and organizational practice profoundly affect the overall testing plan. The main objective of this paper is to understand how testing is integrated into the product development process and how different types of testing are scheduled across the stages of product development. The paper reports a case study in a diesel engine company where the balance of virtual and physical testing is a key concern in reducing design time and cost. Integrating physical and virtual testing is more than process optimization of time and cost. It contributes to recasting the design process in response to changes in customer requirements as well as to design changes which arise during testing. The importance of dependencies across components, subsystems and tests is highlighted using a model using Design Structure Matrices and the advantages of integrating physical and virtual testing are analysed particularly in facilitating task overlap to reduce product development duration.

Keywords: Testing, physical testing, virtual testing, analysis, product development process, engineering design, dependencies, dependency structure matrix (DSM)

1 Introduction

Testing is a vital activity for verifying and validating the performance, reliability, safety and durability of a product. A potential design can be subject to mismatches with customer needs, technical design faults, or issues regarding manufacturability and maintainability of the product (Thomke, Bell 2001, Qian et al. 2010). Testing is a primary way to identify these problems and therefore is central to product development (PD) (Thomke 2003, Dahan, Mendelson 2001). Testing throughout the development process increases confidence because it provides the designers with confidence in the design. But testing is expensive and time consuming. Lengthy testing makes meeting tight project deadline very risky leaving little time for iteration. Therefore, to reduce the cost and time of testing, there is a shift in industry towards virtual testing, including computer aided engineering (CAE) modelling and simulation. Advanced computing facilities improve the speed and economics of this virtual testing process. However, the value of virtual testing is still debated in industry. So, one key concern is how to integrate various physical and virtual testing activities during the PD cycle where from concept selection to final validation, products are continually tested. Companies test products at component level, subsystem level and system level. Tests are linked in that the one test can be carried out for different purposes or a group of tests are required to test one aspect of the product. Tests are also linked in that one test may require inputs from other tests or can prove other tests inadequate or invalid. Thus a systematic way of representing dependencies between tests is vital for effective test planning.

With testing being so expensive in time and resources, it is critical that design process planning deploys test activities effectively throughout the PD process, taking account of dependencies, to assure product quality. This paper reports on an empirical study of current testing practice in a diesel engine company and presents design structure matrix (DSM) methods, as part of test planning, to visualise and analyse: (a) connections between components, (b) relationships between components and (c) and dependencies between tests. The investigation attempted to answer two research questions:

1. How can connections, dependencies and relationships across components, tests and types of testing be captured for effective testing planning?
2. How can virtual testing be integrated into a product development process which has predominantly physical testing?

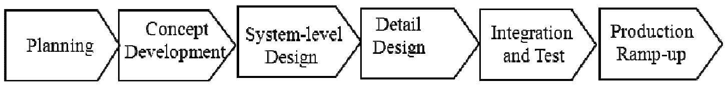
The literature review in Section 2 shows that to date testing has received relatively little attention in product development research. Section 3 describes case study research methodology and Section 4 discusses a case study in the development of a complex engineering product including test planning. In Section 5 a Design Structure Matrix (DSM) model for dependencies across testing and components is developed and Section 6 applies this understanding of dependencies to assessing the potential overlapping design and testing activities and Section 7 proposes how product development plans can effectively incorporate extended virtual testing linked closely to design. Conclusions are drawn about effective test planning, especially for integrating testing more fully in the PD process, emphasizing a view of design process based on response to change, validated through test, and shifting to a greater role for virtual testing.

2 Background and context

Testing is widely recognized, both in research and industry practice, as a key part of the PD process. However, in the academic literature, testing does not receive the same attention as other activities in the PD process. Little analytical effort has been made to plan testing efficiently during the PD process and there is limited attention to testing as part of the PD process (Thomke, Bell 2001, Loch, Terwiesch & Thomke 2001, Van der Auweraer, Leuridan 2005, Hoppe, Engel & Shachar 2007, Lévárdy, Hoppe & Browning 2004) but the most discuss testing in terms of specific techniques.

Typically the cost of testing can consume up to 50% of total development cost (Thomke, Bell 2001). In the spacecraft industry, system level integration and testing (I&T) alone costs approximately 35-50% of total development resources (Weigel, Warmkessel 2000). In the software industry testing can consume fifty percent or more of the development costs (Bertolino 2009). Planning and sequencing of tests in the PD process is self-adaptive and depends on the organizational culture and experience within the company (Lang et al. 2002). The cost of conducting a test including equipment, materials, facilities, staff and other engineering resources is a significant part of overall product development. Thus detailed attention to the testing plan can reduce the overall PD cost.

Figure 1 Product development process (adopted from (Ulrich, Steven 2005))



Although testing is generally seen as a subsidiary step of the whole PD process (Figure 1), it is an integral part of the process. Design and analysis activities drive testing tasks with analysis during product design as a key input to CAE modelling and simulation (i.e. virtual testing) and physical testing. Conversely, virtual and physical testing act as a critical input to design, as well as provides essential validation for design decisions. These information exchanges between design and test provide essential links in the product development process and indicate that testing processes should be integrated more closely with whole PD process. Choosing between virtual and physical testing is a difficult decision for companies. Some engineers believe that physical testing provides greater confidence in the test data; whereas others feel that there are inefficiencies in physical testing especially where repetition is needed for reliable data (Khalaf 2006a). A physical component test can only deal with limited number of variables and cannot always be comprehensive enough to include all the operating conditions. Furthermore physical tests are conducted in a controlled environment and have limited capability to simulate the broad range of operating conditions (Hoy, Center & Herrmann 2008).

A virtual test using a CAE model can handle a spectrum of variability across several interacting variables covering different conditions of use as well as potential manufacturing variability. This can prompt the identification and correction of design deficiencies and faults. However there are risks in using a virtual model, for example if the service conditions are not quantified, it can be difficult to correlate virtual test data with the real world performance results, reducing confidence in virtual testing (Wilkinson 2007). The CAE model can contain flaws which might be undetected until later stages in product development. In some cases CAE models are very complex, require specialized knowledge or training and the associated software can be expensive thus limiting accessibility (Wasserman 2007).

As both virtual and physical test have their own advantages and limitations, the literature suggests a combined approach of physical and virtual testing might help to produce a focused test and increase reliability leading to a minimized iteration (Chua, Teh & Gay 1999, Van Ostaijen & Slingeland 2002, Huizinga, , Zorriassatine et al. 2003, Van der Auweraer, Leuridan 2005, Khalaf 2006a, Khalaf 2006b, Wilkinson 2007, Wasserman 2007). There is no model which integrates physical and virtual testing in the PD process structure and no supporting tool for identifying or connecting these different types of testing activities - physical and virtual – in the PD process.

3 Methodology

The case study was undertaken at a UK based diesel engine manufacturing company. The company has been manufacturing diesel engines since the 1930s. Diesel engines are a mature product that changes incrementally, but one that requires significant levels of testing, because of safety criticality, pressure of legislation and high competiveness. This company was chosen to demonstrate the criticality of testing in complex engineering designs where legally imposed tests play a vital role. As an incremental product, the basis of a testing plan for new product is derived from the previous products.

