A design framework for agile virtual enterprise collaboration

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Declaration

Except where otherwise stated, this thesis is the result of my own research and does not include the outcome of work done in collaboration.

This thesis has not been submitted in whole or in part for consideration for any other degree or qualification at this University or any other institute of learning.

This thesis contains 45,862 words and 19 figures

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Abstract

Keywords: Agility, Responsiveness, Agility Measurement, Engineering Design, Design Process, Design Tools, Collaboration, Turbulent Environment, Unexpected Events

The market in which engineering companies must operate is increasingly turbulent and unpredictable, largely due to the global nature of the engineering industry in the 21st century. This turbulent environment is further exacerbated by the increasing focus on customisation for individual consumers, rather than the mass manufacturing market of the past. In order to thrive in this turbulent environment companies are increasingly focussing on their core competences, and building strategic alliances with complementary partner companies to satisfy the overall needs of an individual project. This is true of the design as well as manufacturing stages of product development.

The increasing levels of collaboration and the requirement for companies to be agile in their response to unexpected events are the background to this research. Specifically, this research addressed the ability of collaborating groups of companies to respond to unexpected events during the design stages of product development. The hypothesis was that through the specific implementation of a novel collection of tools and techniques the agility of collaborative design projects can be increased.

A multi-method approach was adopted for the research, beginning with an industrial survey identifying those tools and techniques from the literature which are linked to an increased level of agility. These results form the basis for the definition of the Agile Design Framework which takes the form of a series of implementation steps carried out by a collaborative design team to put in place tools and techniques for increasing their responsiveness to unexpected events.

The second stage of the research tested the Agile Design Framework in a controlled laboratory environment with both an experimental and control group undertaking the same collaborative design project. Unexpected events were introduced and the responses of both groups are analysed. The experiment group using the Agile Design Framework had a Key Agility Index score of 0.04 compared with a score of 0.13 for the control group. A low score on the Key Agility Index indicates a higher level of agility while high scores tending to 1 have a lower agility level.

The results supported further calibration of the Agile Design Framework for the final stage of the research which was an implementation of the framework in industry for a real-life collaborative design project. This industrial implementation showed an improvement in the agility of the collaborative design project using the Agile Design Framework, improving the Key Agility Index from 0.54 to 0.43.

The research makes three novel contributions to knowledge in this field. The first is the Agile Design Framework which is a set of tools and techniques with a specific implementation process, which has been shown to increase agility for collaborative design projects. Secondly, a four-level classification scheme for unexpected events will be presented which allows categorisation of unexpected events into Trivial, Minor, Major and Fatal, based on specific criteria. Finally, through the use of easily obtainable data the Key Agility Index is validated as a meaningful quantitative metric for the measurement of agility at the project or departmental level.

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Publications

This research has been published in the following conferences, journal publications and book chapters:

Conferences

"An Extended Virtual Enterprise SMARTEAM Engineering Project". Forrest Arnold, Nathan Moody, William Reiter, Cary Maunder, Brian Rogers, Paul Baguley, Peter Chapman, **Chris Lomas**, Defen Zhang, Paul Maropoulos. Proceedings of the 2nd International Conference on DET. Seattle. 13-15th Sep 2004.

"Agile Design and Manufacturing in Collaborative Networks for the Defence Industry". Paul Maropoulos, Nikolaos Armoutis, David Bramall, **Chris Lomas**, Peter Chapman, Brian Rogers. Proceedings of the IFAC Conference on Manufacturing, Modelling, Management and Control. Athens. 21-22nd Oct 2004.

"Foundations of an Agile Design Methodology". Peter Matthews, **Chris Lomas**, Nikos Armoutis, Paul Maropoulos. Proceedings of the International Conference on Agile Manufacturing (ICAM). Helsinki. 27-28th Jul 2005.

"Partner Profiling to support Agile Design". Nikos Armoutis, Peter Matthews, **Chris Lomas**, and Paul Maropoulos. Proceedings of 1st International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV). Munich. 22-23rd Sep 2005.

"Verification of event impact levels for an Agile Design framework". **Chris Lomas**, Peter Matthews, Nikos Armoutis, Paul Maropoulos. Proceedings of International Conference on Manufacturing Engineering (ICMEN). Thessaloniki. 5-7th Oct 2005.

Publications

"A Methodology for Negotiating Change Propagation in Agile Design". Peter Matthews, **Chris Lomas** and Paul Maropoulos. Proceedings of the International Conference on Agile Manufacturing (ICAM). Norfolk, VA. 19-20th Jul 2006.

"Agile resource allocation through pre-emptive planning". Peter Matthews, Graham Coates and **Chris Lomas**. Proceedings of the International Conference on Agile Manufacturing (ICAM). Norfolk, VA. 19-20th Jul 2006.

"Measuring design process agility for the single company product development process". **Chris Lomas**, Jeremy Wilkinson, Paul Maropoulos, Peter Matthews. Proceedings of the International Conference on Agile Manufacturing (ICAM). Norfolk, VA. 19-20th Jul 2006.

"Implementing Digital Enterprise Technologies for Agile Design in the Virtual Enterprise". **Chris Lomas**, Paul Maropoulos, Peter Matthews. Proceedings of the International Conference on Digital Enterprise Technology. Setubal. 18-20th Sep 2006.

"Meta-design for Agile Concurrent Product Design in the Virtual Enterprise". **Chris Lomas** and Peter Matthews. Proceedings of the International Conference on Agile Manufacturing. Durham. 9-11th Jul 2007.

Journal Articles

"Foundations of an Agile Design Methodology". Peter Matthews, **Chris Lomas,** Nikos Armoutis and Paul Maropoulos. International Journal of Agile Manufacturing. Vol. 9(1). Pg 29-38. 2006.

"Measuring design process agility for the single company product development process". **Chris Lomas**, Jeremy Wilkinson, Paul Maropoulos, Peter Matthews. International Journal of Agile Manufacturing. Vol. 9(2). Pg 105-112. 2006.

"Meta-design for agile concurrent product design in the virtual enterprise". **Chris Lomas** and Peter Matthews. International Journal of Agile Manufacturing. Vol. 10(2). Pg 77-88. 2008.

"Establishing agile supply networks through competence profiling". Nikos Armoutis, Paul Maropoulos, Peter Matthews, **Chris Lomas**. International Journal of Computer Integrated Manufacturing, Vol. 21(2). Pg 166–173. 2008.

"A Methodology for Quantitative Estimates for the Work and Disturbance Transformation Matrices". Peter Matthews, **Chris Lomas**. Journal of Engineering Design. In Press. 2008.

Book Chapters

"Implementing Digital Enterprise Technologies for Agile Design in the Virtual Enterprise". **Chris Lomas**, Paul Maropoulos, Peter Matthews. Digital Enterprise Technology: Perspectives and Future Challenges. Pedro Cunha, Paul Maropoulos. (Eds.). Pg 177-185. 2007. ISBN: 978-0-387-49863-8

Contents

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Chapter 1. Introduction

This thesis is concerned with the agility of collaborative engineering design projects. These projects are increasingly commonplace as companies seek to concentrate on their own core competences and build strategic partnerships with complementary businesses. This has the benefit of allowing companies to minimise overheads on skills and resources they do not need all the time, and allows the flexibility to operate in a wider variety of markets without the need to obtain the necessary skills and resources internally, simply by building short-term alliances with complementary companies.

1.1. Overview

Agility at stages of the product development process other than design, especially manufacturing, is well researched. This provides a solid foundation on which to base this research into design agility for collaborative projects. Agility has been defined as "the ability to operate profitably in a competitive environment of continually and unpredictably changing customer opportunities" (Goldman et al., 1995).

Collaboration has been well researched from a number of view-points, predominantly those concerning the technicalities of collaboration such as data-sharing (Goranson, 2003; Kovács & Paganelli, 2003; Krauser et al, 2002; Camarinha-Matos & Pantoja-Lima, 2001). Simultaneously as collaboration has become more common, the external environment in which companies must operate is continuing to become more turbulent and unpredictable (Dove, 2001).

1.2. Research Objectives

This research is concerned with the integration of these areas to explore the levels of agility that can be achieved through collaboration at the design stage of product development. Specifically, the first objective is to define a framework through which collaborative design teams can increase their level of agility in response to external events in this so-called turbulent environment. The second objective is to test the framework in an industrial setting to validate its ability to increase agility in the collaborative design environment.

1.3. Thesis Structure

Figure 1-1 shows the structure of this thesis which is comprised of 8 principal Chapters with additional evidence located in the Appendices.

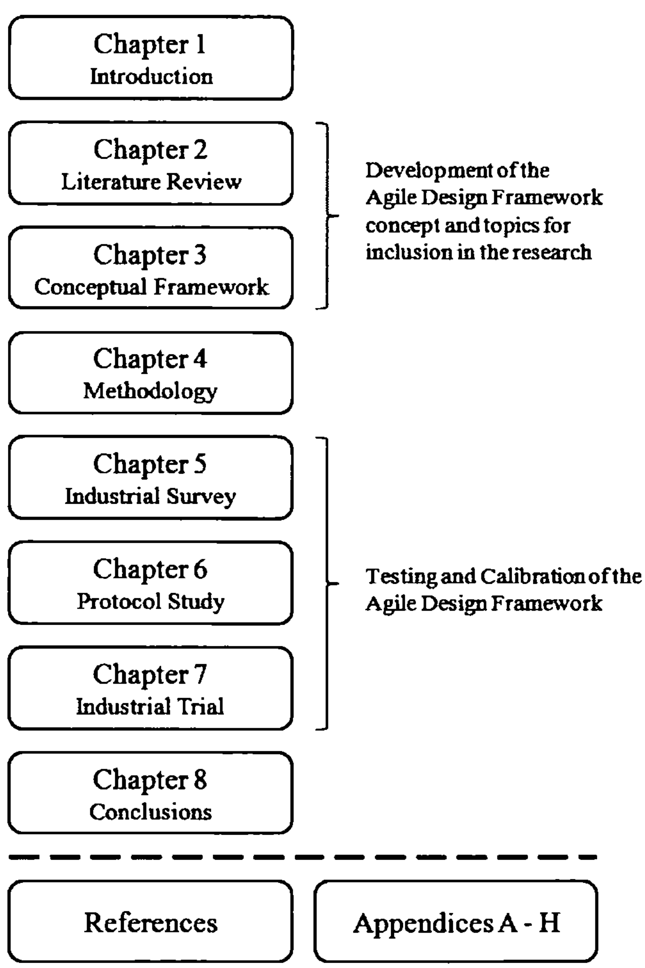

Figure 1-1. Thesis Structure

Chapter 1 briefly introduces the background to this research, including the objectives, and describes the structure of the thesis.

Chapter 2 is a review of the relevant literature undertaken to explore the linkages between research in the domains of collaboration, design and agility. From this review the areas of interest relating to achieving agility, either within other processes such as manufacturing, or as a by-product of other goals such as collaboration, will be extracted.

Chapter 3 sets the context of the work by expanding on the "turbulent environment" as described in the literature review. The definitions of agility are discussed and a working definition is constructed. A suitable measure of agility is discussed and finally a hypothesis is proposed to guide the subsequent research.

Chapter 4 describes the approaches to testing the hypothesis which were considered and introduces the three-stage methodology.

Chapter 5 is the first of the experimental chapters, describing an industrial survey to ascertain the relationship between important factors from the literature and the level of agility currently being achieved in industry.

Chapter 6 describes a laboratory-based experiment which seeks to test an initial framework for increasing agility in a collaborative design project – the Agile Design Framework.

Chapter 7 takes the findings of the previous experiment to provide evidence for refining the framework. The framework is to be applied in this final results section, which describes an industrial implementation of the framework for validation.

Chapter 8 discusses the implications of the results and conclusions from each experimental chapter, critiquing the experiences and results. Areas for future work will also be presented in Chapter 8.

Chapter 2. Literature Review

While agility has been well researched at the manufacturing stage, its applicability to product design is relatively under-researched. The objective of this research is to determine a method by which the modern-day design process, often in a collaborative and geographically distributed environment, can be more agile in response to a turbulent external environment. This review of the literature in the relevant domains provides a starting point from which an agile collaborative design framework will be derived. The framework will then be used to test the hypothesis presented in Section 3.3. The relevant domains to this field are those of design, collaboration and agility. To assist the reader these focus domains are illustrated in Figure 2-1, which also highlights sub-areas of interest and their relative positioning in the research space.

The chapter presents a review of the formal design methodologies from the literature. This will cover the overall design process, including the more general Product Development Process. The focus is specifically on the early stages of design. Design tools such as Design Structure Matrices and Work Transformation Matrices are explored for their use in assessing the dependencies between different aspects of a design, as well as their use in sub-dividing work in a collaborative setting. This collaborative setting is central to any current design-based research in an increasingly global market.

Collaboration techniques and tools will be explored for their role in the design process and the potential agility they provide to any design project. The law of diminishing returns suggests that the early stages of product development have most bearing on the final solution and are therefore of particular interest in this research, particularly the way in which collaborative design teams are established. Following this the structure and operational relationship between the partners of a collaborative project will be evaluated.

Finally, having explored design methods and tools with a particular emphasis on collaborative design projects, the property of agility will be analysed according to the many definitions applied to different aspects of engineering since its inception in the mid-nineties. Importantly, the underlying characteristics of an agile system are of interest, particularly the way they are achieved in domains other than collaborative design. The relationship between agility and "lean" will be explored. This will be concluded by a summary of the latest developments in design, collaboration and agility. The findings will be brought together in the next chapter to form a hypothesis for the definition of a framework which will be applied to a collaborative design project to achieve higher levels of agility.

