Chapter 7

Integrating Physical and Virtual Testing to Improve Confidence in Product Design

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7.1 Introduction

Although testing is a value adding activity and improves confidence in design, lengthy physical testing in one phase can delay the product development process, because testing and design processes are closely intertwined. This study identifies that, due to long procurement times and lengthy physical tests, companies may have no choice but to redesign tasks before testing results are available in order to meet product delivery deadlines. This increases uncertainties therefore reduces confidence in design. This research proposes a model of integrated virtual and physical testing to support the testing and subsequent redesign phases of product development.

An engineered product must comply with its performance requirements; and in addition reliability, safety and durability must be ensured. A potential design may fail to meet requirements, have technical design faults, or raise issues about manufacturability and maintainability (Thomke and Bell, 2001; Qian *et al.*, 2010). Testing identifies these problems and is therefore central to product development (PD) (Thomke, 2003). Testing throughout the development process increases confidence because it corroborates the design. Testing is considered as a means to reduce uncertainty and thus risk. However, physical testing can take a long time, and delayed or negative results in one phase potentially jeopardize project schedules. Therefore, design for the next phase often starts before testing is complete. Redesigning without knowing test results might perpetuate faults or miss opportunities to respond to emerging problems. This paper argues that companies are forced into redesign activities with low confidence because testing results are not available, and therefore restructuring of the design and testing processes taken together could decrease risk in product development.

A case study was undertaken at a UK-based company that designs and manufactures diesel engines with whom we have worked for several years. Diesel engines are complex, highly regulated products with extensive testing to meet customer requirements, performance standards and statutory regulations. Thirteen interviews were carried out by the authors, recorded and transcribed, between March 2011 to August 2012 with six engineers: a senior engineer, a development engineer, a CAE engineer, a verification and validation manager and a validation team leader. We analysed the complex PD process structure with the objective of:

1. Speeding up the testing process without losing confidence in test results.
2. Managing testing and subsequent design activities with reduced uncertainties.

The paper introduces the case study in Section 7.2 and describes the product development process in Section 7.3. Section 7.4 analyses the issues in testing and redesigning, Section 7.5 proposes changes to the process structure for more effective testing and redesign measured through potential costs and benefits in Section 7.6. The case study indicates some general conclusions which are presented in Section 7.7.

7.2 Background to the Case Study

To be competitive and comply with legislation the company needs to introduce new technology. Even if a proven technology is deployed in a new context (for example, different use conditions and environment) it needs to be tested in these new scenarios. The "newness" in terms of new components or technology or reuse in different contexts introduces uncertainties to the system and proves to be challenging for the company. At each stage of the product development process engineers need to reduce these uncertainties and achieve a certain confidence level to proceed to the next stage (as shown in Figure 7.1). While uncertainty and confidence are closely related, the term confidence is used widely in the case study company and indicates how sure the company is that the design can eventually meet given requirements. Engineers can achieve confidence in design at a certain stage of PD process even though there are still a lot of uncertainties.

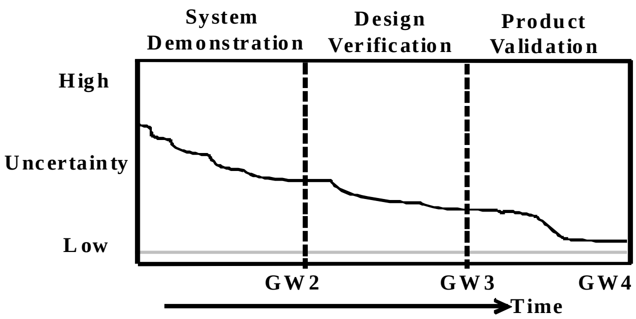

Figure 7.1. Company's uncertainty reduction curve during the product development process through its Gateways GW2, GW3 and GW4

Frequently, engineers in the case study company mention "*testing builds confidence*"or as the validation manger put it "*testing reveals the truth*". Even if testing produces many failures, it also increases understanding and learning especially in the case of uncertain situations. Small failures can create rapid learning and capture the attention of engineers, so that earlier failures can be mitigated in next iteration. Confidence in design reduced when redesigning happens without useful testing results to draw on. Hence, a significant amount of the development effort is spent on testing to acquire confidence in product design and decrease uncertainty and risk for the company. If the uncertainty of the information is low, the team has more confidence in the current information (Yassine *et al*., 2008). Different types of testing lead to different confidence level in the implementation. Physical testing reveals the true characteristics. Virtual testing using CAE and simulation predict the behaviour of the product. In this company, engineers are more confident in physical testing than virtual testing. However, in some component, like flywheel design, engineers have achieved enough confidence in the accuracy of virtual testing to require less testing physically in early stages of the process.