Thirteen interviews were carried out from March 2011 to August 2012 building on a previous series of interviews on system architecture. Six engineers were interviewed at the company site, including a senior engineer, a development engineer, a CAE engineer, a verification & validation manager and a validation team leader. In the first interview a senior engineer gave us a general overview of issues and an idea of expenditure. He pointed out that*"…to develop the Tier4 engines can cost R&D alone an excess of over X million. I would break it down into design and engineering is probably 15%, material is probably around 30%, and actually testing around performance is around 55%. So most of the money in R&D is goes into testing for performance and durability"*. He suggested "*shifting from physical testing to virtual testing as a key means of cost minimization*". We stared with this hypothesis. Interviews with a validation manager and the validation team leader investigated how testing really happens on component, subsystem and system levels. The relation between the verification and validation phase in product design was investigated through interviews with development engineers in the presence of the validation team leader and the validation manager. The interviews were recorded and transcribed. Each interview was approximately two and a half hours in length. The understanding and notes were shared and compared among the authors after each meeting in the company. The analysis of each interview raised several questions which drove the next interview. Sequential interviews were required to bring in a range of engineers, for wider understanding and for identifying the gaps in the current process.

Design/dependency structure matrices (DSMs) were used to capture dependencies and interrelationships of components and tests. The Cambridge Advanced Modeller (CAM) tool was used to create a DSM. The tool also provides flowcharts and process modeling functionality and performs discrete event simulations (Wynn et al. 2010). As the engines have hundreds of components and associated tests, a small part of the engine was modelled. This included dependencies between components and interrelations between tests with the aim of understanding the organization of testing tasks. The model was corroborated by going back to the engineers. The model visualized understanding of the company's current practice and allowed the engineers to reflect on their practice. Then the physical tests were reorganized in the model and virtual testing introduced.

The rationales behind choosing a detailed case study in a single company was to performed a test of the hypothesis that the integral approach of virtual and physical testing can improve the testing process. Both situations of company's model and proposed model were simulated and a comparison of the results of both scenarios showed the benefits of an integrated virtual and physical testing approach.

4 Testing in industrial practice: A case study

Internal factors such as product characteristics, architecture and newness in design have an influence on what is tested and how it is tested. External factors like legislation make some tests mandatory; and thereby determine or shift some of the testing practice in companies. Testing is an on-going activity through the development process, where similar tasks are repeated to reflect a changing focus of the testing activities as changes to the design of the product. In section 4.1 factors and types of testing is described, section 4.2 focuses on PD structure of the company and section 4.3 discusses the testing planning process of the company.

4.1 Factors affect testing

The company mainly categorizes testing with respect to the three key product characteristics: performance, reliability and durability. The product must provide the required performance to be successful in the market. Reliability tests ensure the ability to perform the specified operation without failing over a period of time, and durability tests assure that the product will work given proper maintenance for a given duration. Both reliability and durability depend on how a product is used in the field. Understanding and analyzing the existing product's life cycle helps to predict the likely life span of a new product. It is not feasible to look at reliability in each of the applications for which the product will be used, as it is not economical to run thousands of hours of durability tests. Engineers therefore use statistical analysis to model the variability of the design specification and manufacturing capability (Ferry et al. 2002, Levesley et al. 2003). For performance, one senior engineer explained that, "*performance cannot be achieved only through simulation, we need to physically test*".

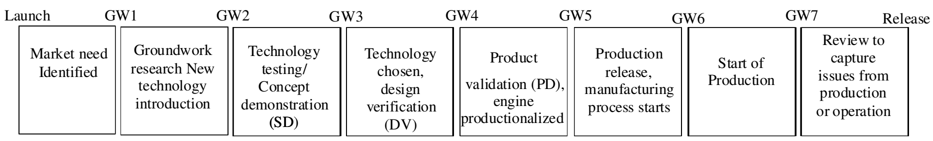
To reduce the cost and risk associated with a new product, the company limits "newness" in the product. Even if an existing component is deployed in a new context or to new requirements, it is considered "new" and therefore needs be tested (Wyatt, Eckert & Clarkson 2009). Some changes propagate, which may have serious consequences resulting in the need for a step change in design. Incremental design changes can be managed with standard testing or validated simulations whereas step changes may require a new test plan. For example, if the company is designing a cylinder block which is a scaled version of a previous product, critically stressed areas would be already known thus it might be possible to assess the risk accurately through simulation.

External factors such as competitiveness and regulation affect testing. Competiveness in different sectors, such as off highway or marine, and under different use conditions, dictates different test methods. Tests need to meet regulations and legislation for certification whilst ensuring that customer requirements continue to be met. For example, new legislation in emission control now plays a vital role in driving design processes and test planning. With regulations revised in shorter timescales and to tighter limits, companies cannot afford to run thousands of hours of physical testing for reliability and durability across each of the applications of a product. In addition rising fuel prices provide an additional incentive to reduce physical testing. So there is a company need for a revised testing strategy.

4.2 Process structure in the case study company

The case study company has a structured gateway process for New Product Introduction (NPI) (Figure 2). It has eight stages starting from "Launch" to "Gateway 7", which represent the review of the product in service. Most of the testing occurs between Gateway 2 (GW2) when the technology has been identified and Gateway 4 (GW4) after which the engine is released to production, thus this research focuses on these three main phases of the PD process (as in Figure 3).

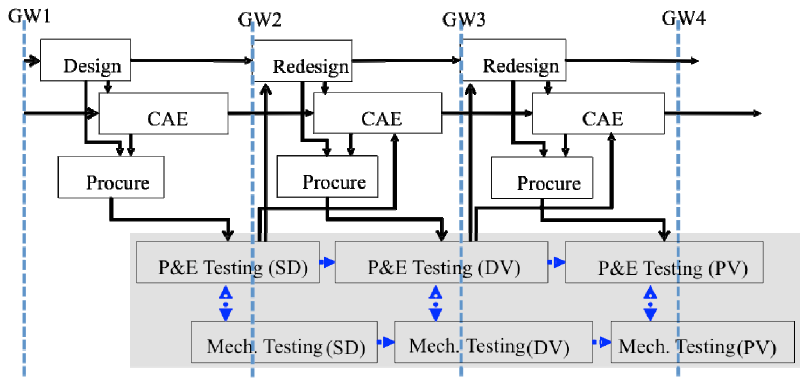
Figure 2 An outline of the company's gateway process



Among the large number of activities in these stages, Design and Redesign, Computer Aided Engineering (CAE) (e.g. analysis and simulation), and Procurement of test prototypes are considered as drivers for testing. For simplicity, Figure 3 presents these key activities as time limited boxes, but in reality, a core team keeps working on Design and CAE throughout the entire period, and Testing goes on almost continuously, in parallel to these activities. There is also a fluctuation in effort through the period, as resources are shared across the different engine projects which are at different stages of development. For example the design team will be heavily involved during gateway 2 and will be brought in for changes in gateway 4 while working on gateway 2 for the project. Design, CAE, Procurement and Testing activities undergo at least three iterations from GW2 to GW 4, and serve different purposes in each stage.