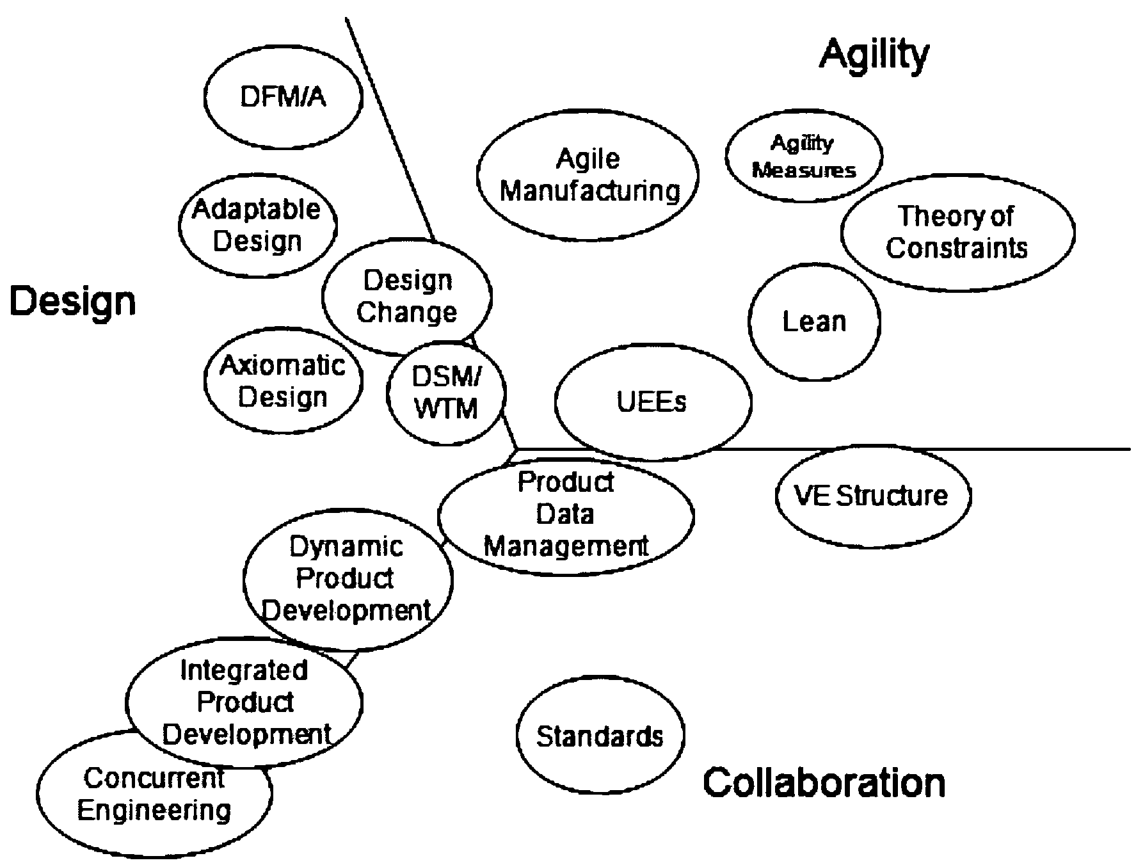

Figure 2-1. A map of the relevant literature

2.1. Design

Whether designs are completely new solutions, or simply variations on existing ones, there will always be a process by which new products are required to satisfy a market demand. This process of converting a set of often ill-defined requirements into a functioning, marketable product is one definition of engineering design. Since the industrial revolution a rapid expansion in knowledge and technological capability has led to designers becoming the centre of the product development process as it has now become known. Designers must apply their considerable experience and knowledge to the problem in hand and devise the most appropriate solution to any problem. Doing this well in a turbulent environment creates a competitive advantage.

2.1.1. Product Design Process

Pahl and Beitz (1996) proposed a systematic approach to engineering design, introducing a common process to be followed for formalising engineering design. The approach asserts that in recognition of the importance of the design process and its increasing complexity, a more systematic methodology is required. The proposal is a four stage process beginning with "Product Planning and Clarifying the Task" and moving on to "Conceptual" and then "Embodiment" and "Detailed" design stages (see Figure 2-2).

The Product Planning stage relates to analysing the market needs and strategic opportunities within it, as well as estimating future developments, both in the market and also in related fields such as relevant technologies. Wheelwright and Clark (1992) in their Development Strategy Framework also emphasise the importance of the planning phase and the ability to adopt new technologies. It is suggested that a lack of planning and a failure to plan sufficiently in advance is the primary reason for problems during product development, because issues such as a changing market and emerging technologies are not considered important enough, if at all, at the planning stage. They suggest that a technology strategy is a fundamental part of pre-project planning because an ability to identify or develop new technologies and implement them in the product or process gives a competitive advantage.

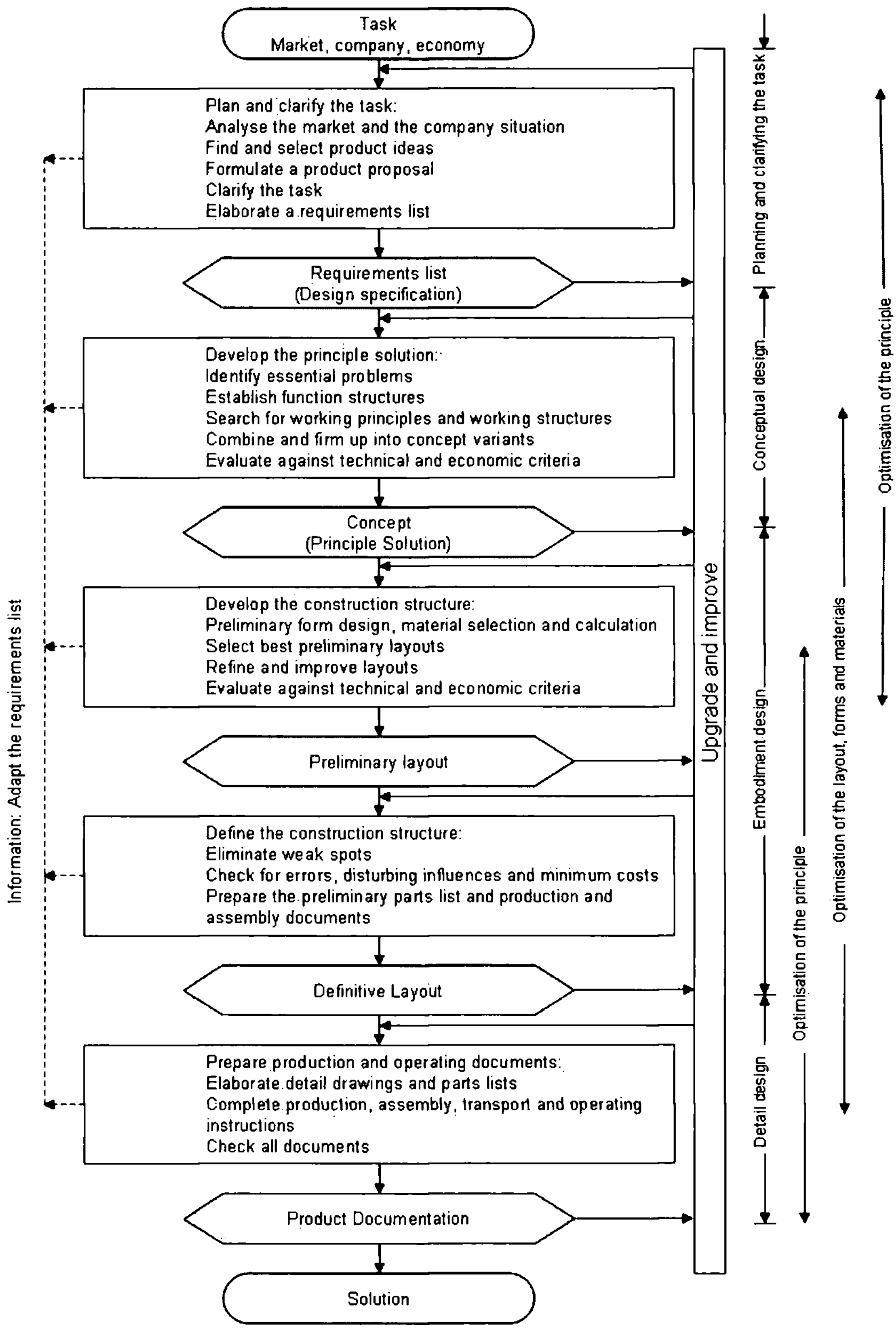

Figure 2-2. The Planning and Design Process as defined by Pahl and Beitz (1995)

Many other approaches to the engineering design process have also been offered, particularly in the last 15 years. Dym (1994) also describes a four-stage process with more of a focus on identifying functional requirements before embarking on detailed design. In this model there is less emphasis on generating multiple concepts and combining aspects of each. Voland (1999) presents a five-stage process, separating the early stages of the process into Needs Assessment and Problem Formulation. Voland places greater emphasis on these early stages to ensure that the problem to be solved satisfies the actual requirements and not the perceived but often biased or misunderstood requirements. The remainder of Voland's process follows a similar pattern to those introduced earlier of Dym and Pahl and Beitz, with ideas generation, analysis and implementation stages to develop concepts into a detailed design. Similarly, Eggert (2005) describes a 5-phase design process: Formulation; Concept Design; Configuration Design; Parametric Design and Detail Design.

Although varying in name and with each author adding their own perspective, the design processes described are all very similar in nature and can be summarised as: A four or five stage process beginning with formulating the correct problem to be solved and therefore the requirements of the eventual solution. This is followed by various means of taking concepts and combining or reducing them, usually by means of an iterative process, to arrive at a detailed design that solves the original problem.

In describing the fundamentals of their strategic approach, Pahl and Beitz are not alone in acknowledging the increasing division of labour during the design process to inter-disciplinary teams found in the concurrent engineering (CE) model (Section 2.1.1). Wheelwright and Clark recognise the importance of inter-disciplinary teams in creating a competitive product development process. However they fail to go as far as discussing multi-company collaboration which will be the topic of the next section of this chapter (Section 2.2).

2.1.2. Design Changes

One characteristic common to all engineering design processes is the iterative nature, particularly in the middle stages of development as ideas are rejected and refined. This combining and revising of ideas is the first of three reasons cited for iterations in the design process. Urban and Hauser (1993) highlight the iterative nature of the design process as a key characteristic of engineering design. Ottosson (2004) has recently proposed Dynamic Product Development as an alternative to the more classical stage-gate product development process of Cooper (2001). One of the key differences between the approaches is the removal of the 'gates' through which a project must pass to proceed to the next stage. In removing these 'gates' Ottosson suggests that iterations can then be larger, allowing designers to go right back to the conceptual stage of design if necessary.

In addition to refining the design to modify concepts, there are two other common reasons cited for iterations in the design process:

The second major cause of iterations cited in the literature is design changes required by the customer, usually to reflect changes they themselves or other suppliers have made to interfacing sections of the product. Rios et al (2007) have worked towards a cost impact projection model for requirements changes in the aircraft industry. They state that requirements changes in this sector are so inevitable that the responsibility and cost implications of requirements changes are agreed between the partners at the outset of the project.

The third cause of iteration is linked to the second and is caused by the outcome of one task influencing another task and vice versa. This means that when part of a design changes, perhaps due to a customer requirements change, it has an effect on another aspect of the design causing iteration to take place. This iteration may in turn cause further iterations elsewhere as designs can quickly become complex as the many aspects interlinked. This concept is addressed in detail by the work of Steward (1981) and later Ulrich and Eppinger (1995) with their work on Design Structure Matrices.

The Design Structure Matrix (DSM) developed by Steward (1981) and later extended by Eppinger et al (1994) is a tool for identifying the linkages and dependencies between tasks in the design process. The matrix illustrates the tasks that each other task is dependent on. The DSM can therefore be used to arrange the tasks in order to minimise the number of iterations required to arrive at a solution. This tool has significant benefits in sectors where the design team have many years experience and the environment is stable. However the DSM and the more detailed Work Transformation Matrix (Smith and Eppinger 1997) can be shown to be unreliable or unusable in a turbulent environment where the process is changing (Cronemyr et al 2001).

	Task A	Task B	Task C	Task D
Task A				**X**
Task B				
Task C		**X**		
Task D		**X**		

Figure 2-3. Design Structure Matrix Before Optimisation

	Task B	Task C	Task D	Task A
Task B				
Task C	**X**			
Task D	**X**			
Task A			**X**	

Figure 2-4. Design Structure Matrix After Optimisation

Figure 2-3 illustrates a Design Structure Matrix showing the relationship dependencies between 4 tasks in a theoretical design project.

Figure 2-4 shows how the tasks can be re-ordered in this example to ensure that the pre-requisite tasks are completed prior to the tasks requiring their outcomes. The aim is to bring all the relationship markers below the diagonal line. The DSM also shows that a requirements change in Task B causes an affect on Tasks C & D.

This literature regarding design changes and design iterations suggests that although design processes are often illustrated as iterative, particularly in the middle stages, there is little evidence that external and unexpected influences have been considered. Rather, the literature focuses on internal relationships and influences rather than those from outside the initial project. Importantly, the tools such as Work Transformation Matrices for modelling design iterations cannot be used in turbulent and unpredictable environments and provide no inputs from outside the pre-determined design tasks.

One approach for reducing the knock-on effect of iteration proposed by Ulrich and Eppinger (1995) is de-coupling tasks to avoid the iteration propagating too far. More specifically the proposal is that by making the tasks as independent as possible an iteration will impact fewer tasks and therefore less rework is required and the development process is completed faster. Other approaches such as Axiomatic Design (Suh, 2001) to reduce product development time, some of which support this approach of de-coupling or modularising tasks, are explored in the following sections (Section 2.1.4).

2.1.3. Design for Manufacture and Assembly

As well as reducing the propagation of iterations within the design tasks, Design for Manufacture and Assembly (DFMA) techniques (Boothroyd et al, 1994) provide a means for reducing the number of iterations in the design process. Boothroyd et al have shown that by spending longer on DFMA in the early stages of product design, there is an overall time saving later in the project because fewer design iterations are necessary once prototyping and production testing start. This is caused by a reduction in the number of manufacturing problems by considering manufacturing and assembly during the design stages.