But physical testing can take a long time to produce any results which are useful for subsequent redesign. Therefore the company has to start redesigning with less confidence than they would like. Long running tests are hugely costly. The business manager in the case study company mentioned that,

> "…to develop the Tier4 engines can cost R&D alone in excess of £X million, I would break it down to design and engineering is probably 15%, material is probably around 30%, and actually testing around performance is the rest at around 55%. So most of the money in R&D goes into testing for performance and durability"

Therefore an effective way of reducing the testing cost without compromising the level of confidence is essential. In the next section we analyse the company's PD process structure and identify the close interdependence of design and testing.

7.3 PD Process Structure in the Company

The case study company has a structured gateway process for New Product Introduction (NPI) (Figure 7.2). It has eight stages starting from "Launch" to "Gateway 7". Most of the testing occurs between Gateway 2 (GW2) to Gateway 4 (GW4). This research focuses on these three main phases of the PD process.

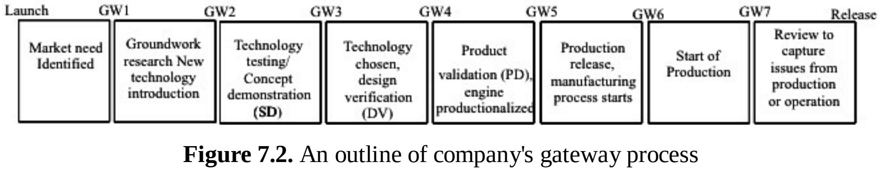

Figure 7.2. An outline of company's gateway process

Figure 7.3 presents four broad activity types: (Re/Design, Computer Aided Engineering (CAE) and Simulation, and Procurement (of test prototypes) and testing.) as time limited boxes, but in reality, a core team keeps working on design and CAE, and testing goes on almost continuously, in parallel to these activities. Design, CAE, procurement and testing undergo at least three iterations from GW2 to GW 4, and serve different purposes in each stage to improve confidence in design.

Initially, understanding of technology, historical expertise, confidence in previous designs are all used to evaluate a potential design. At the early stages (between launch and GW 2), the company uses tools such as quality function development (QFD) to translate the customer requirements into the technical characteristics of product design. Along with QFD, the previous product's health monitoring data and characteristics are used as input for the Design FMEA, which focuses on identifying potential risks so that actions indicating tests can be taken to prevent or minimize the risks. Designs only proceed to GW2 and further if the confidence lies above a level specified in product development plan. FMEAs are used in different phases of PD process to indicate the level of risk in a design.

Three phases of testing are distinguished: (i) Concept/System Demonstration (SD) shows that the technology can deliver the required performance; (ii) Design Verification (DV) aims to ensure that design outputs meet the given requirements under different use conditions, and (iii) Product Validation (PV) tests the product against customer requirements and specifications. Performance and Emission (P&E) and Mechanical Durability and Reliability are tested in each of the three phases. The mandatory tests required for acceptance usually occur during PV phases. The engine level testing blocks (in Figure 7.3) 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 very end of the testing phase.

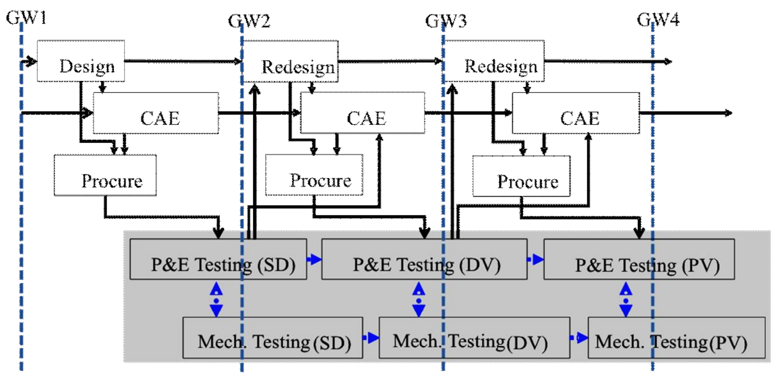

Figure 7.3. A schematic of the PD process from Gateway 2 to Gateway 4

Figure 7.3 also illustrates how engines are tested in sequence for SD, then DV and PV. However, in reality, several versions of the same engine are tested simultaneously in parallel test-beds. Some components are tested for concept demonstration whereas others are tested for design verification. Therefore, in each phase, different tests; some of which are long duration, are overlapped in a complex manner.