Testing in the company falls into three phases: (i) Concept/System Demonstration (SD), (ii) Design Verification (DV), and (iii) Product Validation (PV). Performance and Emission (P&E) as well as the mechanical durability and reliability are tested in each of the three phases. The mandatory tests required for compliance tests usually occur during PV phases. Traditionally the company has sold engines which were stand-alone products, however now, the design of engines, and the design of the vehicles in which they are used, has become more integrated to increase overall performance while accommodating the heavy after treatment required to comply to emissions legislation. This has led to the need for in vehicle testing in addition to traditional system, sub-system and component testing.

Figure 3 A schematic of the PD process from Gateway 2 to Gateway 4



As Figure 3 shows a significant amount of CAE analysis and physical testing happens in each stage of the process. In different stages of the PD process, the roles of tests differ considerably. Initially the PD process is driven by requirements, which are elicited from the customers in workshops and derived from legislation. These requirements are cascaded, i.e. the company aims to meet key requirements and adds more once the previous group of requirements has been met. The process begins with performance requirements around emissions without which the company would not legally be able to sell a product and moves on to key requirements such as fuel consumption. Typically these are achieved through adaptations of the existing engine core with different control and performance parameters. These are both validated analytically in CAE and physically tested.

Concept/system demonstration testing (SD) shows that the technology can deliver the required performance. Alternative concepts are analyzed and evaluated. A combination of old and new parts are built into an engine called a MULE. This MULE engine is tested to verify the performance of new parts. As new parts arrive the old parts are replaced and testing continues. The product specifications evolve as more design decisions are taken during this phase. It is assumed that by GW3, the concept will be selected, the component specified and the whole engine, built with production parts, will be ready to be tested for Design Verification. Design verification (DV) aims to ensure that design outputs meet the given requirements under different use conditions. At this stage, testing focuses on the verification of a chosen design, through detailed analysis and testing of stress, strength, heat transfer and thermodynamics etc. Product validation (PV) tests the product against customer requirements and specifications. In this phase, detailed testing for reliability and durability occurs. This stage validates the intended product. Tests for certification mostly happen during this stage.

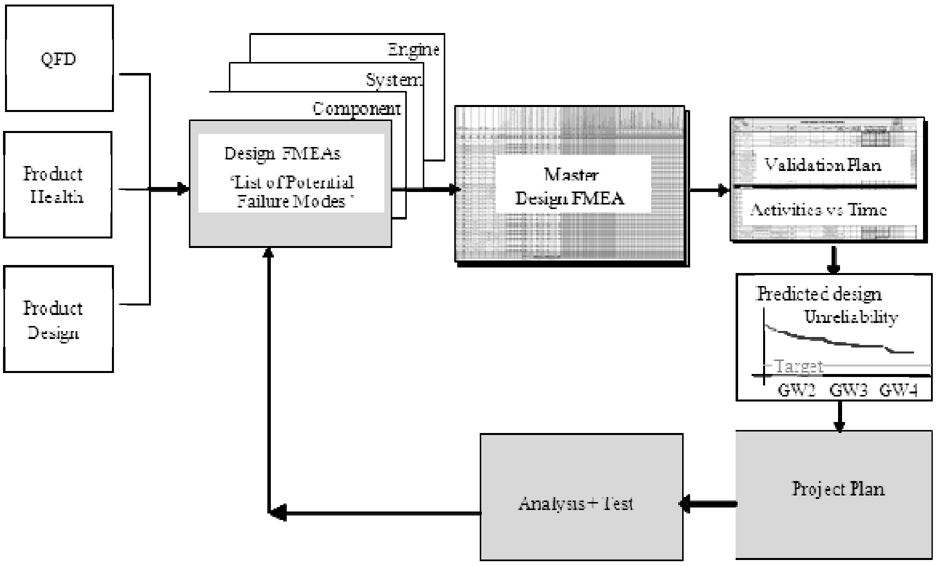
4.3 Test planning

In each stage, the engine level testing blocks contain a large number of tests. Some tests are grouped and some are individual. Some test results can be obtained quickly whereas some require running the tests till the end of the testing phase. Failures can often be identified very quickly while proving success requires the full test to be carried out. The learning from tests is therefore typically bimodal concentrated at the start and at the end of the test.

The basic structure of testing is planned with the rest of PD before gateway 2. The company uses tools such as quality function development (QFD) to translate the customer requirements into the technical characteristics of product design. Health monitoring data from the previous engine and characteristics of product derived from QFD are used as input for the Design Failure Mode and Effect Analysis (DFMEA), which focuses on identifying potential failures so that design actions can be taken to prevent or minimize the effect of a failure. FMEA was introduced in the aerospace industry in the mid-1960s, with the focus on safety issues to prevent failures and accidents. The testing plan is based on the analysis of FMEAs as well as expert judgment of engineers in the company. A flow diagram of the early validation and testing plan is shown in Figure 4.

FMEAs are also used in different phases from GW2 to GW4 to indicate the priorities of actions. The FMEA generates a validation plan, which includes a list of validation activities, starting and finishing dates, which phases of the process to be performed, which item of product, what to measure and so on. However, a typical validation plan rarely includes the dependency and interrelationship between the tests. Even if it is presented in a limited form; it can be difficult to visualize the dependencies in a spreadsheet.

Figure 4 Company's Design FMEA process



Another important influence on the testing plan is design changes. A change of requirements from the customer has a big impact on the test plan, but problems with the emerging design during detail design can lead to urgent redesign (Eckert et al. 2009) and re-testing. Although all the processes are well defined, the engineer mentioned that "the design change has a propagated effect which eradicates some of the testing, introduces more testing, questions whether we have tested in a right way, that's the thing that destabilized the process". As every part of a design is connected at least to one other part, design changes can also be connected (Clarkson, Simons & Eckert 2004). Thus it is important to capture, how the changes propagate, how the changes affect the testing plan, and how to reorganize the testing plan accordingly.

5. Design Structure Matrix for capturing the dependencies

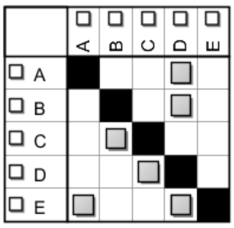
Loch et al. (Loch, Terwiesch & Thomke 2001) identified that optimal testing strategies are influenced by three important factors: cost, learning between tests and feedback time to design. These factors might also have significant influence on whether tests occur sequentially or in parallel (Thomke, Bell 2001, Loch, Terwiesch & Thomke 2001). Lévárdy et al (Lévárdy, Hoppe & Browning 2004) also suggested that the selection of test activities should be based on the maturity of information required to perform the test, which might come from other activities. Therefore the interrelations between the physical tests and learning from the tests are critical for the arrangement of testing activities. It is also important to capture the information flow between other domains of design especially between testing and subsequent redesigning for the next phase. However this paper will only consider dependency and information flow for the testing domain.