The DFMA process requires that the manufacturing and assembly stages of the product development process are represented at the early design stages to provide input to the designers. This supports the use of cross-functional teams as advocated in previous approaches although does not go as far as the inclusion of other interested parties such as marketing or sales representatives.

Additionally, DFMA is achieved through a number of specific techniques including:

- Part Count Reduction: Reducing the part count as far as practical, whilst also considering the economic and technical implications.
- Correct Selection of Materials and Processes: Broadening the designers' knowledge of available materials and processes, rather than just those they are familiar with and "always use".
- Design for Manual Assembly: Designing with the assembly process in mind, for example using symmetrical components wherever possible to reduce the manual manipulation, and filleted edges to make inserting parts into each other more straightforward.
- Process Optimisation: There are also guidelines on optimising designs for each manufacturing process, for example a part which is die cast may be better designed with thin walls and must allow for thermal expansion in the cavities.

2.1.4. Product Development

In addition to the specific product design process, other approaches to design have been proposed which can be considered to operate at a more removed level of detail. These approaches are described in this section in the context of achieving agility.

Concurrent Engineering and Integrated Product Development

Concurrent Engineering (CE), sometimes referred to as Simultaneous Engineering, is a technique which has been in practice in industry since the 1970s. Initially the principle was simple: to reduce the product development time of complex products by carrying out product and process development concurrently. Therefore, as the product was designed by a team of designers, the process designers would become involved at that early stage and begin to plan the manufacturing process, even before the design was finalised, rather than after the design was complete.

More recently Concurrent Engineering has been extended to include other tools and techniques which have evolved as the pressure to reduce product development time has increased. Prasad (1996) incorporates Integrated Product Development (IPD) as a central feature of his Concurrent Engineering model, as well as more extensive use of cross-functional teams, not just design and process planning. However, this contradicts Ottosson (2004) who suggests that IPD is an extension of CE through the addition of more diverse representation in the New Product Development (NPD) team.

The assertion that IPD is an extension of CE holds for early definitions of CE, however as the theory has evolved and other techniques have been used, the boundary between IPD and CE has blurred until the two are undistinguishable. For example IPD makes use of overlapping the NPD activities wherever possible, as with CE, through the adoption of various techniques including IT tools, extended cross-functional teams, independent team leadership and incremental (adaptive) product design. The goal of IPD is typically a reduction in product development time, although other goals including reduced product cost or improved quality are also valid. These objectives and techniques resonate with Prasad's (1996) definition of CE.

Gerwin and Barrowman (2002) performed a review of IPD research from the 1990s and concluded that "cross-functional" teams in the studies they reviewed included only single-company interactions. They cite Doz and Hamel (1998) as recognising that it is increasingly common for companies to form strategic alliances, and therefore the IPD model may not be as applicable in this multi-company environment.

Axiomatic Design

Axiomatic Design (Suh, 2001) is a design theory which seeks to take the objectives of Pahl and Beitz from a systematic approach to a scientific approach: the application of science to the previously creative process of design. Axiomatic Design is concerned with a design framework built on the axioms of design derived from observations of many previous design projects. This framework comprises a four-step approach to design, each centring on a specific domain.

The customer domain is the first, in which the definition of specific customer requirements is done. These are referred to as Customer Attributes (CA). Then from the CAs it is possible to move into the functional domain and determine a set of independent Functional Requirements (FRs). In this domain the Constraints (C) are also defined, based on both input constraints from the customer requirements, and system constraints imposed by the system or environment of the product.

Once the Functional Requirements are established they are mapped onto Design Parameters (DPs) in the Physical Domain. It is this mapping which includes the conventional design activities of generating concepts and developing a solution. The DPs are then mapped into a set of processes required to produce (manufacture) the solution in the Process Domain. The interesting and significant aspect of this approach is the importance given to the functional independence of the FRs and their relationship with the DPs. Suh asserts that the number of FRs must be equal to or less than the number of DPs in order for the design to be optimal. If the number of FRs is greater than DPs then one of the DPs is fulfilling multiple FRs. In this situation a change to one of those FRs then has a knock-on effect on other FRs because of the link caused by the shared DP. For the interest of this research, this also means that each individual DP has one or more specific functions to perform, which are independent from the rest of the product.

This uncoupled approach can be illustrated by the example from Suh (2001) of a fridge door. In designing a fridge door two Functional Requirements (FRs) are identified:

1. Provide access to the contents of the fridge
2. Minimise energy loss

A conventional solution comprising: a vertically hung fridge door (DP_1) with thermally insulating material (DP_2) can be described by the design matrix shown:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$ **Equation 1**

From the design matrix in Equation 1 it can be seen that FR_2, the necessity to minimise energy loss is affected by both the Design Parameters. This is because the energy loss is not prevented by a vertically hung door when it is opened to access the food, despite the thermally insulated material. This makes this solution a "decoupled" design.

If all FRs were affected by all DPs then the design would be "coupled". This method of describing potential solutions allows designers to identify the inter-relationships between aspects of the design and, where these can be minimised, the influence of a change in one or more of the FRs (such as a change in requirements from the customer) can also be minimised.

A more satisfactory design would be one where the FRs and DPs had a one-to-one relationship – this is called "uncoupled" and described by Equation 2:

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$ **Equation 2**

In recognising the benefits of limiting the impact of design changes, the axiomatic design framework encourages a design process whereby the individual sub-components or assemblies (as they would be for a mechanical design) are separated functionally if not physically from the other sub-assemblies or components. This has the benefit of minimising the knock-on effect of a design change or iteration because the design parameter is not affected by a change to another functional requirement.

Adaptable Design

Gu et al (2004) introduce the concept of Adaptable Design as a guiding philosophy for product development, identifying that adaptations of a product design in the future may be necessary. These adaptations fall into two categories:

1. Foreseeable extensions of utility, such as upgrading of software to run an engine management system on a car, and

2. Unforeseeable improvements, for example a new engine type because of a new emerging technology.

In order to achieve this adaptability Gu highlights functional independence as described by Suh as being critical, i.e. the vehicle is designed in such a way that a new engine could be fitted in place of the existing one with standard connections and without having to consequently replace other aspects of the vehicle. This could be a retro-fit to an existing vehicle or it could be a modification to new versions of the vehicle, either way the knock-on effect should be minimised.

Additionally, Gu explicitly states that the underlying principle of segregated architecture (modular design) is to prevent changes in some part of the product from propagating to the rest of it. In this way both Axiomatic and Adaptable Design principles can contribute to the agility of product development by minimising the propagation of iterations in the design process that have been identified as necessary for an optimal solution.

Dynamic Product Development

Ottosson (2004) proposes Dynamic Product Development (DPD) as a successor to both Integrated Product Development and Concurrent Engineering. It is suggested that the objectives and methods of IPD are sound, however they focus on adaptive design (re-engineering) which stifles the opportunity for new ideas and solutions.

Additionally, DPD places less emphasis on in-depth planning at the beginning of the project and relies more on dynamic planning in many short bursts as the project is carried out. The project team is structured with a Concept Group carrying out the initial conceptual design and thereafter acting as the steering group for the project. The Project Manager is a member of the Concept Group. The Concept Group liaise regularly with the satellite Development Teams who are responsible for carrying out the more detailed design work. The Development Teams can be from multiple organisations and communication is crucial between the Concept Group and the Development Teams in order to successfully achieve the dynamic project management.

One of the arguments against significant detailed planning at the early stages is that this is used to "fix" the concept and requirements which cannot then be easily changed as the project unfolds. In a turbulent environment Dynamic Product Development allows for a more flexible planning process to respond to changes in the product requirements.

2.1.5. Design Summary

It is evident from the literature on Engineering Design that a common systematic process has emerged. The process is defined by different authors in a number of ways, each adding or emphasising a different aspect, however core elements are evident: a solid definition of the problem and the requirements for the solution; some conceptual design during which many ideas are generated; an embodiment of those concepts during which time ideas are combined, embellished and rejected until a feasible solution emerges; and a detailed design stage during which the materials, production techniques and exact design are defined.

A prominent characteristic of Engineering Design is the iterative nature of the process which is recognised by any study of the topic. Tools have been proposed for reducing the number of iterations or reducing their impact on the overall product development time. Decomposing the design into a series of smaller independent modules is seen as important in reducing the impact of iterations caused by requirements changes or changes to other aspects of the design.

The predominant themes from Concurrent Engineering, Integrated Product Development, Axiomatic and Adaptable design are the use of cross-functional teams and modular designs. Cross-functional teams reduce the rework associated with preventable problems further down the product development timeline and modularity, as explained previously, limits the propagation of design iterations.

Dynamic Product Development advocates minimal in-depth planning in the early stages to allow the project to unfold in a dynamic manner with regular short bursts of planning. This model requires a well informed project manager leading both a Concept group and a Development Team with whom good communication is essential.

DFMA advocates the use of cross-functional teams as found in Concurrent Engineering and other techniques to reduce design iteration. Additionally, DFMA aims to reduce part count which may reduce the influence of the external environment by reducing suppliers and therefore susceptibility to change. However the adoption of custom and bespoke parts and tooling to reduce part count and assembly time could lead to vulnerability in a turbulent market if the supplier fails, where as using standard parts available from many suppliers may increase robustness to the external conditions.

To summarise, the emerging themes are modularity in design, cross-functional teams from one or more organisations, some level of technological integration between teams to facilitate good communications, and dynamic, fluid project planning.

2.2. Collaboration

Collaboration between multiple companies or divisions within a company has been emerging for many years. Nagalingam and Lin (1999) state that "Today's competitive and agility requirements of the global market can be only met by virtual enterprises". The term virtual enterprise (VE) can be taken to mean companies operating together at the same level; however Morden (2007) asserts that as much as 70% of the value of a product is added by companies other than the final assembler. This suggests a high level of collaboration between suppliers/customers in getting products to market, as well as same-level partnerships. Empirical evidence would suggest this to be the case (Copeland, 2007), particularly in sectors such as automotive where much of the design and sub-assembly work is done by partner companies who then supply the final assembler.

2.2.1. Collaborative Methods

Concurrent Engineering as described in the previous section (Section 2.1.4) is one approach to collaboration, albeit typically between divisions within a single company. This approach is also described by cross-functional teams whereby people may have a departmental hierarchy but also report to a project leader in a cross-functional project.

Collaboration can also be described by geographically distributed teams where members of the same department can be spread across a country, continent or globally.

This is particularly true of global companies such as aerospace and automotive companies where expertise between design offices around the world is combined on new projects.

However it is collaboration between multiple companies which has attracted most focus in recent years. The need for collaboration and the formation of virtual enterprises can take different forms depending on the circumstances. Martinez et al. (2001) propose 3 types of VE:

- **Short-term VE** – is set up to respond to a specific market need. The project can usually be split into a series of linked modules for each partner to take on. A Product Data Management system (PDM) is sufficient for data sharing. The VE disbands on completion of the project.
- **Extended Enterprise** – is a development of the supply chain or supply network, commonly seen in the automotive industry, whereby a large number of suppliers work on numerous projects with a customer over a more sustained period of time. The Extended Enterprise usually requires a higher degree of commonality between systems for effective collaboration.
- **Consortium VE** – is a set of companies collaborating to obtain work, marketing a combination of their combined core competences. Nevertheless, competition remains within the VE and there is a high degree of internal flexibility for systems used.

Yusuf et al (1999) propose 3 levels of relationship between organisations as illustrated in Figure 2-5, leading to a virtual enterprise at level 3 with cooperation at both the organisational and operation levels.

One of the significant opportunities presented by collaboration is that of re-configuration. That is, the ability to reconfigure the overall capability, size and expertise of a business through strategic alliances with other complementary partners. As discussed in the next section (Section 2.3), this reconfiguration can facilitate agility because a partnership can re-configure in order to meet changing demands or respond to an event in the external environment (Browne et al 1995, Goldman et al 1995, Wortmann et al 1997). Existing partners may be unable to satisfy new requirements and new partners may be brought in with the necessary expertise or resources.

Additionally, Yusuf et al. (1999) state that Small and Medium sized Enterprises (SMEs) are uniquely placed to capitalise on agile principles by forming dynamic partnerships in response to changing markets, to develop products that none of the individual partners could produce alone.

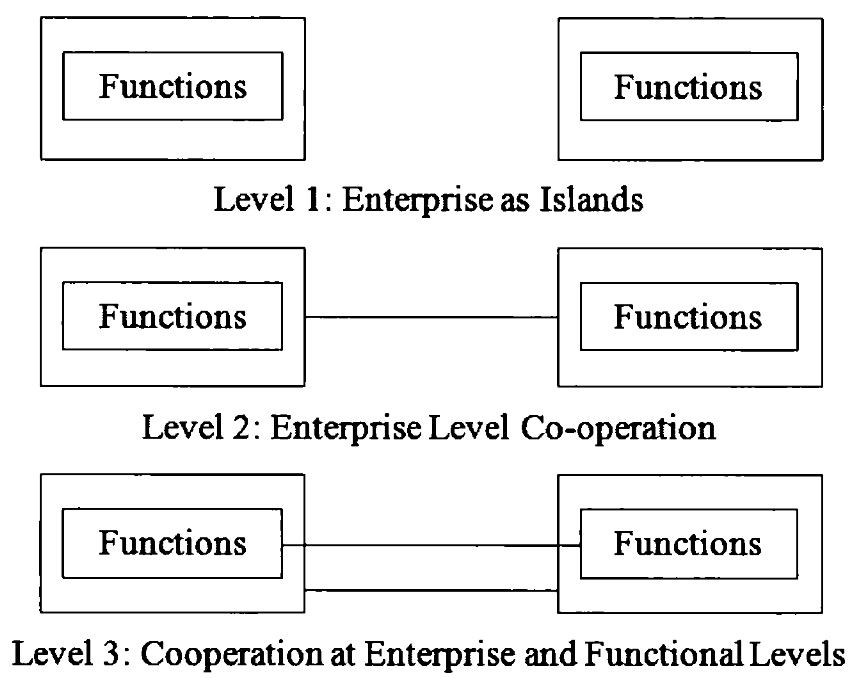

Figure 2-5. Partnership Development Model (Yusuf et al. 1999)

2.2.2. Inter-operability

An area of particular attention in collaboration research remains the sharing of data between partners, specifically the use of Information and Communication Technology (ICT) tools for sharing project related data. The main emphasis of the research lies with the inter-operability between platforms, that is: ensuring that companies using different internal systems for their design and other business operations can exchange data seamlessly between the two (Goranson, 2003; Kovács and Paganelli, 2003; Lubell et al, 2004).

