Optimizing overlap between testing and design in engineering product development processes

Conference or Workshop Item

How to cite:

Tahera, Khadija; Eckert, Claudia and Earl, Christopher (2013). Optimizing overlap between testing and design in engineering product development processes. In: 23rd CIRP Design Conference, 14-15 Mar 2013, Bochum, Germany, Springer, pp. 201–210.

Version: Accepted Manuscript

Link(s) to article on publisher's website:
http://dx.doi.org/doi:10.1007/978-3-642-30817-8$_20$

Optimizing Overlap between Testing and Design in Engineering Product Development Processes

K.Tahera, C.M.Eckert, C.F.Earl

Department of Design, Development, Environment and Materials, The Open University, Milton Keynes, MK7 6AA, UK
`{K.Tahera, C.M.Eckert, C.F.Earl}@open.ac.uk`

Abstract. To reduce product development time, upstream testing and downstream design processes are often overlapped. Existing studies do not recommend overlapping in situations where test results may have a significant effect on downstream redesign. However, this study identifies that, due to long procurement time and lengthy physical tests, companies may have no choice but to overlap these tasks to meet product delivery deadlines. This research investigates how a case study company manages these overlaps, and proposes a model to support the overlapping of testing and subsequent redesign phases during the development phases.

Keywords: Product development process, physical testing, virtual testing, overlapping

1 Introduction

For engineered products to succeed in competitive markets, performance, reliability, safety and durability are critical issues. A potential design may fail to meet customer requirements, have technical design faults, or raise issues about manufacturability and maintainability [1, 2]. Testing can identify these problems and is central to product development (PD) [3]. Product development is not a linear process of “design-build-test”; rather, the design process and the testing process are intertwined. However, physical testing can take a long time, and delayed or negative results in one phase potentially jeopardise project schedules. Therefore, design for the next phase often starts before testing is complete, causing testing and design activities to overlap.

Overlapping testing and design activities can incur risk, since redesigning without test results might perpetuate faults or miss opportunities to respond to emerging problems. The literature suggests that overlap models of product development do not apply well where most changes occur towards the end of the process perhaps due to long duration testing (ie slow evolution) and where substantial redesign results from these changes (ie high sensitivity). This paper proposes modifications to the product development process structure which identify a more prominent role for virtual testing and, allow overlap models to be applied more effectively.

2 Background

Overlapping occurs when a downstream activity is started before completing an upstream activity. This can reduce development time. The advantage of overlapping has been recognized in several studies [4-7]. Clark and Fujimoto [4] suggest that optimal overlapping may depend on organizational characteristics and effective communication. Overlapping might identify design flaws [5], but may allow accidental omission of key steps [6] and may introduce uncertainties which can increase iterations [7]. In the worst case, development costs may increase and product quality may worsen [7] .

Two studies are particularly relevant in setting the context and background for this research in modifying process structure for effective overlap. First, Krishnan et al. [7] develop a model which formalizes the tradeoffs based on two key concepts: upstream evolution and downstream sensitivity. If the primary information about a product's parameter values are given as intervals, as the product development progresses the intervals are narrowed and finalized, some faster than others. When the final values are achieved early in the process this is called fast evolution, whilst slow evolution occurs if most design changes happen towards the end. In low downstream sensitivity, substantial changes in the upstream tasks can be accommodated readily in the downstream activities. High downstream sensitivity happens when small upstream changes require large amounts of iteration in downstream activity. This analysis concludes that in general a fast evolution and low sensitivity situation is favorable to overlapping, and conversely, high sensitivity and slow evolution is less favourable.

Second, Terwiesch and Loch [8] present a statistical measurement of the effectiveness of overlapping development activities in reducing project completion time. Fast uncertainty resolution projects benefit from overlapping. This is similar to Krishnan's conclusion above. This paper also identifies that testing in projects with fast uncertainty resolution seems to have a delaying rather than an accelerating effect. These conclusions might implies that testing with long lead time and slow uncertainty resolution is not favorable for overlapping test with redesign unless accompanied by structural changes in the product development process.

It is observed that engineering companies overlap testing and design as essential practice; regardless of the situation with respect to evolution, sensitivities and resolution, and this happens in the case study company. This paper proposes modifications to the structure of design and testing processes which allow effective overlap for fast evolution and low sensitivity as well as in situations without fast uncertainty resolution. The benefits of overlapping can then be realized more widely in practice.

3 Methodology and case study

A case study was undertaken at a UK-based company that designs and manufactures diesel engines; complex, highly regulated products with high levels of testing to meet customer requirements, performance standards and statutory regulations. Interviews were carried out, recorded and transcribed, between March 2011 to May 2012 with six engineers: a senior engineer, a development engineer, a CAE engineer, a verification & validation manager and a validation team leader.