Several underlying factors were recognized for capturing the dependencies between tests: (i) a change in one test might affect other tests; for example tests can render each other obsolete or invalid, (ii) changes to a single component can affect testing plans, and (iii) a change to one component of the product may result in changes to other components or parts and lead to associated changes in tests. These factors imply not only the interrelationship between tests but also that connecting each test with physical parts/components is essential for testing plan. The insights from the case study have been used to develop a Dependency Structure Matrix approach.

5.1 Overview of Dependency Structure Matrix (DSM)

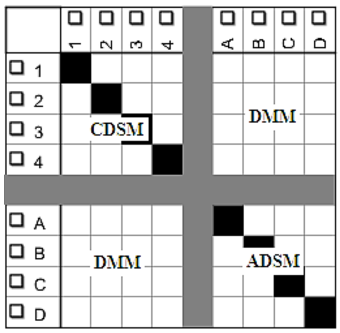
The Dependency Structure Matrix (DSM) is an established method for capturing the complex interaction of design tasks (Browning 2001) and is used to capture the dependencies. A DSM provides a simple visualization of the dependencies in the system. The DSM is a square matrix (as shown in Figure 5), where the rows and columns are named and ordered identically. All the elements of the domain of analysis are assigned along rows and corresponding columns. A component-based DSM (CDSM) represents interactions between components in a complex system architecture.

Figure 5 A representation of Dependency structure matrix (DSM)



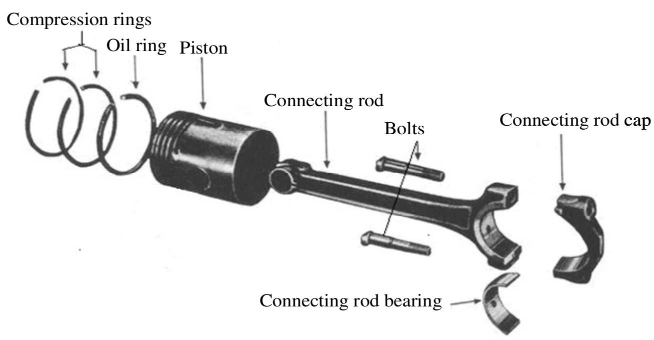
In an activity-base DSM (ADSM), the order of activities in the rows and columns indicate some appropriate ‘time-ordering’, perhaps in terms of starting time. The entries in a single row represent all the elements whose output is required to perform the task corresponding to that row. For example, in Figure 5, **C** needs information from **B**. When an activity is dependent on information from a task, which is scheduled for a later execution, for example **A** needing information from **D**, iteration is likely to occur as estimated values are adjusted. Links above the diagonal represents potential rework or iteration loops, which are likely to be undesirable. A number of algorithms have been developed to sequence the activities to the lower diagonal to minimize such iterations (Browning 2001, Eppinger, Browning 2012, Eppinger, Whitney & Gebala 1992).

Figure 6 A schema of Multiple Domain Matrix (MDM)



A Domain Mapping Matrix (DMM) presented in Figure 6, which essentially related two types of information, is used to establish a mapping between tests and components – which components require which tests. DSM and DMM can be combined into a model called a Multiple Domain Matrix (MDM), so that a complete system (testing activities and components) can be represented. Details on MDM can be found in Maurer and Lindemann (Maurer, Lindemann 2008).

Figure 7 Decomposition of piston and connecting rod

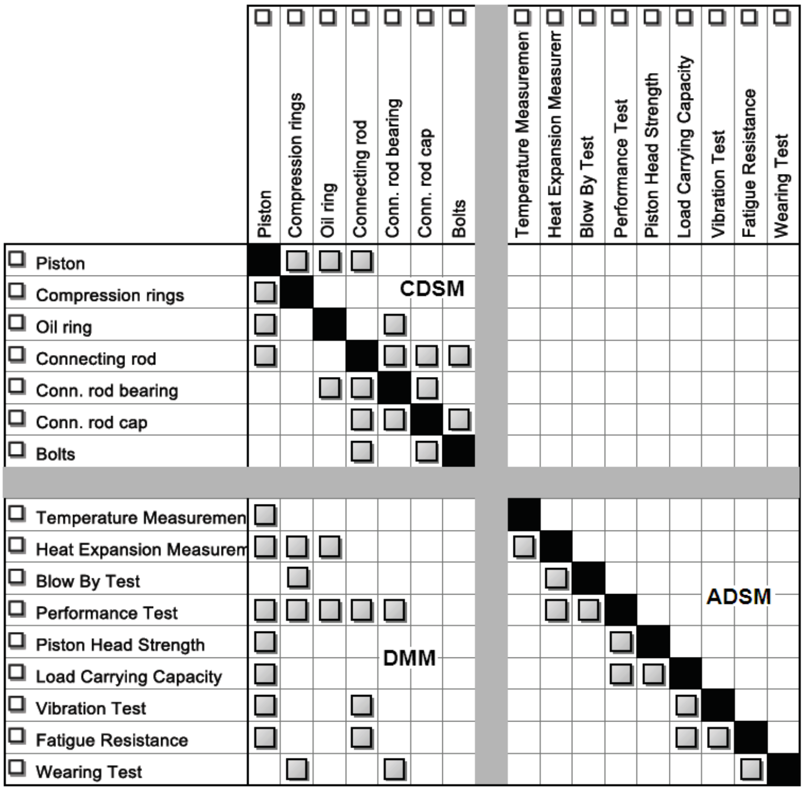


5.2 MDM for tests and components

In this section the dependencies and interrelations between tests are discussed. A small part of the engine i.e. piston and connecting rod (Figure 7) was considered as an illustration of the approach and the tests confined to design verification (DV).

A static CDSM is used to capture the connections between the existing components of the product (top left matrix in **Error! Not a valid bookmark self-reference.**). The relations between piston, compression rings, connecting rod etc. are modelled in this matrix. These relations are mainly spatial and functional. For example, the oil ring may not have any spatial relation with the connecting rod bearing but oil passes through bearing to the connecting rod to the oil ring to lubricate the piston and this process establishes a connection between oil ring and connecting rod bearing.

Figure 8 CDSM, ADSM and DMM for piston and connecting rod.



In **Error! Not a valid bookmark self-reference.**, the bottom left DMM shows the relationship between tests and components of the product. It presents which tests are performed on which components. For example, the 'blow by' test is performed on compression rings. A further activity based DSM (ADSM) has been used to capture the sequences and the information flow between different tests (bottom right matrix in **Error! Not a valid bookmark self-reference.**). For example, the 'blow by' test needs information from measurements of heat expansion. The sequence of tests on a piston will be taken care of performance first and then move to mechanical tests like strength and vibration tests.

The MDM in **Error! Not a valid bookmark self-reference.** helps to visualize the complex connectivity in a matrix form. These activity and component based DSMs offer the potential to examine the consequences of changing a test or a component. Change propagation through the product architecture and its influence on the testing plan can also be captured by comparing these DSMs. This paper will consider the local optimization of tests in one phase through the analysis of ADSM.