There have been numerous projects investigating this area, from independent cases to Europe-wide research programs which have attracted large amounts of funding. The iViP (Integrated Virtual Product Creation) project (Krauser et al 2002) succeeded in creating a single software environment for virtual product creation through the use of "wrappers" to translate data as it exited and entered different legacy systems used by the partners of the Virtual Enterprise. PRODNET (Camarinha-Matos et al 2001) is an example of workflow interoperability, allowing multiple partners to access, modify and control the workflow of a project through their own legacy systems and a multi-layer processing co-ordination mechanism which allows each system to communicate with the others.

However, despite the apparent success of such projects as those described above and more, there exist many barriers to inter-operability of legacy systems for successful communication within a virtual enterprise. In recent years there has been a consolidation of software companies encroaching into each other's territory. CAD vendors have developed PDM systems which interface directly with the CAD software, such as PDMWorks for SolidWorks, in the hope that this will force their suppliers and partners to use the same CAD system to share data. Similarly, traditional PDM and ERP vendors such as PTC and SAP are spreading into other areas of business software such as PDM, Customer Relationship Management (CRM) and even CAD through acquisitions.

The use of translators (wrappers) for converting data either into one of the legacy formats or an independent standard also has its problems, not least the number of translators required increases as the square of the number of systems. For example ten partners, each with their own PDM systems, would require in the region of $10^2 = 100$ translators to communicate between each of them. Furthermore, any upgrade to a legacy system may cause the translators to fail and therefore a re-write to be undertaken. This approach has been defined as a "tool-centred approach" to the design process (Panchal and Schaefer, 2007) because it has the objective of enhancing collaboration through the ability to share data electronically between a set of heterogeneous stakeholders' IT systems.

One solution to this problem is for all companies within the VE to use the same PDM system, which has clear benefits because the inter-operability issue is removed. This was the subject of a trial by the Global Digital Enterprise Research Laboratory (GDERL) of Durham (UK) and Oregon State (USA) Universities (Arnold et al 2004) who carried out a re-design project using the SmarTeam PDM system from Dassault Système. The project concluded that although there were significant benefits for file-sharing to this approach, there still remain problems of inter-operability between the other software systems. For example the CAD files which were shared using this common PDM system were still not compatible with both CAD packages used by the partners. Therefore data-sharing was improved but the data was still not useable by all parties. The experiment also identified that although the common PDM system improved file-sharing between partners, this was only because both partners had installed the same software on all machines. Sharing with an additional partner in the future would require them to follow the same installation process.

An alternative method is an independent web-based system (Liu and Xu, 2001) such as 4Projects, Windchill, ENOVIA and others. In the case of 4Projects the cost is covered by the project co-ordinator who can then have as many users as required. In this way all members of the project can share data securely without the need for any local client-side software, and without any cost to the individual partners. This has particular benefits when working with smaller partners who have the necessary expertise but perhaps not the budget for expensive software licenses. This web-based approach is further supported by the Web Computer Supported Cooperative Work utilising the independent VRML format (Eynard et al, 2005) which concludes that an asynchronous web-based system can significantly improve project management and sharing of information between partners.

2.2.3. International Standards and Data Formats

There exist many different international standards world-wide, from those widely accepted such as the units of time, to those for which there are multiple and often controversial different standards. Even measurement "standards" such as metric and imperial units of length have been known to cause confusion and in some well-known cases catastrophic failure of projects because it was not clear to which "standard" the project partners were working.

Lubell et al (2004) define three types of standards relevant to successful collaboration between companies in a virtual enterprise:

- **Open Standards** – an agreement between stake holders in an industry group to facilitate collaboration. Open Standards are merely specifications for how data should be represented; STEP (ISO 10303) is an example of an open standard developed by the industry group International Organisation for Standardisation (ISO).
- **Industry Standards** – are technologies which are common but are not managed by a user group, but rather by a company or group of companies. Java is an example of an industry standard.
- **De Facto Standards** – are in wide use because of their association with other technologies or their unique value, for example Microsoft Excel file format is a *de facto* standard for electronic spreadsheets files.

In addition to standards of units, there are also independent file formats for digital data, such as the ISO 10303 (STEP) format for CAD models. Although the major CAD vendors all support exporting models in this or other independent file formats, empirical evidence suggests that it is not the norm to store files in this way, but rather using the native file formats of the particular software. The same is true of *de facto* standard software programs such as Microsoft Office products, where an assumption is made that recipients can access the software specific files.

2.2.4. Identifying Partners

As introduced in Section 2.2.1, the ability to create dynamic virtual enterprises by assembling a complete set of competencies allows companies to target new markets and adapt to changes in their external environment. One of the critical activities in this process is the identification and selection of the correct business partners (Vernadat, 1999; Camarinha-Matos et al, 2003). There are many processes for identifying partners with not only suitable competencies, but also track records of collaboration, experience in particular fields and so on. These include the use of Internal Supplier Directories of existing or previous partners; External directories – both publicly available and subscription based services and directories listing the members of clusters – i.e. those who have signed up to a scheme for potential collaboration.

Each method has its benefits: - for example internal directories are more likely to include past experiences of dealing with companies, where as external directories will have a broader range and higher number of companies from which to select. Cluster directories are likely to contain details of companies who have a similar attitude to collaboration which can be helpful. Camarinha-Matos et al. (2003) propose a "breeding ground" structure for creating virtual enterprises whereby a diverse group of companies all working together over a sustained period of time to achieve inter-operability of systems so that in the event that a collaboration opportunity arises, the companies are well-placed to cooperate quickly.

Armoutis and Bal (2001) have developed a system of "competence profiling" whereby company profiles are entered into a web-based database in a common format through the use of a self-administered questionnaire. This covers not only company competence or capability such as machines, facilities, resources, but also people and their individual skills and expertise. This is an important element of competence searching as Prahalad and Hamel (1990) state: "people are the competence carriers". The profiles are normalised and validated by experts before becoming searchable through a web-based clustering tool. The search tool allows multiple competence requirements to be entered in a single search, along with further criteria based on location, experience, size etc. The competence profiling system then returns a recommended cluster based on its search of the profiles in the database. This methodology has clear advantages in that it can quickly recommend entire clusters for an initial consultation, along with alternatives. However the system is limited by the profiles in the database, which is normally restricted to the members of an overseeing organisation such as a trade organisation, cluster administrator or prime contractor. A further concern is the reliability of the data in the database which can become out-of-date if not properly maintained by individual companies.

2.2.5. Collaboration Summary

Collaboration is increasingly common as companies strive to focus on their core competencies and build strategic partnerships to complete their requirements for a particular project. Steps have been made towards an asynchronous collaboration environment without barriers, where product and project data can be shared seamlessly between partners. However, the research presented here suggests that difficulties still exist, particularly in the use of software independent standards and web-based PDM systems which may have a bearing on the agility levels of collaborative projects.

In terms of partner identification the structure of the virtual enterprise has a bearing on the methods available for finding suitable partners, due to the alignment or non-alignment of technologies such as communication systems. It can be argued that a scenario where companies can form partnerships with any other enables a higher level of agility than scenarios where companies are restricted to partnering only with other companies who have previously adopted complementary communications processes.

2.3. Agility

The term agility was first coined at the Iacocca Institute of Lehigh University in 1991, following a large scale study into the future of the manufacturing industry and ways in which the West could compete with Japan and emerging Eastern economies. Kidd (1994) suggested that in the future the market will face demand for higher product variety and lower production runs. Since then there have been many varying definitions of agility. Van Oosterhout et al. (2006) have compiled the following definitions as representing the broad range of interpretations of agility: (Note that words in italic indicate frequently used terms and will be explained at the end of the definitions)

- "Agility is the ability to thrive in a competitive *environment* of *continuous* and unanticipated *change* and to respond quickly to rapidly *changing*, fragmenting global markets that are served by networked competitors with routine access to a worldwide production system and are driven by demand for *high-quality*, high-performance, low-cost, customer-configured products and services." Goldman et al., 1995.

- "Agility is primarily concerned with the ability of enterprises to cope with unexpected *changes*, to survive unprecedented threats from the business *environment*, and to take advantage of *changes* as opportunities." Zhang & Sharifi, 2000.
- "The ability of an organisation to thrive in a *continuously changing*, unpredictable business *environment*." Dove, 2001.
- "The ability of an enterprise to develop and exploit its inter- and intra-organisational capabilities." Hooper et al., 2001.
- "Agility is the successful exploration of competitive bases (Speed, flexibility, innovation, *pro-activity*, quality, and profitability) through the integration of reconfigurable resources, and best practices, in a knowledge-rich *environment* to provide customer-driven products and services in a fast-changing market *environment*." Ramasesh et al., 2001.
- "Agility is the *continual* readiness of an entity to rapidly or inherently, *proactively* or reactively, embrace *change*, through *high quality*, simplistic, economical components and relationships with its *environment*." Conboy & Fitzgerald, 2004.

An analysis of these definitions shows that the words occurring more than once are:

- change/changing (6)
- environment (6)
- continuous(ly) (3)
- pro-active/proactively (2)
- high-quality (2)

Combining other similar terms suggests that the following themes are also important in defining agility:

- Unpredictable/unanticipated/unexpected
- React/respond/develop/thrive
- Global/Worldwide/networked
- Customer-configured/customer-driven

From this study of multiple definitions of agility it is possible to suggest that agility is the ability to respond to a continuously changing and unpredictable global environment in order to produce high quality customer-focussed products or services.

2.3.1. Agility in Different Disciplines

It has been identified that agility is a necessary attribute of any successful company in the modern climate, and that "collaboration" can be a contributor to a certain level of agility through dynamic reconfigurable virtual enterprises. However, until recently the goal of achieving agility has been focussed on manufacturing companies. This is at the overall organisational level (Sharifi and Zhang, 1999; Ismail et al 2007) or the individual agility of factory configuration, machine versatility (Lee, 1998; Mears and Kurfess. 2005) and material handling techniques (Hong et al., 1996; Newman et al., 2000).

There have been many methodologies developed for increasing agility at both ends of this spectrum. Jin-Hai et al (2003) have compiled a comprehensive review of the evolution of agile manufacturing and propose Real Agile Manufacturing (RAM) as a synthesis of the existing techniques to achieve agility whereby there are multiple beneficiaries (manufacturers, suppliers and customers). This is achieved through integration of departments, organisations, resources and technologies; appropriate use of IT; and a focus on core competences.

Addressing the implementation of an agile philosophy or strategy for agility into organisations at the micro and macro scales, Sharifi & Zhang (2001), Arokiam et al. (2005) and Ivanov and Ilieva (2005) have all conducted research in this field. Sharifi and Zhang conclude that it is possible to enhance agility through analysing the agility drivers in a particular business which drives the need for agility, and the capabilities required to satisfy those drivers. A plan is then formulated for plugging this "agility gap" through agility providers which develop the necessary capabilities. They conclude that it is important to recognise the individuality of market sectors and the different needs of each business in becoming "agile".

However, the area of agility applied to the design process is relatively unexplored (Panchal et al. 2007), particularly in the collaborative environment of virtual enterprises and when dealing with Small and Medium sized Enterprises (SMEs). Reich et al (1999) have explored the implementation of an Agile Design Information System (ADIS). ADIS is an information system which can be used to link design teams in a virtual enterprise for successful collaboration, while recognising the need for future flexibility and integration of existing management practices and legacy tools. N-dim is the tool which Reich et al have developed for this purpose. It is a collaboration tool which acts like a PDM system for software development projects, allowing partners with the necessary privileges access to a complete project history including the ability to view "published" models and create copies of them for new projects.

Independent of the attempts in traditional engineering fields to increase organisational and manufacturing agility, the software development community also identified agility as a critical success factor. The "Manifesto for Agile Software Development" (The Agile Alliance, 2001) devised four principles which appeared to contradict software development best-practise, but which enabled a more agile methodology. Specifically, in the software development environment, the Agile Manifesto favours individuals and personal interaction over processes and tools. This is demonstrated by the desire to have developers working in the same place and communicating in an almost continuous dialogue face-to-face rather than through electronic media. Secondly, working software is valued over comprehensive documentation. The suggestion is not that comprehensive documentation is not required, but that it is more important to deliver working software regularly for customer testing, rather than labour on comprehensive documentation as is done traditionally, when the software may change. Thirdly, rather than complex contract negotiation, the Agile Manifesto places greater value on customer collaboration. This means extending the development team to involve the customer throughout the development rather than spending time defining a detailed specification. In this way the customer can directly influence the development as they require in the face of their own changing needs. Finally, responding to change is more important than following a plan. This continues from the previous point to suggest that delivering the right software to the customer and embracing changes as they occur is more agile than following a rigid plan set out at the beginning of the project and then reworking the solution at the end.

Although developed for the software development community, there are clear similarities between these principles and some strategies adopted in the manufacturing sector, in particular the customer collaboration.