Complex overlapping activities were observed in the company, but this study focused on single layer overlapping where much of the existing research has been conducted. There were two main objectives:

1. To identify a means of effective overlap, even where the upstream evolution of information is slow and downstream sensitivity is high.
2. To identify ways to speed up testing to give quicker uncertainty resolution.

The next section starts by reviewing the process structure and overlapping in the case study company, then section 4 analyses the ways that the company overlaps testing and design, and section 5 proposes changes to the process structure for more effective overlapping of testing and design.

3.1 Process structure in the case study company

The case study company has a structured gateway process for New Product Introduction (NPI) (Fig. 1). It has eight stages starting from "Launch" to "Gateway 7". Most of the testing occurs between Gateway 2 (GW2) to Gateway 4 (GW4), thus this research focuses on these three main phases of the PD process (as in Fig. 2).

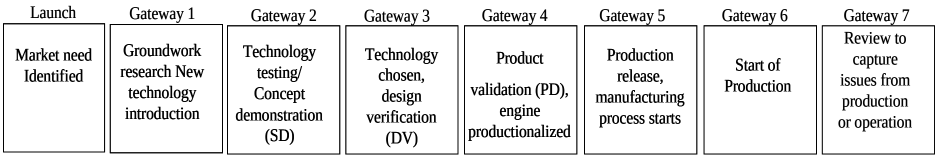

Fig. 1. An outline of the company's gateway process

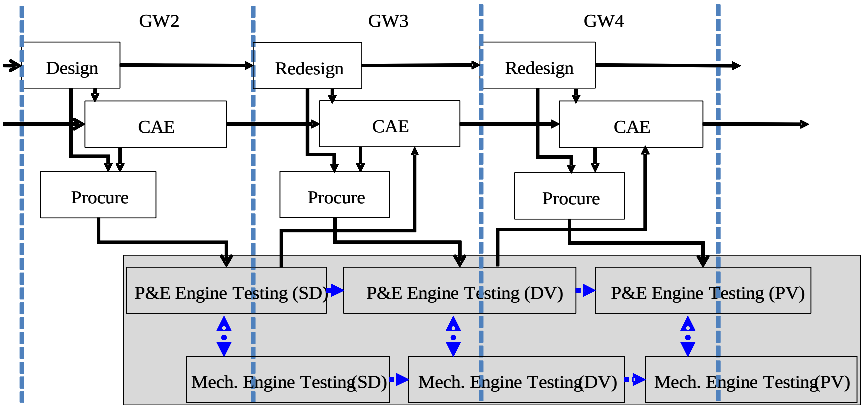

Fig. 2. A schematic of the PD process from Gateway 2 to Gateway 4

Among the large number of activities in these stages, Re/Design, Computer Aided Engineering (CAE) (eg Simulation), and Procurement (of test prototypes) are considered as drivers for testing. For simplicity Fig. 2 presents these activities 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.

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) which tests the product against customer requirements and specifications. Both the product's characteristics: Performance and Emission (P&E) and the 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 (Fig. 2) 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.

3.2 Overlaps with testing in a single product development stage

In each gateway stage there are overlaps between activities. Design, CAE and Procurement overlap but the focus is on their overlaps with testing:

- CAE - P&E testing: CAE analysis, e.g. Computational Fluid Dynamics (CFD) is used to support the design, optimization and verification of an engine's fluid system. As the company freezes the design, some CAE work is still ongoing, and/or additional CAE work might be required parallel to the physical testing.
- CAE-mechanical testing: Finite Element Analysis (FEA) provides accurate, timely and cost-effective guidance when testing the durability of engine components.
- Procurement-testing: Testing starts as soon as a component arrives at site to minimize the testing lead time. Even system-level testing continues with prototype parts.
- P&E testing-mechanical testing: Early results from P&E enable the mechanical testing phase to start earlier.

Note that the significant overlaps which occur between testing and (re)design in the next phase, is an area of interest of this paper. Fig. 2 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, each testing phase overlaps in a complex manner.

4 Analysis of overlapping design and testing in the case study company

In analysing the company's design and testing processes, two key issues emerge in overlapping tasks. Firstly, long lead time procurement and secondly, the long duration physical tests.

4.1 Long lead-time for procurement

There are some 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. These alternative tests may give a risk reduction of, for example, 30% instead of the planned 50%. 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.