5.3 Analysis of ADSM

The ADSM presented in **Error! Not a valid bookmark self-reference.** shows the tests in 'time-ordered' sequence. Another representation of the ADSM is in Figure 9 as a flow diagram of the tests. In an ideal case these tests should be planned to be performed sequentially. However, from the Gantt chart in Figure 9b, we can see some of the mechanical tests like fatigue resistance and wearing tests take a significant time, therefore the company cannot wait to do all these tests sequentially. In such a case the company would start these lengthy tests earlier with some assumptions based on previous tests.

In the example the fatigue resistance test requires input from the load carrying capacity and vibration test. To allow the fatigue resistance test to start earlier and move earlier in the sequence, requires making some assumptions about the results from downstream tests. The same applies to the wearing test. The fatigue resistance test will make assumptions about the vibration test and the wearing test will make assumptions about the fatigue resistance.

Figure 9 (a) Flow diagram and (b) Gantt chart for ADSM presented in 5.2 MDM for tests and components

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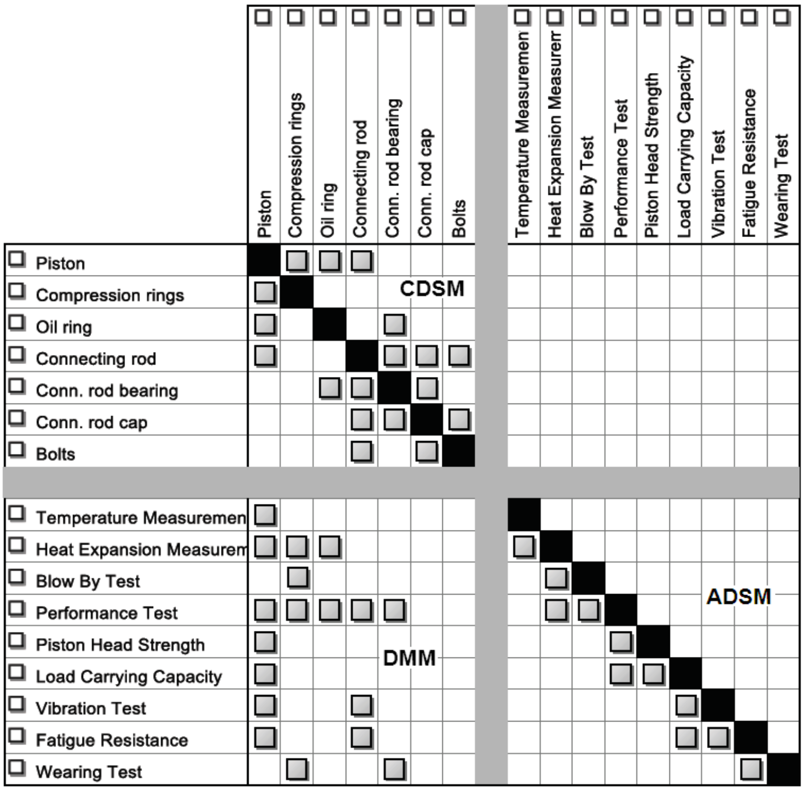

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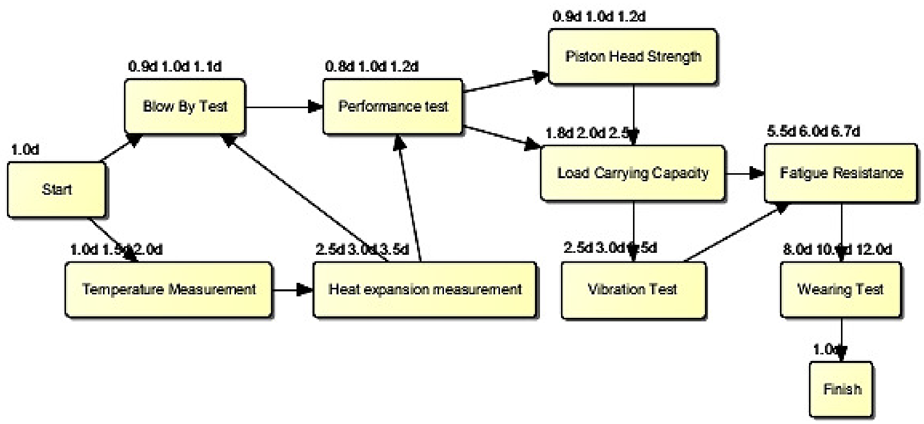
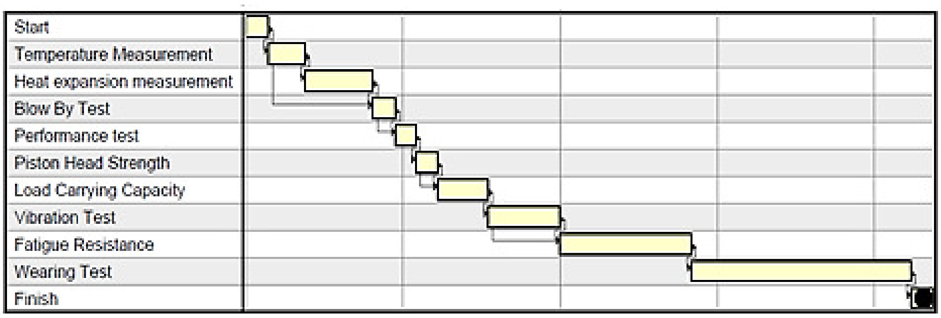
(a)



(b)



6. Overlapping testing to accelerate the process and analysis

The process of starting an activity before finishing the downstream activities is called overlapping. This can reduce development time or the testing time for our case. Companies often overlap lengthy physical tests to minimize the process duration. The advantage of overlapping has been recognized in several studies (Clark, Fujimoto 1991, Ha, Porteus 1995, Smith, Reinertsen 1992, Krishnan, Eppinger & Whitney 1997), but may introduce uncertainties in the process, which can increase iterations (Krishnan, Eppinger & Whitney 1997) and decrease the confidence in design. In the worst case, development costs may increase and product quality may worsen (Krishnan, Eppinger & Whitney 1997). For the company, the assumptions about the inputs need to be accurate enough so that the engineer can be confident in the process. A practical way of planning the overlapping of the tests is presented below.