2.3.2. Agility Measures

Zhang and Sharifi (2000) propose a method for identifying the "current agility level" which is based on the "agility need level". A review of the agility needs of the company is carried out by analysing the business and its operating environment, broken down into seven key areas:

1. **Marketplace** - Structure, Demand, Saturation, Fragmentation
2. **Competition** - Competitors responsiveness, Competition environment
3. **Customer Requirements** - Expectations, Priorities (Quality, Cost, Delivery), Desire
4. **Technology** - Technology Change, Introduction of new technology
5. **Social Factors** - Environmental/Legislative/Governmental pressures
6. **Complexity of External Conditions (Supplier Problems)** - Relation with and Reliability/Responsiveness of suppliers
7. **Internal Complexity of the Company** - Number of Products, Complexity of Products, Design and Manufacturing Process Complexity

Each of these areas has sub-themes in which specific questions are asked through the use of a self-administered questionnaire. Each question is answered with a turbulence score from 1 to 10 with 10 indicating the most turbulent environment. The average score of all factors represents the agility needs of the company. A similar study is carried out to determine the agility providers in use by the company, which studies have shown to contribute to agility in the areas identified as turbulent in the first analysis. These providers will be specific to the company or market sector based on the responses to the initial agility needs level assessment. A high level of adoption of the required agility providers indicates a high level of agility.

Yusuf et al (1999) have undertaken a review of the attributes suggested as defining agility, and in doing so propose a similar method for measuring agility levels by summarising 32 key attributes in 10 decision domains for an agile manufacturing enterprise (Table 2-1). A company which has these attributes is said to be agile.

Ren et al (2001) summarise six agility attributes which have evolved in the literature since the mid 1960s, from four competitive bases (Speed, Cost, Quality and Flexibility) to include Pro-activity and Innovation as the agility concept has become more prevalent. Ren et al suggest that it may not be possible to achieve all of these characteristics to the full extent, but rather companies must decide on their priorities.

Both Yusuf et al and Ren et al differ from the approach of Zhang and Sharifi in that they suggest the adoption of the respective capabilities leads to agility irrespective of the market sector; Zhang and Sharifi suggest that the agility level is determined by adoption of only the capabilities relevant for that business as determined by a previous "agility needs" analysis.

An alternative method of agility measurement is a more quantitative approach, rather than attainment of a set of qualitative attributes. Kumar and Motwani (1995) propose a methodology for assessing time-based competitive advantage, but again through the use of a self-assessed survey. Giachetti et al. (2001) use the measurement of structural properties of the business rather than operational properties for assessing agility, i.e. the information and material flows, organisational relationships and communication networks instead of batch sizes, change-over time, etc. Arteta and Giachetti (2004) propose the assessment of a firm's complexity is directly related to its agility, and that backward looking assessments (in terms of time) do not suggest how a company may behave in the future to further unpredictable events.

Ramasesh et al. (2001) suggest a quantitative framework to explore the value of agility in financial terms, the Net Present Value of all relevant cash flows being the measure of agility. Another quantitative approach is that of Yauch (2005), defining the measure of agility as the ability to succeed in a turbulent environment. The agility score is derived from organisational success (financial performance from public data) and the level of environmental turbulence for that market sector (determined by experts).

Table 2-1. The Attributes of an Agile Organisation (Yusuf et al. 1999)

Decision Domain	Attribute
Integration	Concurrent execution of activities
	Enterprise integration
	Information accessible to employees
Competence	Multi-venturing capabilities
	Developed business practice difficult to copy
Team Building	Empowered individuals working in teams
	Cross functional teams
	Teams across company borders
	Decentralised decision making
Technology	Technology awareness
	Leadership in the use of current technology
	Skill and knowledge enhancing technologies
	Flexible production technology
Quality	Quality over product life
	Products with substantial value-addition
	First-time right design
	Short development cycle-times
Change	Continuous improvement
	Culture of change
Partnership	Rapid partnership formation
	Strategic relationship with customers
	Close relationship with suppliers
	Trust-based relationship with customers/suppliers
Market	New product introduction
	Customer-driven innovations
	Customer satisfaction
	Response to changing market requirements
Education	Learning organisation
	Multi-skilled and flexible people
	Workforce skill upgrade
	Continuous training and development
Welfare	Employee satisfaction

Youssef (1994) argues that agility "should not be equated just with speed of doing things, for it goes far beyond speed", however, Ren et al (2001), in ranking the effect of agile attributes on competitive priorities rank Speed as the most important, followed by: Pro-activity; Flexibility; Cost; Quality and Innovation. The descriptions of agility summarised earlier in this chapter highlighted speed as a factor, but focussed on other terms such as change and pro-activity rather than simply speed, suggesting that speed is relevant, but not paramount in striving for agility.

Lomas et al. (2006) present the Key Agility Index (KAI), which uses expert interview or a questionnaire to obtain coarse timing data relating to a particular project. This level of coarse data is usually readily available through access to the correct staff, overcoming any concerns regarding the availability/reliability of more detailed data. It also allows a more useful measure for individual companies at an operational level than the use of global, publicly available data for entire organisations.

The KAI is defined as the ratio of the time taken to complete change related tasks to the time taken to complete the whole project. This provides a measure of the proportion of project time spent completing change related tasks, i.e. responding to Unexpected External Events (UEEs). Specifically, reducing the time-response to UEEs results in a lower KAI score. For example, a project which is intended to be completed in 12 weeks actually takes 16 weeks because of additional work caused by a new material the client would like included in the design. The 4 weeks are taken up researching the new material, sourcing expert assistance and revisiting other aspects of the design work which have also been affected by the inclusion of the new material. The KAI is calculated as 4 (the additional time spent) divided by 16 (the eventual project time) which gives a KAI of 0.25. If the company learns from this experience and next time puts in place steps to improve their agility, then a similar project expected to take 12 weeks may suffer the same event again, but the delay only causes 3 weeks of delay instead of 4, resulting in a KAI of $3/15 = 0.2 < 0.25$, an improvement of 0.05.

Calculating the KAI using a ratio allows a direct comparison between projects within a company and between companies in a similar sector. This ability to assess agility at the project level represents a deviation from the previously discussed approaches to agility metrics as it does not rely on a set of company-wide characteristics. Furthermore, the level of coarse timing data required for the analysis does not require in-depth analysis of the company environment, long-term goals or successes, but rather requires just a single interview with the correct member of staff. The appropriate member of staff can be easily identified through an organisation chart of the project to identify somebody with the necessary overview and knowledge of the project in its entirety. Consequently the KAI is a readily deployable metric which can also be used across the total Product Development Cycle, or for specific stages of the process to assess agility within the manufacturing stage or design stage.

A further benefit of the KAI over other approaches to measuring agility, is the quantitative value for comparison to other projects, rather than analysing the presence of a set of characteristics within an organisation which is more difficult to quantify. Also, the ability to easily compare projects of different types, departments or even organisations is a benefit, although different levels should be expected for different sectors due to their inherent level of turbulence. For example, it is unlikely a company in a very turbulent market could achieve a KAI score of zero because of the inherent turbulence, some time has to be spent responding to that turbulence, no matter how well managed that process is. However companies operating in a very stable environment may appear to be very agile because a lack of turbulence allows for a very low KAI score. This represents a potential flaw in comparisons made using this measure, which can be rectified by ensuring comparisons are made between projects, companies or departments with similar environmental turbulence.

2.3.3. Agile vs Lean

"Lean" as a production technique, although later applied to many other business processes, has its origins in Japan, specifically at the Toyota automotive plant in the 1940s and 1950s. The Lean philosophy is based on the identification of the value stream through a process whereby value is added to the product. Lean aims to eliminate or minimise all activities which do not contribute to this value-adding process, which are known as "waste" activities. Many tools have been developed to help with implementing Lean principles including value stream mapping to identify the value-adding processes, through to Single Minute Exchange of Die (SMED) which is a technique for reducing the changeover time of any production process to less than ten minutes (the term 'Die' originating from the original automotive press shops where different vehicle panels were made on the same press).

Agility has been seen as a successor to Lean, however comparisons between the two which outline the differences and similarities are scarce. From the definitions of agility noted in the previous section (Section 2.3) there appears to be a discrepancy between the application of lean principles and the environment in which agility is required. Specifically, agility is the ability of an organisation to thrive in a turbulent, constantly changing and unpredictable, global environment. While Lean principles support this to an extent through the reduction of wasteful processes, Lean thrives when the environment is changing but predictable, i.e. changing within known parameters.

For example, SMED as described earlier allows the rapid changing from one setup to another on the value stream, such as changing dies in a press shop. However on closer inspection of the SMED process it requires a prior knowledge of the forthcoming setup in order to carry out some aspects of the changeover "off-line", or, before the process is stopped. Therefore, SMED is only of most benefit when the change is between two known states with sufficient warning. Agility is the ability of an organisation to configure itself to react when the changes are unexpected and the subsequent state is unknown.

Theory of Constraints (ToC) (Goldratt, 1999) is also a modern business technique with its origins in production but applicable to all business processes. The principles underlying ToC propose that in order to maximise efficiency it is necessary to identify bottlenecks in the process and subordinate all other processes to ensuring that the bottleneck operates at maximum throughput. This is in contrast to Lean where the objective is to reduce waste at every opportunity, not just at the bottleneck process.

The link with Agility is that ToC states that as long as the bottleneck is operating at maximum capacity, then spare capacity is acceptable and having resources underused is better than using that resource to over-produce. Over production risks creating Work in Progress (WiP) which is essentially revenue tied up in stock, and also reduces efficiency if the WiP is never needed. Cockburn (2005) suggests that in an agile system this spare resource, be it human or otherwise, which is not situated at a bottleneck, can be used to increase agility. Cockburn proposes that efficiency is a "spendable" resource and that by using spare capacity and reducing efficiency it may be possible to plan or produce for unexpected events and therefore increase agility.

Matthews et al (2006) have explored this idea in greater detail, developing a simulation of a design project. The project was configured with two tasks in series on a critical path. The second task cannot be started until the outcome of the first is known. Instead of waiting for task 1 to complete, the spare capacity of the task 2 designers who are assumed to be idle and therefore spare, begin work on a number of different potential designs based on a statistical distribution placed on the potential outcomes of task 1. It has been successfully demonstrated that by spending efficiency and utilising this spare capacity in the design process, in this case human designers, the agility can be increased at the cost of the efficiency decreasing.

This scenario can be likened to the knowledge that a change in legislation is expected with regard to fuel emissions from petrol cars. Although the timing and outcome of the decision may be unknown, there are certain parameters within which the decision is likely to fall. Based on this automotive companies may consider multiple options while designing new vehicles. The company knows that some design effort may go wasted but their response to the eventual decision, and therefore their time to market with a vehicle meeting the new legislation, will be reduced. This provides a competitive advantage over their competitors.

In summary, although Lean has potential benefits for the agility of an organisation through waste reduction and identifying value-adding activities, taken to the extreme and eliminating all waste from a process may result in reduced agility as some waste can be beneficial in reacting to unexpected changes in the environment. Theory of Constraints allows "waste" in the system as long as the bottleneck is always operating at full capacity. This spare capacity created by idle resources can be used in the way described by Matthews et al (2006) to increase agility through working on alternatives created by turbulence in the environment.

2.3.4. Agility Summary

This section has introduced many definitions of agility which has been a manufacturing philosophy since the early 1990s. Despite the variations in definitions there are certain themes which are common throughout, and from this a working definition of agility has been defined for this research: the ability to respond to a continuously changing and unpredictable global environment in order to produce high quality customer-focussed products or services. Although agility has predominantly been researched at the manufacturing stage, it has also shown benefits when applied across whole organisations and across a range of industrial sectors other than manufacturing. Agility in other disciplines has been discussed, in particular the approach of Reich et al with the *n-dim* system for Agile Design. While the *n-dim* approach has been shown to benefit agility in the design process, this software solution is limited in its scope and may benefit from being supplemented by some of the other approaches identified by other authors. Additionally, agility in software development is well researched by a collection of authors who place greater importance on software that works rather than a well documented solution which takes longer and is less flexible in its development.

There exist a range of methods for measuring agility which require varying degrees of detail and provide a measure for agility at different levels from organisation to individual project level.

Finally, agility was compared to Lean and Theory of Constraints as the other dominant manufacturing philosophies. The similarities and differences were discussed in order to show the way in which they differ with regard to their priorities and therefore approaches.

2.4. Summary

This chapter has summarised the literature surrounding the three main areas for this research: Design; Collaboration; and Agility. From this review characteristics of an agile system were identified, and aspects of existing collaboration and design research which have the potential to assist in achieving those agile characteristics in a collaborative design environment were also identified.

The common aspects of the design process have been identified, particularly the importance of a systematic approach with emphasis on the early stages. Common aspects of the traditional and more recent design philosophies were identified as cross-functional teams and modular designs/de-coupled tasks which have the agile characteristic of reducing iterations and propagation of change in the design process.

Collaboration is becoming increasingly common as companies strive to focus on their own core competences and build partnerships with other complementary companies for larger projects, becoming a virtual enterprise. Different formats of virtual enterprise were discussed which involve different levels of integration. This integration of the companies has been identified as a potential barrier to success, particularly when integrating IT systems for data sharing. The extent to which IT systems should be integrated can be related to the type of virtual enterprise adopted; however the literature has shown that some level of integration is desirable at any level of collaboration. Multiple projects dedicated to addressing the barriers to this integration in collaboration were presented and from them key characteristics were identified: specifically the use of common standards and formats for the interchange of data between partners.

Different approaches to project management in multi-company/multi-department teams were discussed, with Dynamic Product Development having particularly agile characteristics through the use of short regular planning meetings and a flexible cross-functional management team. This allows for changes in the project to be integrated easily rather than fixing the project too specifically at the outset.

The success of a virtual enterprise can also be linked to the ability to find appropriate companies for partnering both during initial setup and also as the project develops, and methods of achieving this were discussed. It is suggested that identifying the correct companies quickly can have a significant benefit on the agility of a collaborative project.