7.4 Testing in the Case Study Company

In analyzing the company's PD processes, two key issues concerning test emerge which affect how the whole process is managed. Firstly, long lead times for procurement of test component and secondly, the long duration physical tests.

Lead time for procurement of new engine components for testing is four to six months for the company. There are cases, for example during design verification (DV), when the company needs to start a certain test to meet the schedule of the next GW stage, but a core hardware component is not available from the supplier. The company cannot afford delay, and instead tests using alternative components. The validation managers need to identify suitable alternatives and calculate trade-offs. For example, an engine requires a piston to run a test, but the piston will not be delivered until a later date, so they will either continue physical tests with a prototype piston, or else simulate the ideal engine computationally and identify the associated risk. In this scenario the product cannot be signed off yet, and physical testing of the new piston in an engine is still necessary for verification or validation. This situation causes the DV or PV phases to extend over two GW stages instead of one.

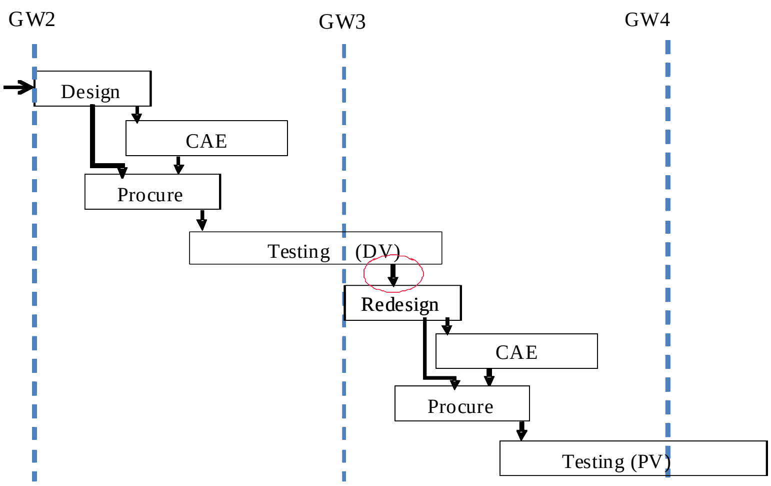

Figure 7.4. Overlapping between testing and redesign in two phases

Ideally, physical testing results from one phase should drive the (re)design and CAE of the next phase. However since testing takes a long time, it is often not viable to wait. For instance, the SD phase testing may still be on-going while the (re)design for the DV phase is started (and sometimes finished), and while procurement for the subsequent DV testing begins, as seen in Figure 7.4. Without the testing results being available, there will be uncertainties in redesigning and procuring for the next phase, resulting in significant number of iterations in subsequent phases to accrue the confidence. For instance, in cases where results from a physical test cannot be delivered before the end of the test, the durability testing of a new engine component may not produce any failure until very late in the testing process. This type of failure can prompt modifications with serious consequences (such as material changes) and may lead to an additional iteration in design and procurement. Knowing the associated risk of an extensive rework, the company has no choice but redesign because a design proposal is needed to commence another lengthy procurement process. However, running the testing is still useful and brings valuable insights of the product characteristics. Thus for this case, a way of accelerating the testing process was essential.

To overcome these issues, the company has developed two main approaches: an accurate level of specification to the supplier and reducing physical testing time through supporting CAE. To minimize long lead time procurement, initially a clear and appropriate level of specification of the product is required. The company also does CAE analysis and makes virtual prototypes with many iterations to enable the first physical prototype to be built closer to target. One engineer commented,

> "computer simulation is becoming increasingly important to the companies to minimize the effort and expense involved in product development".

The company uses CAE analysis and simulation, to identify improved boundary conditions for physical test, therefore physical testing becomes more focused. CAE analysis also can identify engine settings for test. For example in a performance test, simulation can predict when to measure a value or in which conditions, so less time is spent on the physical test.

7.5 Proposed PD Process Structure

We suggest that this case study company can respond to these issues through introducing virtual testing in parallel to the physical testing in each PD phase, as shown in the model in Figure 7.5. The proposed model separates virtual testing from the initial CAE analysis. Virtual testing can be regarded as distinct from CAE analysis proper. Initial CAE analyses may check interference and stress on components and assemblies using general purpose tools, such as FEA. A virtual test is designed specifically for a given situation and conditions and is representative of a physical test. Virtual testing of a piston should 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 the software development team in formulating mathematical models for the interacting engine components, writing appropriate numerical solution algorithms, and integrating the resultant programs into workable analysis. However, it is also noted that physical test results help to improve and validate virtual test models and this iteration is important. Initial CAE analysis should define the specification for procurement and virtual testing should assist the physical testing.