Figure 10 (a) The original ADSM as in 5.2 MDM for tests and components

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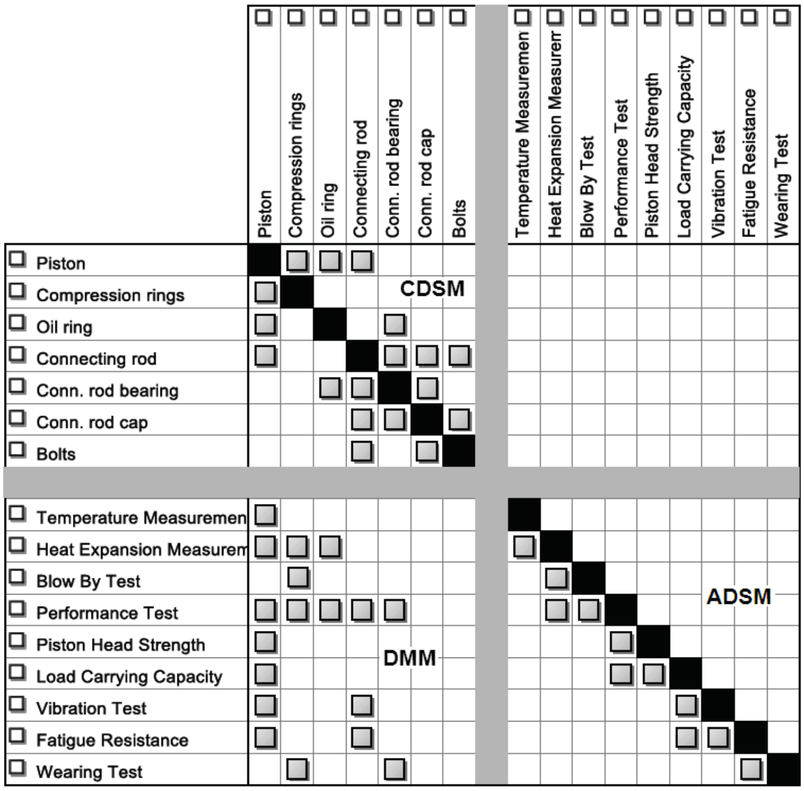
Figure 8 CDSM, ADSM and DMM for piston and connecting rod.



In **Error! Not a valid bookmark self-reference.**, the bottom left DMM shows the relationship between tests and components of the product. It presents which tests are performed on which components. For example, the 'blow by' test is performed on compression rings. A further activity based DSM (ADSM) has been used to capture the sequences and the information flow between different tests (bottom right matrix in **Error! Not a valid bookmark self-reference.**). For example, the 'blow by' test needs information from measurements of heat expansion. The sequence of tests on a piston will be taken care of performance first and then move to mechanical tests like strength and vibration tests.

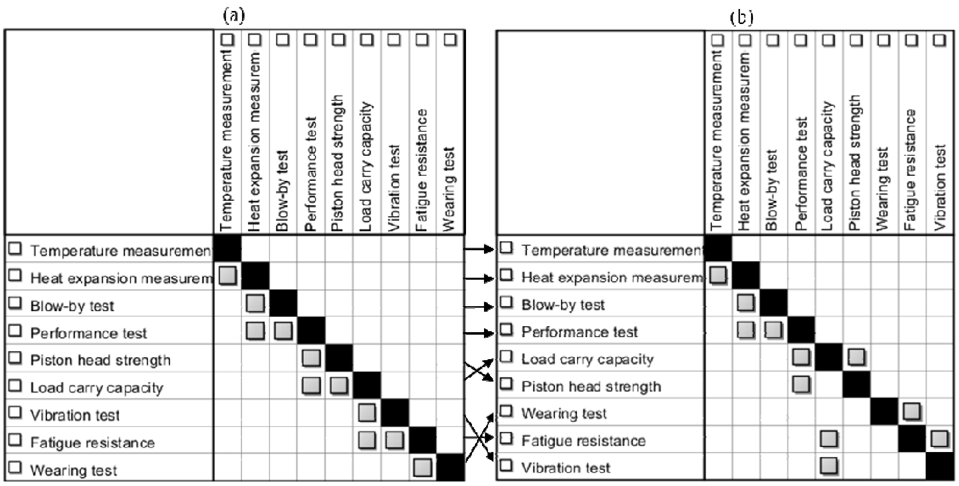
The MDM in **Error! Not a valid bookmark self-reference.** helps to visualize the complex connectivity in a matrix form. These activity and component based DSMs offer the potential to examine the consequences of changing a test or a component. Change propagation through the product architecture and its influence on the testing plan can also be captured by comparing these DSMs. This paper will consider the local optimization of tests in one phase through the analysis of ADSM.

5.3 Analysis of ADSM

The ADSM presented in **Error! Not a valid bookmark self-reference.** shows the tests in ‘time-ordered’ sequence. Another representation of the ADSM is in Figure 9 as a flow diagram of the tests. In an ideal case these tests should be planned to be performed sequentially. However, from the Gantt chart in Figure 9b, we can see some of the mechanical tests like fatigue resistance and wearing tests take a significant time, therefore the company cannot wait to do all these tests sequentially. In such a case the company would start these lengthy tests earlier with some assumptions based on previous tests.

In the example the fatigue resistance test requires input from the load carrying capacity and vibration test. To allow the fatigue resistance test to start earlier and move earlier in the sequence, requires making some assumptions about the results from downstream tests. The same applies to the wearing test. The fatigue resistance test will make assumptions about the vibration test and the wearing test will make assumptions about the fatigue resistance.

, (b) altered ADSM for increasing concurrency in the process



Consider the reordering of rows and columns in the ADSM in Figure 10 (a) to give the new ADSM in Figure 10 (b). The marks above the diagonal in Figure 10 (b) (ie load carry capacity, wearing test, and fatigue resistance) are the tests that are proposed to start earlier to accelerate the whole process of testing.

6.1 Linking up virtual and physical testing to enable overlapping

The shift to virtual modeling of products is accelerating the design and testing process. One engineer in the case study company commented, "*computer simulation is becoming increasingly important to the companies to minimize the effort and expense involved in product development especially in testing*". CAE analysis and simulation can assist physical testing to make more accurate assumptions about inputs. There is a fine line between CAE and virtual testing. While CAE is aimed at analyzing a design with a set-up of standard variables, virtual testing systematically varies the parameters to gain a broader picture. CAE models are corroborated and tuned through physical testing. For the case under consideration virtual testing (including CAE analysis) for the fatigue resistance and wearing test and linking up with physical testing is required to accelerate the process.

The initial CAE analysis (for procurement) can be very different from the CAE analysis and simulation which can assist the physical testing. We call the CAE analysis and simulation of second type as "virtual testing". Virtual testing can be regarded as distinct from CAE analysis in the following way. Initial CAE analyses may check interference and stress on components and assemblies using general purpose tools, such as FEA. Most of these analysis tools are generic and commercially available. On the other hand a virtual test is designed specifically for a given situation and covers test conditions representative of a physical test. The company might use the same tool as CAE analysis or develop further tools, perhaps augmented by statistical analysis, for virtual testing. Virtual load carrying capacity testing of a piston would create a use scenario over the full range of parameters which might be encountered in a test bed. This virtual test for a piston would not be appropriate for another component like a connecting rod. Such virtual test models are founded on the technical understanding of product and require specialized software development in formulating mathematical models for the interacting engine components incorporating appropriate numerical algorithms, and integrating all parts together as a workable model for the product development engineers.