Finally agility has been introduced as a concept which follows on, chronologically at least, from Lean principles and the Theory of Constraints. A comparison of the objectives of each has been made, and specifically the contradictions in the objectives were highlighted as a result of the environment in which each concept thrives.

Characteristics of agile systems have been summarised from the literature as well as the sources of turbulence which require agile responses. The application of agility in different disciplines was discussed; particularly the little work that has been done in the field of Agile Design, and the lessons which can be taken from Agile Software Development.

In identifying agile characteristics and sources of turbulence the area of metrics for agility is relevant as existing metrics make use of both characteristics lists and relative environmental turbulence in assessing/measuring a company's turbulence. Contrary to this approach the Key Agility Index was introduced as an alternative technique for measuring agility levels at the more detailed project and departmental level rather than the company/organisation level.

From this literature review there have been common themes which have emerged as having a potential influence on agility at some level. While agile characteristics have been shown to be achievable through the use of these themes in certain aspects of the product development process, primarily manufacturing, there exists a gap in the knowledge whereby the existence of agile characteristics can be correlated to any of these themes in a collaborative design environment. The themes are summarised in Table 2-2 and will be central to the next stages of this research. The objectives of the next stages of this research are the achievement of agility in a collaborative design environment through the application of a specific framework which will be developed.

The next chapter will define the context of this research in more detail. The following chapters will develop the themes from this literature review into a framework which can be applied specifically in the collaborative design environment to improve agility. A methodology for testing this framework will be presented in Chapter 4, followed by the testing and refinement of the framework based on the findings of this and each subsequent experimental stage.

Table 2-2. Factors with a potential influence on agility in Engineering Design

Factor and Study	Authors in this field	Agile Characteristics
Product Planning • Systematic Design • Development Strategy Framework	Pahl & Beitz (1995) Wheelwright and Clark (1992)	Reduced impact of market developments such as new technologies
Modularity/De-coupled tasks • Axiomatic Design • Adaptable Design • Design for Manufacture/Assembly	Suh (2001) Gu et al (2004) Boothroyd et al (1994) Ulrich (1995)	Ease of incorporating design change Reduced number of iterations
Cross-Functional/Multi-Company Teams • Concurrent Engineering • IPD • Real Agile Manufacturing • Competence Profiling • iViP • PRODNET	Prasad (1997) Ottosson (2004) Jin-Hai et al (2003) Camarinha-Matos et al (2003) Armoutis and Bal (2001) Krauser (2002)	Reduced development time Reduced number of iterations Dynamic partnerships Increased Quality Responsiveness
Integrated/Aligned Technology • IPD • Real Agile Manufacturing • PRODNET • iViP • GDERL • n-dim	Ottosson (2004) Jin-Hai (2003) Camarinha-Matos et al (2001) Krauser et al (2002) Arnold et al (2004) Eynard et al (2005) Reich et al (1999) Liu et al (2001)	Effective communication and data sharing between partners
Dynamic Planning Throughout the Project after Initial Setup • Dynamic Product Development • Agile Manifesto (agile software development)	Ottosson (2004) The Agile Alliance (2001)	To manage the cross-functional team without departmental/ company alliance
Common Standards and Terminology • International Standards • Common Terminology	Lubell et al (2004)	Robust communication

Chapter 3. Conceptual Framework

This chapter sets the context of the work by expanding on the "turbulent environment" concept as identified in the previous chapter, through the concept of Unexpected External Events (UEEs) and specifically the different forms and magnitudes of severity that UEEs can take. Some examples of UEEs are presented using empirical evidence gathered through multiple methods and from multiple engineering disciplines. The way in which the penalty or opportunity provided by a UEE is managed is discussed.

The literature introduced aspects of design and collaboration which share common aims or outcomes with agility research, providing evidence of where agile characteristics have been achieved through their application. The previous chapter also provided a review of the approaches to agility from different disciplines and the definitions of agility that have evolved (Section 2.3). This chapter examines these definitions more closely, and develops a working definition of agility for collaborative design. Furthermore, the metrics of agility identified in the literature will be analysed against a set of criteria for their applicability in this research context. Finally, the Key Agility Index (KAI) will be discussed as a suitable metric for this work.

The chapter concludes by proposing the hypothesis that, through the specific application of a set of tools and techniques identified in the literature, a more agile collaborative design process can be achieved. This implementation of tools and techniques is referred to as the Agile Design Framework.

3.1. Unexpected External Events

It has been well documented that the global market in which engineering companies must now compete is increasingly turbulent (Goldman et al, 1995; Prasad, 1996; Dove, 2001). Customer demand for new products with multiple variations and the latest technology are just two of many factors influencing the drive for shorter lead times and therefore product development processes. The objective of this section is to explore the concept of an Unexpected External Event as a defining feature of this turbulent market.

3.1.1. Sources of UEE

Wheelwright and Clarke as early as 1992 identified that a failure to anticipate new technologies in the relevant fields and integrate them into product planning would lead to companies losing their competitive advantage. However this makes the assumption that the emerging technology identified at the early planning stage will still be sufficiently new if implemented into the product design at that point in time. There may be cases where the rate of development of new technologies exceeds the development process of the product, particularly in fields such as defence and aerospace with long lead times and a heavy reliance on technology in the eventual solution. Where the new technology emerges during the latter design stages but offers significant benefits to the overall design, it may be necessary to interrupt the design process to integrate the new technology into a modified design. New communications and weaponry systems are good examples of this scenario. In this situation the design team may be required to integrate the new technology into the design with little notice and little expertise in the emerging technology.

However, new technologies are not the only external source of design changes. Yauch (2005) identified 13 sources of environmental turbulence faced by manufacturing plants, some of which are internal to the organisation and some of which are external (Table 3-1). A Multi-Attribute Utility Model was used to assign a weight to each factor, recognising that different factors exert a different influence on environmental turbulence.

Through the observations of a panel of experts, these 13 factors and their "weights" are used to score the companies in terms of how turbulent their environment is. This is then compared to "success" which is a combination of Gross Margin percentage and Inventory Turns to provide a measure of the agility of an organisation.

Table 3-1. Sources of Turbulence ordered by weight (Yauch, 2005)

Factor	Description	Weight
General Economy	Influence of both the domestic and international economy	.117
International Business	Relates to the influence of international suppliers and competitors	.098
Corporate Parent	Protection from 'the environment' offered by the Corporate parent such as shielding from economic fluctuations	.093
Competitive Pressure	Perceived pressure from major competitors	.090
Unions	Relates to the extent to which unions represent workers, the number of unions and the number of strikes which can all cause turbulence	.085
Stock Market	Relates simply to public or private ownership of the company	.083
Technology	A source of turbulence is the level of automation in the factory combined with the technical complexity of the product	.079
Government	Extent to which government legislation, standards and policy impact on a company, whether at the local, national or international level.	.074
Weather	Disruption to operations caused by weather phenomena	.060
Product Customisation	Requirement to customise products to respond to competitors' products	.059
Supplier Criticality	Impact of lead times and other influences of suppliers on the company	.059
Product Variety	Ability of a consumer to order a variation on a product	.058
Product Complexity	Measured by the number of supplier-provided components in the Bill of Materials	.045

Ramesesh et al (2001) categorises three domains of unanticipated change:

- Output related change: relating to unexpected changes in demand, emergence of new products and customers, disappearance of existing products and customers.
- Input-related change: emergence of a new raw material, loss of availability of existing raw material.
- Process-related change: emergence of a radically new process technology, imposition of radically new environmental regulations.

This 3-category approach distinguishes between internal and external factors but does not provide as comprehensive analysis of the environment as other earlier analyses. Sharifi and Zhang (1999) group external 'change factors' into the following headings:

- Marketplace: Including political changes; growing/shrinking markets; and rate of change of product models
- Competition: Changing markets; responsiveness of competitors; pressure on cost; reduced development time; and increased innovation
- Customer Requirements: Increased quality, variety and cost expectation; sudden changes in quantity and specification
- Technology: Improved production systems; hardware and software IT developments
- Social Factors: Workforce/workplace expectations; cultural and social problems; legal/political/environmental pressures

These five classifications of the sources of external turbulence fall into the domains identified by Ramesesh et al (2001) above. A combination of the additional external categories (such as Weather and General Economy) identified by Yauch (2005) provides a comprehensive list of sources of unexpected external factors influencing engineering design.

3.1.2. Effects of Unexpected External Events

In addition to the sources of UEEs as identified in the previous section, the impact of those unexpected events can vary greatly, presenting either a penalty or an opportunity.

Firstly, the impact may not necessarily be a time-delay. Indeed, in many cases a time-delay may not be acceptable as in many industries the financial cost of missing a completion date greatly outweighs the cost of increasing resources to compensate for the effects of the event.

Therefore the impact of a UEE can be:

- A time delay caused by knock-on effects on the critical path of the project. This leads to a violation of the completion date for the project.
- A resource penalty meaning that in order to respond to the event and still satisfy the completion date an increase in resources is required in order to manage any additional work.
- A quality penalty whereby the company, in order to satisfy the deadline, but perhaps without additional resources or funding available, will instead opt for a reduction in quality. The quality reduction can be realised in two different ways:
    - Through a reduction in the features included in a particular design. By removing these features the quality of the product in terms of its desirability to the customer may be reduced, however the cost and time penalty is minimised because of the reduction in workload. A side effect of this quality penalty is that reduced desirability can lead to reduced competitiveness in the marketplace, and so a balance must be struck by the project team, to both minimise the penalty and satisfy the design requirements as far as possible; or
    - Through the re-use of old designs instead of identifying novel and more suitable designs. This approach can save significant time but can produce sub-optimal solutions.

Which of these responses (or which combination of these responses) is realised in any given situation will be dependent on the companies involved and their own priorities for that particular project.

In addition to these three impacts, there also exists an opportunity for a UEE to have a positive impact on a project. This situation arises when an event means that less work is required to complete the design, such as a change in legislation making it feasible to adopt an easier solution than was previously possible. Although this is a genuine potential consequence of a UEE, the issues concerned with harnessing this impact and capitalising on it are different to the issues related to limiting the impact of negative events. Therefore, while acknowledging this possibility, the scope of this research shall remain with increasing agility in response to negative events in the manner described above.

In addition to the way in which companies respond, the magnitude of the effect of a UEE can also vary. Taking a collaborative design project as the basis of this analysis, it has been suggested (Lomas et al, 2006) that the magnitude of the UEE can be classified into 4 levels.

1. **Trivial** - the problem can be resolved completely at the local level; a small penalty is incurred.
2. **Minor** - the problem requires the collaborating partner to seek external assistance, or minor redeployment of part of the work to another partner within the virtual enterprise. The penalty is increased and the form of the penalty to be absorbed requires consideration (quality/cost/time).
3. **Major** - the problem cannot be resolved by the partner or other member of the virtual enterprise. A new member is needed to join the virtual enterprise, and the redeployment of work and initiation of the new member to the project causes a significant penalty.
4. **Fatal** - the problem cannot be resolved by the partner, and there exists no external potential partner that can provide support. Effectively, the design becomes fundamentally flawed and is not realisable.

For example a "Trivial" event in the detailing stage might only require the affected partner to restart this stage. The more serious "Minor" event might result in the partner returning to the embodiment stage while a "Major" event will result in a new partner starting this part of the design work from fresh. Another possibility in the "Minor"/"Major" cases is that several other design partners are affected, to the respective degrees of the event classification. Finally, in the case of a "Fatal" event, it is assumed that the whole design collapses due to the event. In this case the design requires fundamental rework and hence all partners will start from fresh, effectively under a new virtual enterprise.

3.1.3. Illustration

A simplified scenario of an aircraft design can be applied to demonstrate the effects of the scenarios discussed. For example, consider an aircraft manufacturer called AirCoach to be developing a new aircraft for the airline market in response to the changing shape of the air travel industry. AirCoach is responsible for managing the design of the aeroplane but does not possess the skills, resources or expertise in-house to complete the full aircraft design. Instead the aircraft is sub-divided into its constituent parts, many of which are then distributed to other partner companies to design and often manufacture. The benefit of this method is the ability to build alliances with different partners for each product line depending on the skills required, rather than having to develop and support all those skills internally.

In order to keep the illustration simple, it is decided that AirCoach will split the project into 5 sub-projects, namely: fuselage; wings; engines; electronic systems; and landing gear. For each module a partner company or team of companies is identified and brought into a virtual enterprise which will design the entire aircraft. The virtual enterprise comprises AirCoach and 5 partners. The virtual enterprise model allows the project partners to share information about the project, understand the influence a design change will have elsewhere, and allows AirCoach an overall view of the entire project. Additionally, some integrators (such as AirCoach in this case) use this model for setting common goals and allowing profit sharing rather than a more traditional Customer-Supplier relationship.