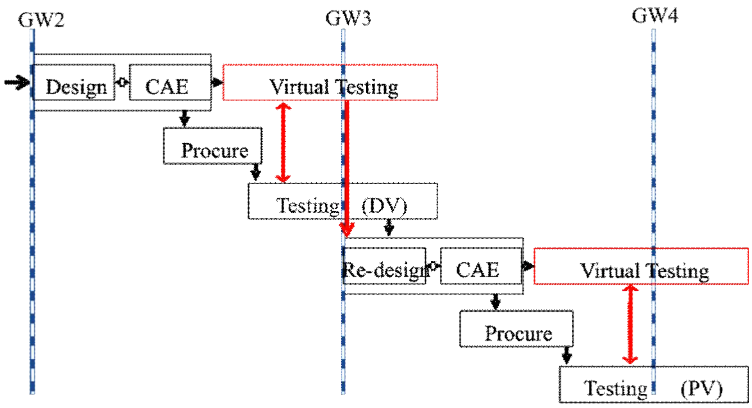

Figure 7.5. The proposed process structure with additional virtual testing actively

Initially, it is necessary to build a virtual test model before the actual physical testing starts. Engineering experience, prior understanding of the product, previous product testing and historical data should all contribute to the boundary conditions for the virtual test model. 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 test is required to validate the simulated result".

The virtual test model is further validated and adjusted against the values gained from the physical tests. 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 achieve enough confidence in the virtual testing model. Iteration in virtual testing supports fine tuning of selected parameters and rapidly produces new models of components or products. Effective communication between physical testing and the CAE team is a key success factor for this structure of parallel physical and virtual testing. Once a virtual testing model is matured, it will produce faster testing results than physical testing.

As discussed in Section 7.4, two improvements in the company's process are required. One is to produce fast and accurate specifications for procurement by frontloading of tasks and knowledge. Front loading a) increases the rate of problem solving cycles at early stages through enough CAE analysis (activity frontloading) or b) uses prior knowledge about tests on existing products to learn for the new product (knowledge frontloading) to reduce the necessary number of testing and redesign cycles at later stages (Clark and Fujimoto, 1991). Initial CAE analysis should drive design requirements. Optimization should take place earlier in the product development cycle (front loaded), to improve product specification to the supplier.

Another improvement required in the process is to make the physical testing process faster. Especially for the case, when a test needs to run for a significant amount of time to produce any useful information and subsequent redesign is highly dependent on that information, Krishnan *et al.* (1997) suggested that exchange of information should be disaggregated, to see if any information can evolve faster or can be practically transferred in a primary form. The virtual testing in the proposed model should evolve useful information faster than the actual physical testing and should provide required confidence in subsequent design tasks. The virtual testing is also aimed more at reducing the time and effort of physical testing however not all physical tests require virtual testing, or might be assisted by it.

7.6 Cost-benefit Analysis of the Model

Companies might be reluctant to accept the introduction of a virtual testing model if the costs are higher than the benefit. The cost will depend on two main factors: communication cost and the cost of establishing the virtual testing model.

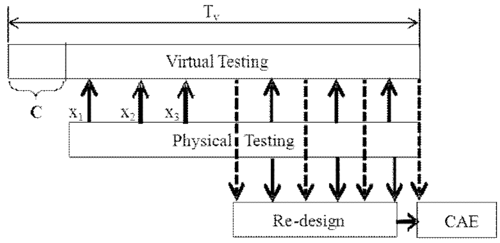

Figure 7.6. Information exchange between virtual testing, physical testing and design