Engineering experience, prior understanding of the product, previous product testing and historical data all contribute the virtual test model. The case study company may choose to carry out a physical test for the baseline product. One engineer mentioned: "*the baseline product definition is physically tested and that information is fairly adequate for simulation to run for multiple variables for longer time to find the optimum setup. Then a physical testing measurement and data is required to validate the simulated result*". The performance, reliability and durability predictions of engine components using CAE models are developing rapidly. For example understanding fatigue behaviour in complex materials is increasingly done by virtual testing. This knowledge, combined with historical data from applications, modelled in commercial (and internal) software, means that the durability of engine components can be reliably predicted. Engineers apply probability distributions to perform failure rate calculations. This virtual test model is validated and adjusted against measurements from physical tests.

The detailed process of integrating virtual and physical testing is discussed in Tahera, Earl & Eckert 2013a. Initially, the results from virtual (simulated) and physical testing may differ in several ways. The limits of variation in the variables are adjusted in the virtual testing model through several iterations until the simulation model is representative of the physical tests and engineers can acquire sufficient confidence in the virtual testing model.

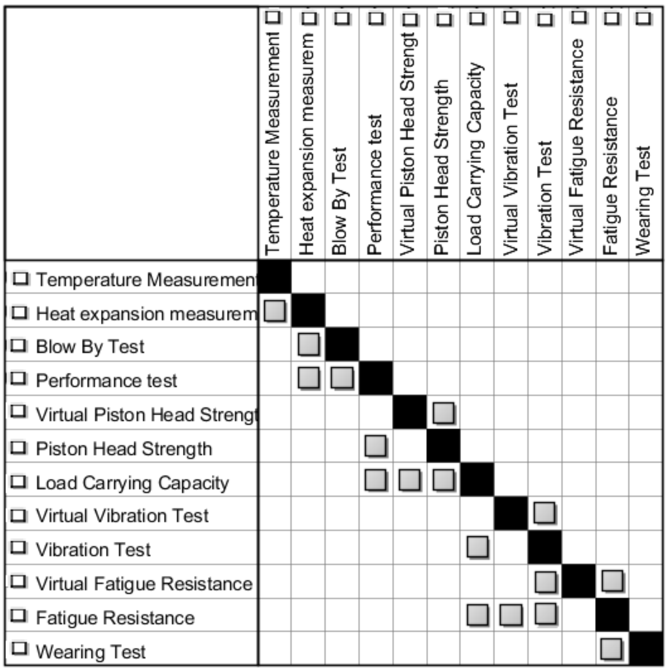
6.2 Simulation and Analysis of the model

In Figure 11 (a), in the final ADSM, we have introduced virtual tests to the testing process. Figure 11 (b) shows a Gantt chart including overlapping activities facilitated by the introduction of virtual testing.

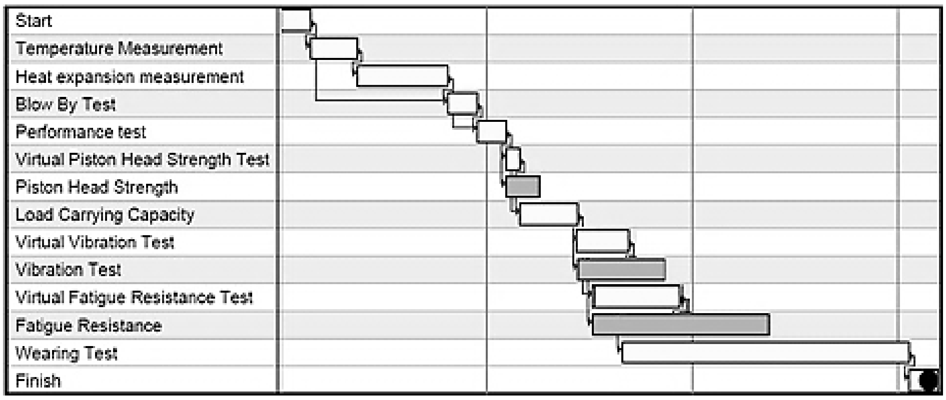
The number and duration of physical tests remain the same, but they now overlap significantly because the virtual testing allows earlier relevant, albeit preliminary, results to be acquired. For each activity representative minimum, expected and maximum duration of each test are estimated (although actual values are not presented to preserve the company's confidentiality). They are distributed as a triangular probability density function. Also the duration for each virtual test was assigned in the same way. In each case it was assumed that at least three iterations were required between virtual and physical testing to achieve a mature, and sufficiently reliable, virtual test result.

Figure 11 (a) ADSM for testing plan supported by virtual testing, (b) Gantt chart with supported virtual testing.

(a)



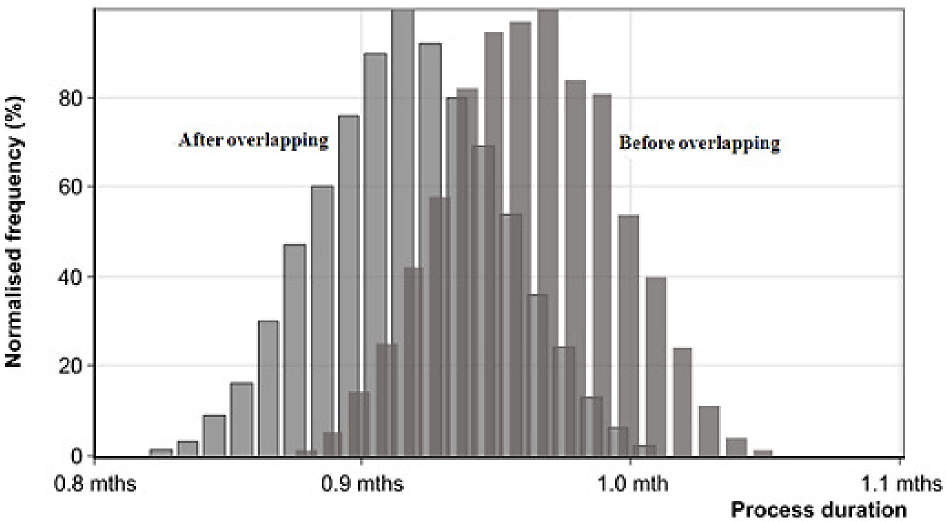
(b)



The two scenarios first with sequential physical testing and second with overlapping testing (facilitated by the 'interleaved' virtual tests) were executed using 10000 Monte

Carlo simulation runs. Figure 12 compares the resulting histograms and highlights the time saving through overlapping.

Figure 12 Histogram comparing duration for original testing plan and proposed testing plan



An independent sample student t-test was performed to determine statistically significant difference between the means in both situations. There was a difference in the scores for sequential testing (M=29.35, Standard Deviation=0.95) and with overlapping (Mean=27.30, Standard Deviation=0.94) conditions; t(19998)=1.96, p =2.34E-239. These results suggest that overlapping can reduce the time required for testing. However, the real benefit of this integrated approach is the use of virtual tests to minimising uncertainties caused by overlapping the physical tests. It is clear that the cost and resources in this phase of the process might be increased through addition virtual model creation and virtual testing. Balancing costs and time savings is a critical decision in product development.