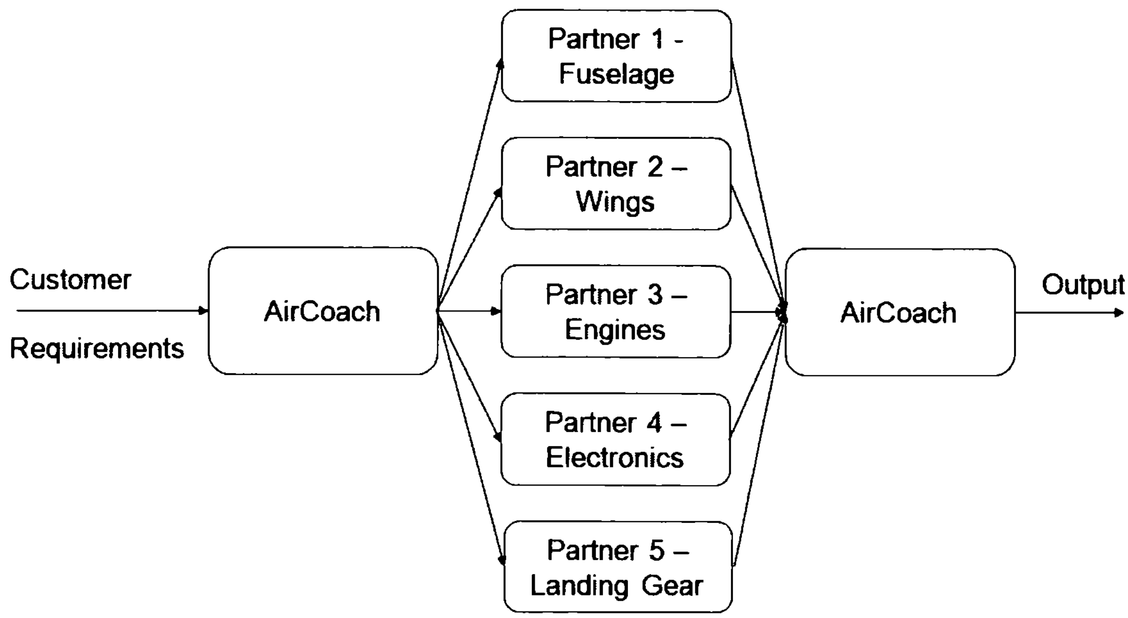

Figure 3-1. A Simplified Virtual Enterprise Process for Aircraft Design

This scenario can now be applied to illustrate the effects of each of the 4 classifications of external event. It should be considered that the expected time for each partner to complete its work is the same period, i.e. the critical chain is dictated by each partner equally, and a delay to any partner represents a delay to the overall time of the process.

Trivial event

An example of a trivial event is that during the product design process an external event occurs in the form of a requirements change from the customer. The fuselage is initially designed to have 3 emergency exits along each side in accordance with current guidelines. However due to a change in legislation the number of emergency exits required on a plane of this type rises to 4, meaning a change in design. Partner 1 is responsible for the fuselage design and must respond to the event appropriately.

The affect of this external event can be illustrated as reducing how close the partner is to achieving the necessary output, because the partner is now further from the desired solution than before the event. This loss of work is illustrated in Figure 3-2. The shape of the curve has been assumed for illustration purposes but represents the law of diminishing returns which governs typical project progress.

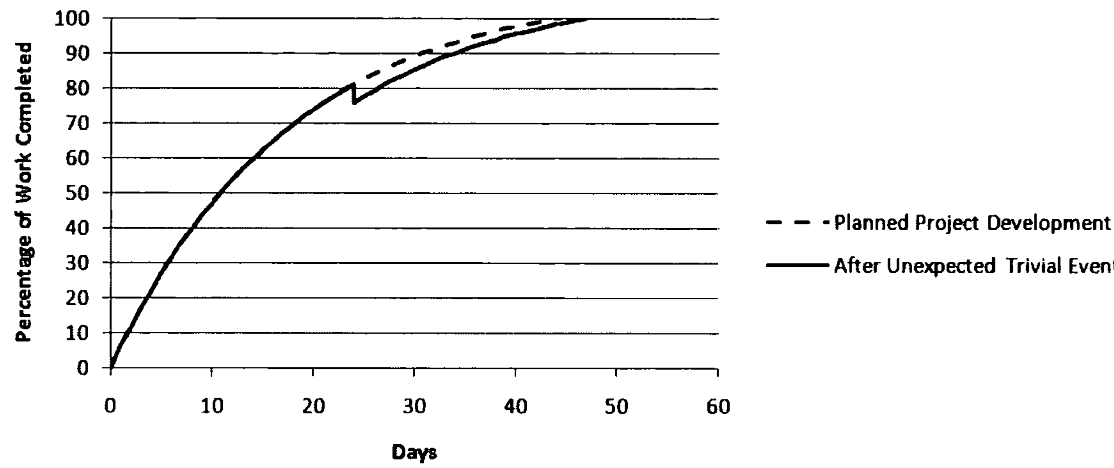

Figure 3-2. Effect of a Trivial UEE on the Progress of a Design

Figure 3-2 illustrates an external event at day 24 of a design process, with a magnitude of 5.5% of the work already carried out. The time taken for the partner to return to the position at which it was before the event is 3 days in this case. This is defined as the Time-Response to an external event. The amount of time the process should have taken without the external events is 44 days, however the total time is 47 days, in this example.

The event illustrated is classified as Trivial because it can be dealt with in-house, with a minimal time penalty. However this is not always the case. Empirical evidence suggests that events often require the use of additional resource, often of an expert nature, to resolve problems raised by unpredictable external events.

Minor event

Minor events describe events which dictate that the partners no longer have all the skills, resources or knowledge to develop an in-house solution, or that to do so would be more costly than the use of expert help. In this scenario the partner must rapidly identify a partner with the necessary skills, resources or knowledge to "plug the gap" created by the event. This is where the agility of the process will allow the response time to be reduced, and the benefits exploited.

Continuing the AirCoach illustration, a Minor event is represented by a new technology such as weight saving materials becoming mature enough for inclusion in the aircraft. The technologies will provide significant benefits but Partner 2 responsible for the wings and Partner 1 responsible for the fuselage do not have sufficient knowledge of the new weight saving materials to incorporate them without assistance.

In this case a new partner is integrated into the virtual enterprise to work with Partner 1 and Partner 2 and incorporate the new features into the design. Integration in this context includes identifying the suitable partner and integrating them into the project. This includes project history, the scope of their work and the collaboration procedures to be followed within the virtual enterprise. The success with which this can be done will be representative of the agility level of the virtual enterprise because the impact on the project is minimised.

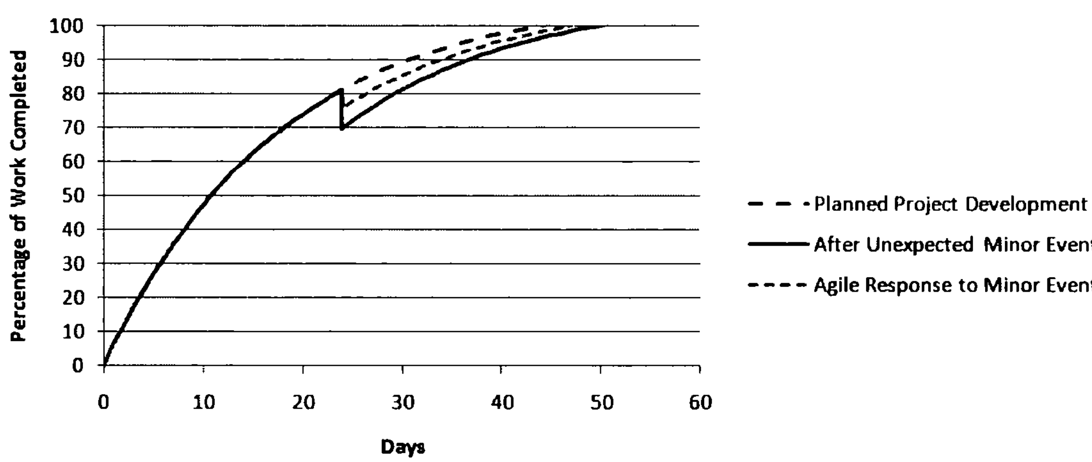

Figure 3-3. Effect of a Minor External Event and an Agile Response to that Event

Figure 3-3 illustrates the impact of a Minor event on the project after 24 days, causing a 6 day delay to the project which represents 11.5% of the completed work. A sample agile response is also shown in Figure 3-3 whereby the delay is minimised. In this example this could be achieved through successful and timely integration of a new partner into the project. Reducing the impact of the event by a half to 5.75% of work completed, would have a 3 day saving to the project compared to the unagile response.

Major event

A major event is defined by the failure of a partner to satisfy the demands put upon it by the greater organisation or system. This means that it cannot deliver the output assigned to it as part of the virtual enterprise and as such must be replaced.

In this illustration Partner 3, responsible for the engines, experiences a political external event in the form of a change in legislation regarding noise and emissions of aircraft engines. Partner 3 simply does not have the knowledge, experience and/or resources to meet the new demands generated by this unexpected and strict change in legislation.

This is classified as a major external event and the time penalty is likely to be significant, as the work completed is to be reset to near zero.

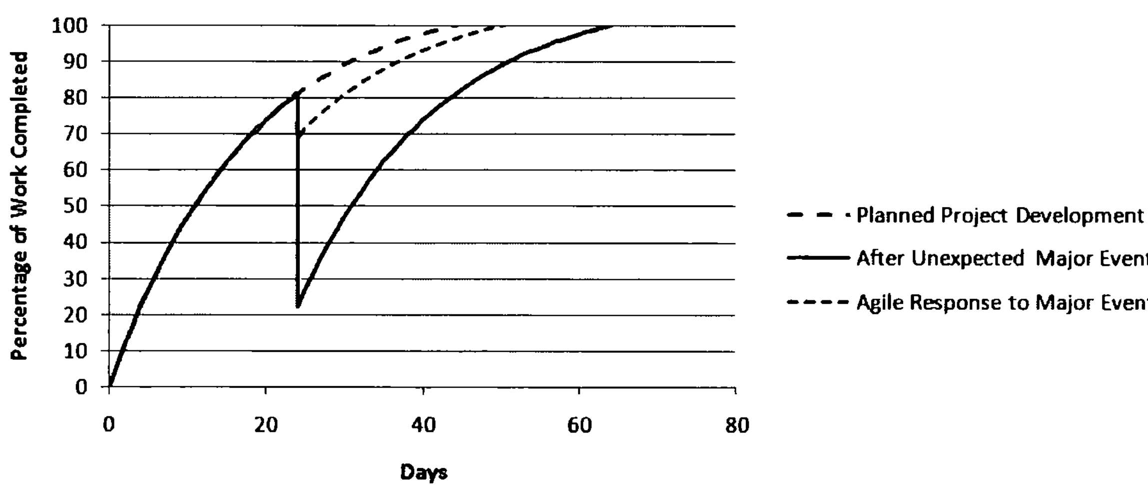

Figure 3-4. Effect of a major external event

In this situation the partner is deemed to have failed and another partner is required to take control of that specific process and join the virtual enterprise. The speed with which this can be achieved is a function of the agility of the organisation as a whole. The example shown in Figure 3-4 shows a 20 day delay to a process which should have taken 44 days, due to unpredictable failure after 24 days. An example of an agile response which could have been achieved through rapid integration of the new partner is shown for illustrative purposes.

Fatal Event

The fatal event is an external event which is catastrophic to the design as a whole, not just for any individual partner. An example of a fatal event might be the introduction of legislation stating that emissions of greenhouse gases for any mode of transport must be below a given level. This event would impact directly the partner responsible for the engines, in this example Partner 3; however the effect is that the design of the overall process is fundamentally flawed. No replacement of Partner 3 will be able to produce the output required for the project to be realised.

In the case of Fatal Events the Agile Design Framework would not be able to resolve the effects of the event; the only options would be complete diversification or cancellation of the project.

3.1.4. Summary

To summarise, it is suggested that Unexpected External Events are classified in terms of their impact on affected parties. The classification proposed defines four levels: Trivial, whereby the impact of the event is manageable within the immediately affected party or parties; Minor, meaning that additional assistance is required from outside the virtual enterprise; Major, which requires the replacement of a partner within the collaborative team due to failure to fulfil requirements; and Fatal, meaning the project is no longer feasible in its current form.

The classification of UEEs into these four categories allows better understanding of the UEEs to be used when setting scenarios in the experimental chapters of this thesis and when studying the real-life events of any case material or industrial trials.

3.2. Collaborative Design Environment

As was discussed in the previous chapter, collaboration can occur in a number of valid forms:

- collaboration between multiple companies (virtual enterprise),
- collaboration between multiple sites within a single company (geographically dispersed), and

- collaboration between multiple departments within a company (cross-functional teams, concurrent engineering)

As long as at least one of these situations occurs the design process can be said to be collaborative. The specific environment with which this research is concerned is that of collaborative engineering design, where any one of the above criteria is satisfied. Furthermore, adopting the definition of agility from the previous chapter, the research focuses on the ability of a collaborative design team to respond to a continuously changing and unpredictable global environment as defined by Unexpected External Events, in order to produce high quality customer-focussed products or services.

3.3. Hypothesis

The previous sections of this thesis have introduced three areas of interest: Engineering Design; Collaboration and Agility. Each area has developed along its own path in recent years, as well as the pairings of two from these three areas, such as Collaborative Design. The first section of this chapter also introduced an interpretation of the environment in which most engineering companies now find themselves: turbulent and unpredictable. It is in these circumstances that successful companies must succeed.

Furthermore, the literature review (Chapter 2) identified themes/factors which are considered to have some influence on the agility of a design process or successful collaboration or both. These factors can be classified as specific tools which can be implemented, or as management/organisational techniques.

Having reviewed the literature relating to the core themes of Engineering Design, Collaboration and Agility and identified common potential and perceived benefits of other approaches from within that literature, the hypothesis is that a specific set of tools and techniques can be implemented to increase agility. The tools and techniques are taken from the themes identified in the literature review to form the components of an Agile Design Framework. An important part of the framework is also the implementation phase during which the tools and techniques are applied to a collaborative design process. In exploring this potential increase in agility the definition of agility as described in the literature review will be adopted: the ability to respond to a continuously changing and unpredictable global environment in order to produce high quality customer-focussed products or services. The way in which the agility will be measured for testing the hypothesis is discussed in the following section.

The hypothesis assumes that the benefits will be tested exclusively in a collaborative design environment. In this context "collaborative" is taken as two or more individuals or organisations working together towards a common design solution. They may or may not be geographically co-located. "Design" project implies that the framework will be of benefit during the design stages only. Although knock-on effects may be observed during experimentation they are not of primary interest to this study.

Finally, the research requires that the hypothesis be tested in a turbulent environment in order to show any significant change in agility level. Environments with no turbulence, by definition, do not require agility and therefore any change in agility cannot be measured.