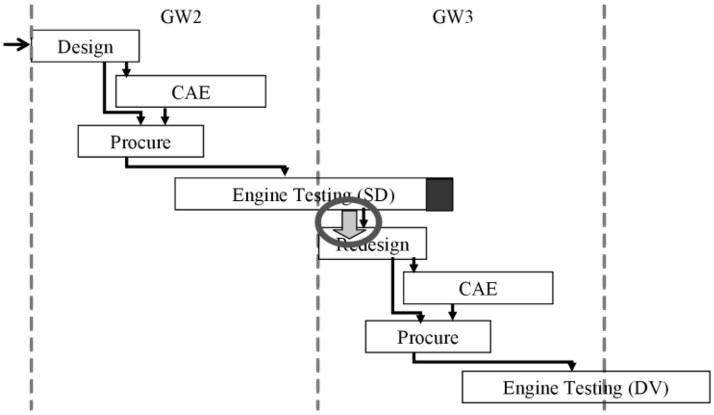

Fig. 3. Overlapping between testing and redesign in two phases

4.2 Lengthy physical tests

Testing physical prototypes is essentially a slow and expensive process. However, it is a high fidelity method for ensuring the product's characteristics and in some cases is mandatory for acceptance and essential for assuring the product's function and behaviour. Ideally, physical testing results from one phase should drive the design and CAE of the next phase. However since testing takes a long time, it is not often 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 Fig. 3.

Without the testing results being available, there will be uncertainties in redesigning and procuring for the next phase. This is a case where upstream evolution of testing information is slow and has high sensitivity on downstream design phase, resulting in significant number of iterations in subsequent phases.

4.3 The current approach to the issues

To overcome the issues mentioned above, the company has developed two main methods: firstly frontloading the tasks, and secondly reducing physical testing through supporting CAE.

Front loading (a) increases the rate of problem solving cycles at early stages (activity frontloading) or (b) uses prior knowledge about past problem solving (knowledge frontloading) to reduce the necessary number of problem solving cycles at later stages [4]. To minimize long lead time procurement, a clear and accurate specification of the product is required. CAE analysis drives design requirements and engine settings for test. Optimization takes place earlier in the product development cycle (front loaded), to improve product specification to the supplier. The company 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*".

Reducing physical testing through CAE analysis and simulation, can identify improved boundary conditions for physical test, which then becomes more focused. For example in a performance test, simulation can predict when to measure a value or conditions, so less time is spent on the physical test. Physical test results validate the product as well as the simulation model, which is then reusable for future products, reducing time and cost for subsequent iterations of the model. Iteration in physical product testing requires building a new physical prototype and might involve redesigning, reordering, building and testing, In contrast, virtual testing supports fine tuning of selected parameters and rapidly produces new models of components or products.

5 Proposed process structure

In the review of literature in Section 2 two key papers [7, 8] were identified. Krishnan, V. et al. [7] recommend circumstances where activities should be overlapped. From their model, the worst case is where the upstream evolution is slow and the downstream sensitivity is high; in this case overlapping is not recommended. In this situation, it is suggested that exchanges of information should be disaggregated, to see if any information can evolve faster, or can be practically transferred in a primary form.

On the other hand, in the other key paper, Terwiesch and Loch [8] indicated that lengthy testing might have a delaying effect on a fast uncertainty resolution project. For this case study company, it is difficult to gauge the speed of uncertainty resolution. The company has to finish a project on a given timeline and bring the product to the market. Even for a complex new product, the timeline may vary little. Terwiesch and Loch [8] also suggest that "*if the uncertainty resolution over the course of the project is unfavourable for overlapping activities and cannot be sufficiently accelerated by defining standards and architectures, the project organization has to search for other means of uncertainty resolution*" [8]. For the case study company, testing is the primary method for uncertainty confirmation and identification. Subsequent tasks such as redesign are uncertainty elimination tasks. Testing is a slow process; so the company undertakes downstream design activities before testing is finished. Knowing the associated risk of an extensive rework, the company has no choice but to overlap these design tasks with testing, a design proposal is needed to commence another lengthy procurement process. Thus for this case, a way of accelerating the testing process was essential.

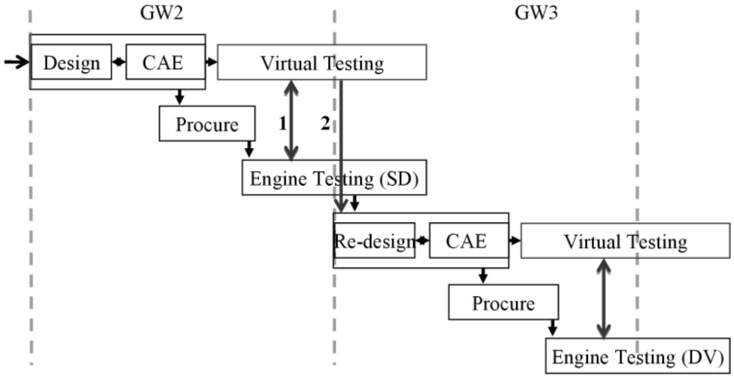

Fig. 4. The proposed process structure

It is suggested for this case that these issues can be solved by introducing virtual testing parallel to the physical testing in each PD phase, as shown in the model presented in Fig. 4. Simulation or 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 on a piston 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 expertise of engineers 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. Early CAE analysis helps to reduce uncertainty, thus frontloading activities. In contrast virtual testing is aimed more at reducing the time and effort of physical testing.