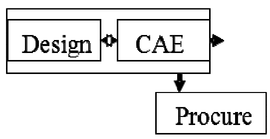
7 Proposed structure of the product development process

In this section the ways that the proposed model of integrated virtual and physical testing might fit to the overall PD process is discussed. Two areas, identified in the interviews, where CAE analysis plays an important role are: 1) providing accurate product specification to the supplier and 2) assisting physical testing. To minimize long lead time procurement, a clear and accurate specification of the product is required. Using CAE, the company makes virtual prototypes with many iterations to enable the first physical prototype to be built closer to the accurate specification. Further CAE analyses are increasingly important during performance and mechanical testing. In each stage, the company already uses CAE analysis to provide engine settings for physical tests. CAE analysis and simulation help to focus on the conditions that are needed for physical testing and optimization of physical testing. One engineer mentioned "*twenty hours of focused testing is better or equivalent then thousands hours of non-focused testing*". We suggest the structural changes of the company's product development process by introducing virtual testing in parallel to the physical testing in each PDP phase. The proposed model separates virtual testing from the initial CAE analysis.

7.1 CAE for procurement

Using initial CAE modelling and analysis, design team can iterate the design process to develop a product that better meets cost, performance, and other constraints. CAE analyses enable the company to carry out optimization earlier in the product development cycle (front loaded), to improve product specification to the supplier. Clear, precise and accurate specification can reduce the procurement time (as mentioned by an engineer). It is often difficult to separate the design tasks and CAE tasks, because design and CAE analysis almost happens in together. Therefore the proposed model incorporates design and CAE analysis and suggests more iteration through CAE analysis before procurement of prototypes (as shown in Figure 13). Further CAE analysis will also help to set-up physical test conditions, input parameters and sensors locations for physical testing.

Figure 13 Design and CAE before procurement



7.2 Parallel virtual testing to assist lengthy physical testing

Proposed PDP structure carefully place the virtual testing parallel to the physical testing. There are two aims: 1) to improve the overlapping process with intermediary physical testing results which will enable to start subsequent redesign tasks with less uncertainties, 2) reduce the physical testing duration or number of iteration in physical tests. Figure 14 shows the information flows between virtual and physical testing and subsequent design phases.

Figure 14 Information exchange between virtual testing, physical testing and design

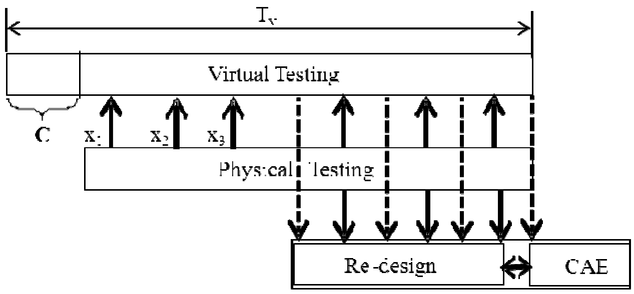
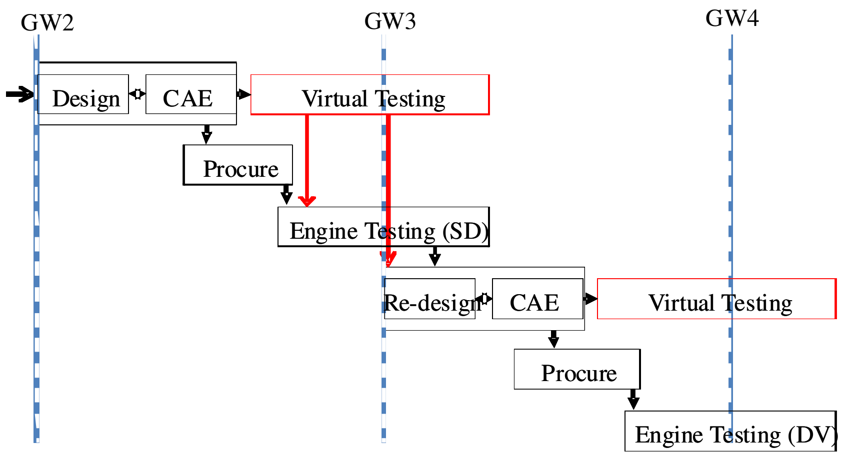


Figure 15 represents the proposed PDP model, can be achieved by incorporating Figure 13 and Figure 14. We validated the proposed model with the senior engineer in the company. It was highlighted that this combined approach of physical and virtual testing methods had the potential to reduce iterations and thereby the number of physical prototypes saving time and cost.

Figure 15 The proposed process structure with additional virtual testing activities.



Different tests benefit from integrating virtual testing with physical testing in different ways. Some benefit by focusing the tests, and identifying future values to minimize the number of iterations to yield a confidence in design, while others require running for shorter periods of time. For example, for constant speed and load, an engine has its intakes of fuel and air regulated, with the goal of achieving desired power ratings. An engine might require several iterations in design and testing to achieve these desired power ratings. Virtual testing using a mature model can predict the likely consequences of certain values of fuel and air intake of the engine, thus suggesting appropriate values for next iteration. When a virtual test is able to accurately predict the behaviour of the engine, then the number of physical testing hours for durability can be minimized, saving time and reducing cost. Therefore the approach of virtual and physical testing integration looks promising to the engineers of the company.

The integrated model of virtual and physical testing specifies durations and assumes effective overlap with iterations between virtual and physical testing. As this is an analytical model and timing in the virtual model is estimated, the time saving shown in result (in Figure 12) may be unrealistic. The time required for virtual model creation depends on the company's CAE department and experience of software engineers, and depends on similar models developed. The number of iterations between virtual and physical testing will vary for several reasons such as the level of uncertainty, as well as the accuracy and completeness of communication between testing engineers, design engineer and software engineers etc. (Loch, Terwiesch 1998).

8. Conclusion and Future work

This research draws several conclusions based on the case study and subsequent analysis. This research highlights the importance of studying the testing process as an integral part of the product development process. To integrate testing throughout the PD process upfront analysis of QFD and FMEA can play a vital role in linking design considerations with the testing plan. Early planning of testing might help effective resource allocation and shift quality management upfront. This would re-plan the testing activities according to any design changes and allow optimization of testing for the actual design. A combined approach of virtual and physical testing could provide more effective implementation of testing activities, as virtual testing can reduce lengthy physical testing and increase confidence in (early) testing results.

Identifying the dependencies and interrelations between tests assists effective planning of the testing process. The proposed DSM model captures the dependencies between tests. The proposed model offers the potential to restructure the tests in the PD process. At the same time the connectivity network between the tests and the components will help to visualize how effectively testing information is used.

Responding to engineering change during product development is particularly dependent on understanding how testing processes (which often drive and validate the changes) are integrated with overall product development. This model will be also useful for identifying how the propagation of design changes affects component testing.

Further work will validate these models in an industrial context, including the original case study company. The proposed model which increases overlap through combining virtual and physical testing has potential for time and cost savings. Application of the model to products at different scale, complexity and maturity will be compared. Further work will examine further the detailed analysis of cost and time savings through integrating virtual and physical testing.

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