Initially, the results from virtual (simulated) and physical testing may differ in several ways. These discrepancies may determine the number of meetings required which may increase with the level of uncertainty and potential dependencies between design and testing (Loch and Terwiesch, 1998). The cost of introducing the virtual testing block can be calculated as follows. Initially a fixed cost C is required to build the virtual model (as shown in Figure 7.6). This cost will depend on the company's capability in CAE modelling and simulation. With a well-established CAE department this cost might be lower than outsourcing. We are assuming that the cost for each meeting is X_i, for meetings $i = 1, 2,..n$. After the model is mature, the frequency of meetings is reduced. Each meeting results in modifications and further simulation in the virtual model, at cost Y_i. A regular maintenance and opportunity cost M is incurred per unit time, for the virtual test duration T_V. If a company has committed human resources for CAE analysis throughout the process, this maintenance might not add extra marginal costs. Thus the cost of additional virtual testing model is:

$$C_{VT} = C + \sum (X_i + Y_i) + M\, T_V \qquad (7.1)$$

Savings denoted C_T will be accumulated in several ways. Learning from the parallel virtual testing will reduce the uncertainties in design and procurement. The gain is highly dependent on the amount of rework required for redesign. It is assumed that this virtual testing will make the physical tests shorter without any quality loss, given that the virtual test is assumed to be representative of the physical testing. A benefit in using parallel virtual testing will accrue when $C_T > C_{VT}$. However, the real benefit of using parallel virtual testing continues during iterations as this might avoid extending a testing into a subsequent gateway (GW). Even with another iteration (of DV for example), the cost of running the virtual testing phase will be approximately $\sum (X_i + Y_i) + MT_V$, as the model building cost C will be small as the virtual testing model is already mature, the number of meetings will also be relatively low. The duration of physical testing in this phase will be shorter, and uncertainty decreased. Thus larger savings in physical testing are possible.

The benefit of integrating virtual testing into the process structure can help to address the key objectives in Section 7.1. The first objective is to make testing faster. The proposed model of virtual testing can accelerate the physical testing process. 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 test to achieve these desired power ratings. A 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.

Reliability and durability tests ensure performance without failure over an extended period of time. 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. The virtual testing might also indicate the points where the product might fail, making it possible to avoid unnecessary testing, or to replace a component before it fails and damages the whole engine.

The second objective is to produce effective information when testing evolves useful information very late and subsequent redesign is highly dependent on testing results. In such a case, we suggest using parallel virtual testing and starting the downstream design work once the virtual testing has produced results which are representative of the physical testing results that means virtual model is mature. Virtual test model simulation will predict parameter values faster than a physical test, and faster evolution or disaggregation of useful results will be possible. Early prediction or indication of failure can support an early design decision.

The third benefit from virtual testing is improved confidence in overall testing. Although a physical test will provide greater confidence in the test data; there are much inefficiency in physical testing especially where repetition is needed for reliable data, as mentioned during the interviews. A physical component test can deal with only limited 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, whereas virtual testing can handle a whole spectrum of variability across many interacting variables. Therefore, an integrated approach of physical and virtual testing might help to produce a focused and faster test, increase confidence and minimize iteration.

7.7 Discussion and Conclusions

The question remains as to whether such virtual testing models can be constructed. The case study company has partially done this, both to assist the physical testing and to apply when physical components are not ready. The performance, reliability and durability predictions of engine components using CAE is developing rapidly. For example, the material and structural analysis group's understanding of the principles of fatigue behaviour in complex materials, combined with historical data from high temperature applications, modelled in commercial (and internal) software, with a comprehensive materials database means that the durability of engine components can be reliably predicted and probability distributions applied to perform failure rate calculations. Whilst the company recognises there are still many technical challenges to overcome, on-going investigative work in virtual testing currently includes gas flows and combustion chemistry, cavitation in bearing oil films and metal fatigue under extreme temperatures. Moreover, to reduce the time and cost of physical testing by integrating virtual testing, procedures must be put in place to demonstrate that the virtual tests are able to replicate actual tests and to generate the necessary confidence within the design and certification communities (Maropoulos *et al.*, 2010).

This research suggests a process model to improve confidence in PD through integrating virtual testing in the process. This model is also useful to reduce the uncertainties associated with overlapping between testing and redesign. Overlapping has been studied in greater extend in several papers (Clark and Fujimoto, 1991; Krishnan *et al.*, 1997; Terwiesch and Loch 1999). This paper has considered the scenario where the information evolution of upstream testing is slow and the sensitivity on downstream design is high, a case which Krishnan *et al.* (1997) suggest does not provide favourable conditions for overlapping. However, companies often have no choice but to overlap activities. The proposed model suggests a possible strategy for overlapping providing several benefits: 1. reduced uncertainty in design and procurement, 2. improved confidence in physical testing, 3. faster physical tests and 4. reduced iteration and overall cost saving.

Further work will extend validation of this model in an industrial context, including the original case study company; in particular, considerations for the design and testing of products at different scale, complexity and maturity will be compared.

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