The proposed model separates virtual testing from the initial CAE analysis. Initial CAE analysis should define the specification for procurement and virtual testing should assist the physical testing. Not all physical tests require virtual testing, or might be assisted by it. Initially, it is necessary to build a virtual test model, which is representative of the physical test, and can be validated in physically. 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. The model is further validated 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.

5.1 Benefit from virtual testing

Integrating virtual testing into the process structure can help to address the two key objectives in Section 3. The first objective is to create effective overlap when upstream evolution is slow and downstream sensitivity is high. 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. As information does not evolve quickly in upstream testing, which has a high level of sensitivity to downstream design, overlapping is not favorable. This paper suggests using parallel virtual testing. When the sensitivity in the downstream design is high, the faster evolution of useful test results is required to make the overlapping possible. In this case, this paper suggests starting the downstream design work once the virtual testing has produced results which are representative of the physical testing results. Virtual test model simulation will predict parameter values faster than a physical test, and the faster evolution or disaggregation of useful results will be possible. Early prediction or indication of failure can support an early design decision.

The second objective is to make testing faster. 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 satisfactory 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.

5.2 Costs for introducing parallel virtual testing

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 virtual testing model establishment cost. Effective communication between physical testing and the CAE team is a key success factor for this structure of parallel physical and virtual testing.

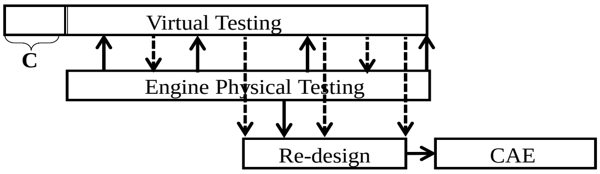

Fig. 5. Information exchange between virtual testing, physical testing and design

Initially, virtual (simulated) and physical testing results may differ in several ways. Discrepancies may determine the number of meetings required, and increase with the level of uncertainty and potential dependencies [9]. The cost for 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 Fig. 5). This cost will depend on the company's capability in CAE modelling and simulation. With a well established CAE department then 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:

$$C_{VT} = C + \sum (X_i + Y_i) + M\,T_V \qquad (1)$$

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 sensitivity of the downstream work. It is assumed that this virtual testing will make the physical tests shorter without any quality loss, and that the virtual test is 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. 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.

6 Discussion and conclusion

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, ongoing investigative work in virtual testing currently includes gas flows and combustion chemistry, cavitations in bearing oil films and metal fatigue under extreme temperatures.

This research suggests a model to reduce the uncertainties associated with overlapping between testing and redesign. 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 the literature suggests do not provide favourable conditions for overlapping. However, companies often have no other choice but to practice overlapping. The proposed model suggests a possible strategy for overlapping providing several benefits: (1) reduced uncertainty in design and procurement, (2) focused physical testing, (3) reduced duration of physical tests (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, overlapping considerations for the design and testing of products at different scale, complexity and maturity will be compared. The model will be extended to consider multiple layered overlapping.

References

1. Thomke, S., and Bell, D. E.: Sequential Testing in Product Development. Management Science. pp. 308-323(2001)
2. Qian, Y., Xie, M., Goh, T. N.: Optimal Testing Strategies in Overlapped Design Process. European Journal of Operational Research. 206(1) pp. 131-143(2010)
3. Thomke, S.H.: Experimentation matters: unlocking the potential of new technologies for innovation. Harvard Business Press (2003)
4. Clark, K.B., and Fujimoto, T.: Product development performance: Strategy, organization, and management in the world auto industry. Harvard Business Press (1991)
5. Ha, A. Y., and Porteus, E. L.: Optimal Timing of Reviews in Concurrent Design for Manufacturability. Management Science. pp. 1431-1447(1995)
6. Smith, P. G., and Reinertsen, D. G.: Shortening the Product Development Cycle. Research Technology Management, 35(3) pp. 44-49(1992)
7. Krishnan, V., Eppinger, S. D., and Whitney, D. E.: A ModelBased Framework to Overlap Product Development Activities. Management Science, pp. 437-451(1997)
8. Terwiesch, C., and Loch, C. H.: Measuring the Effectiveness of Overlapping Development Activities. Management Science, pp. 455-465(1999)
9. Loch, C. H., and Terwiesch, C.: Communication and Uncertainty in Concurrent Engineering. Management Science, pp. 1032-1048 (1998)