3.3.1. Hypothesis measure

In order to test the hypothesis it is necessary to adopt a measure of agility which can be used to identify any changes in agility as a result of the tools and techniques to be investigated. Section 2.3.2 presented a number of approaches for the measurement of agility in an organisation. However the metrics identified were for use at an organisational level to measure company-wide agility, rather than at a more detailed project level. While recognising the requirement for and value of such metrics, this level of measure is not suitable for the purposes of this research where the experiments and practical implementations will not be able to demonstrate changes in organisational agility, only more locally at project or departmental level.

Therefore a suitable metric is required which will allow the agility of this specific process to be quantified. Using this metric it will then be possible to identify any change in the agility levels of the design process as a result of the research conducted. In this way it will be possible to test the hypothesis.

For this purpose the most suitable agility metric identified in the literature is the Key Agility Index (KAI). The KAI can be applied to all or part of a business process and is a ratio of the proportion of time which is spent on change related tasks to the eventual project time requirement.

UEEs cause disruption to a project and potential additional work to be carried out, thus increasing the overall project time and increasing the KAI score, reflecting lower agility. Companies which are considered agile are able to respond to these UEEs in a timely and effective manner, meaning the ratio of time spent on unplanned tasks to the eventual completion time of the project will be low. However, companies without the ability to respond efficiently to such UEEs will have a high ratio of time spent on unplanned events to overall project time: a high KAI score. Perfect agility would be described by a score of zero meaning no delay was caused by responding to unexpected events, while poor agility scores tend to a score of 1 meaning all the time spent on the project was responding to unexpected events.

3.3.2. Case Study

During the development of the Key Agility Index the following case study was used to illustrate the measure in use.

The project involves the partial design and manufacture of an Aircraft Service Tug. The estimated delivery date from the receipt of order was 10 weeks (N=10); however the actual delivery date was 16 weeks due to external events ($\delta=\delta_1+\delta_2=6$). The project began with a re-design of some components to satisfy a change in the requirements from the customer upon ordering the tug ($\delta_1=2$). Once complete, the project was divided between a number of collaborating partners. The second delay was caused by the failure of one partner to satisfy their requirements for delivery of one component. This was a partner located on the critical path of the project and so the delay caused a knock-on effect of four weeks delay ($\delta_2=4$). The KAI for this project can be calculated as:

$$\kappa = \frac{\delta}{N+\delta} = \frac{6}{16} = 0.375$$

Equation 3

Using the classification system of four levels of unpredictable external event, the re-design and the delay of the delivery of part of the project were minor events, as they could be handled internally. If, in the case of the failure of a partner to deliver their part of the project on-time, a replacement partner had been required to complete that task instead, then the classification would move to major and a more significant penalty would be expected.

It should be noted that it is not possible to relate the KAI score directly to the classification of UEEs as the KAI is determined by a profile of all the events across the lifecycle of the project, rather than by any one specific event which can be classified.

3.3.3. Validation of KAI for hypothesis testing

The suitability of this measure for the purpose of hypothesis testing is validated by the following points:

1. It operates at project and departmental level rather than corporate level so is suitable for individual design projects, the only available metric to do this.

2. It facilitates a direct comparison between numerical scores for projects, clearly illustrating any improvement in agility without complex calculation.

3. The level of data required for the metric is available through questionnaire, interview or observation without significant time overhead being required.

The Key Agility Index does not consider the frequency or magnitude of Unexpected Events in its calculation, only the amount of time spent responding to these events. Therefore, the measure has a significant limitation in that one company with very few and very small UEEs will appear agile as they spend little time in responding to events, when in reality this apparent agility is due to a lack of turbulence in their environment. Conversely, companies operating in very turbulent environments may respond in an agile manner but appear unagile because of the high frequency and magnitude of the events with which they must deal.

In order to counter this effect the number and magnitude of the unexpected events experience during a particular project or time period could be incorporated into the measure. Each event could be classified into the four levels as described in Section 3.1.2. Each of these levels would be weighted based on experimental data to reflect the expected penalty. A sum could then be calculated for the multiples of the events and their levels throughout the period, and the KAI score divided by this sum. This would have the effect of recognising companies whose turbulence is much higher but who respond in the same time over the same period as being more agile.

In describing this flaw in the Key Agility Index as it has been presented here, the assumption has been that the comparison is between two different sets of circumstances, be they different projects or different project teams experiencing different levels of turbulence on the same project. However, in the case of this experimental work the comparison will focus on identical projects with identical unexpected events, or on a single project with one set of unexpected events, but with and without the Agile Design Framework. These scenarios will be described in more detail in the following chapter. Therefore, there is no requirement to adapt the Key Agility Index for its use in this research, although it would provide an interesting area of future work.

On this basis the experimental aspects of the research described in the next chapters will utilise the KAI measure to provide quantitative evidence of any change in the agility level (κ) of collaborative design projects as described below. A smaller value of KAI, represented here by κ, indicates a higher level of agility.

κ_0 indicates agility level before the Agile Design Framework is implemented and κ_1 is the agility level after the implementation.

H_0: Agile Design Framework makes no difference to agility in collaborative design projects in a turbulent environment: $\kappa_0 = \kappa_1$

H_1: Agile Design Framework increases agility level in collaborative design projects in a turbulent environment: $\kappa_0 > \kappa_1$

Utilising the KAI in this way allow for meaningful comparisons to be drawn between projects in the experimental stages to determine the impact of any changes in terms of the agility level achieved. The null hypothesis (H_0) supposes that there will be no difference in agility level and the before and after levels of agility will be equal. The hypothesis (H_1) proposes an increase in agility (κ) will be observed.

3.4. Summary

This chapter has expanded on the term "unpredictable environment" by introducing the concept of Unexpected External Events. UEEs have been classified into 4 categories to represent the impact of the event in terms of the required response by the affected project partners.

The collaboration element of the research context was also defined as including not just inter-organisational collaboration but also collaboration between departments or geographically distributed elements of the same organisation.

Finally, a working definition of agility for the context of this research was derived from the literature review summary of agility definitions. The metrics for measuring agility were discussed with regard to this research and the Key Agility Index was argued and validated as the most appropriate measure for the context defined in earlier sections of the chapter.

The hypothesis was presented in this chapter, proposing that a specific set of tools and techniques can be implemented to increase agility. The null hypothesis is that there will be no difference in agility levels before and after the implementation of these tools and techniques.

Chapter 4. Methodology

The previous chapter introduced a turbulent and unpredictable environment in which unexpected events beyond the control of the project team impact upon the design process. The source, level and magnitude of these unexpected events are variable and the penalty or opportunity can impart itself on one or more of the following project characteristics: quality, cost or delivery time.

The hypothesis presented in the previous chapter proposed the concept of an Agile Design Framework. This framework combines a number of tools and techniques from the literature into a process to be carried out at the beginning of the design process. This chapter considers the relevant research methods, rejecting those that are not suitable and developing the approach to test the hypothesis.

Ottosson (2006) notes that due to the large variation in design and manufacturing projects, and the variability within such projects, research in industrial fields such as design is particularly difficult. Ottosson goes on to suggest that the reliability of industrial research is directly proportional to the proximity of the measure to the object of the study as illustrated in Figure 4-1. This model of reliability is suited to the research presented here and thus provides guidance for the methodology developed in this chapter.

There are many approaches to research in the "softer" aspects of industry such as design and project management. These techniques include questionnaires and surveys, interviews, simulations and more. Many of the techniques are based on empirical evidence while others seek to make use of existing or new data gathered from within the subject/sample organisations to derive quantitative analysis of the area of interest.

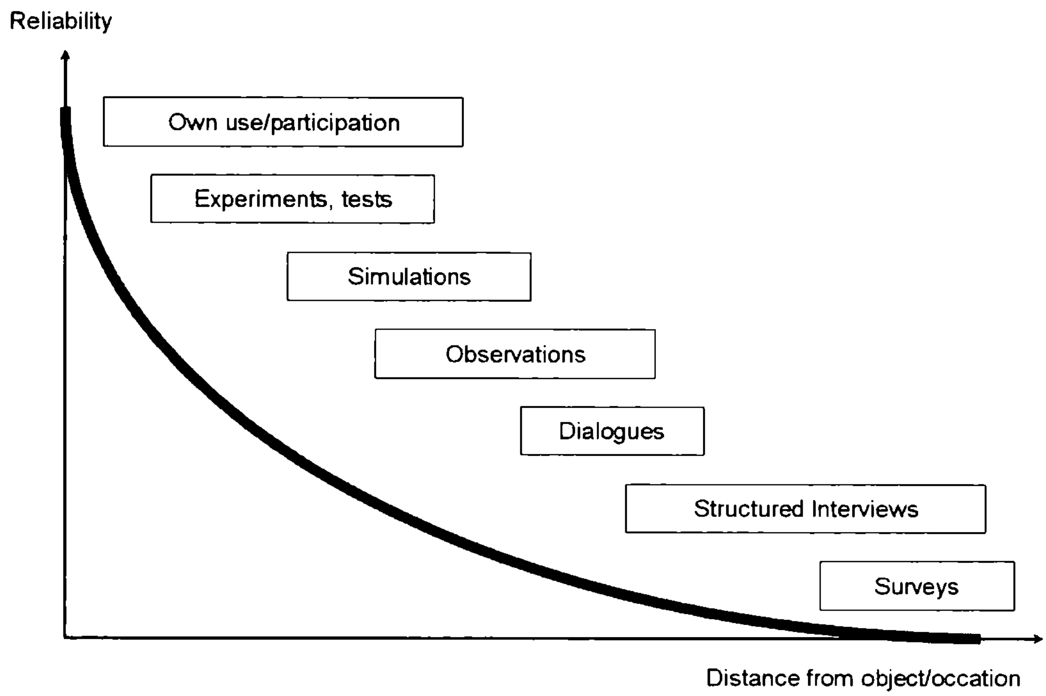

Figure 4-1. Relationship between research method and reliability (Ottosson, 2006)

Green et al. (2002) assert that four methods are currently at the fore of design research:

1. **Protocol Studies** during which activity of a (typically) controlled experiment is undertaken. This is often with the use of video recordings and post-experiment analysis.
2. **Ethnographic Observation** which shares the same objectives as the Protocol Study – specifically the identification of the rules and behaviours of a subject group, however Ethnographic Observation is typically undertaken in a real-life environment rather than a controlled experiment.
3. **Historical Analysis** is the use of both primary and secondary sources of historical data to analyse previous design activity.
4. **Experiential Analysis** relies on the personal experiences of the researcher who will typically have a background in industry or have had considerable exposure to industrial design activity through their own previous research.

Although there are clear differences between each of these approaches, the bias towards industrial participation and real-life industrial evidence is clear, suggesting that design research requires a significant element of industrial participation at best and industrial involvement in controlled experiments as a minimum.

4.1. Industrial Participation

Despite Ottosson's assertion that reliability is increased with proximity to the industrial object of research, it is well-known that industry participation in university research programmes can be difficult to achieve. While most companies would recognise the potential benefits, the investment in terms of time and manpower is often a barrier to their involvement without hard evidence of what the company can gain. In short, the risk is considered too great for companies to be the "test-bed" for academic theories. This is in contrast to proven theories implemented by consultants where the benefits are "guaranteed".

Therefore, a challenge presenting itself at the outset of this research, which is particularly industry-focussed, was the requirement to engage industrial partners in the research. Industrial participation allows the testing of the hypothesis by conducting the research in the environment in which the perceived benefits of the Agile Design Framework are to be realised. It also increases the reliability of the results and therefore improving confidence in the hypothesis testing. The ultimate goal therefore, was to validate the hypothesis through industrial implementation. However, as stated, it was not possible to go direct to industry with the concept without previously gathering evidence that there were real benefits to be gained.

Working with industry also brings with it unique challenges when compared to traditional laboratory-based research. The number of variables increases by orders of magnitude as humans become involved. Experiments cannot be repeated as readily as mechanical testing, for example, because the goodwill of industrialists is as precious as any physical resource. However the use of companies in this research is crucial if realistic results are to be claimed. Therefore, the use of companies must be managed in such a way that they are not wasted as resource.

4.2. Multi-method approach

In their review of engineering design research, Green et al (2002) advocate the use of a multi-method approach. The multi-method approach can take two forms: between-methods meaning multiple different methods are used to observe the same subject; and within-method in which the same method is used on different occasions, for example running the same experiment at different times of year. This allows the researcher to verify the results of one approach by comparing them to that of another approach to the same problem. Data triangulation is one suggested implementation of this model whereby three different methods are used to study a single subject.

The application of these theories, both the proximity to industry and the multi-method approach, is crucial as the field of design/product development is repeatedly described as difficult to observe and measure. Therefore the methodology adopted must consider these contributions to ensure that the experimental method is capable of allowing the hypothesis to be tested reliably and the results clearly defined.

Based on the combination of the evidence described, the desired methodology must overcome the barriers to company involvement and allow for eventual industrial implementation of the theoretical model to test the hypothesis. To reflect the need for a participatory research methodology whilst accepting the difficulties in setting that up without prior evidence of the benefits, a three-stage process was developed which facilitates an increase in the exposure level to industry.

The first stage of the methodology is a questionnaire approach to many companies which requires very little time or resource for their participation. Through this approach companies had the opportunity to express an interest in the field of research and being further involved in the research. This voluntary expression of interest would identify companies most likely to be approachable for the second stage of the research involving an increase in commitment through participation in a controlled experiment. Finally, from those participants a suitable and interested company would be identified for the third and final experimental stage involving an industrial implementation of the theory.

4.2.1. Stage One: Questionnaire

Stage one involved an industrial survey of defence and aerospace companies, mainly in the North-East of England. The survey population will be discussed in detail in Section 5.1. The objective of the survey was to establish the extent to which the tools and techniques identified in the literature were in use, and explore the correlation between these tools and techniques and the agility of the projects using them. This would allow the preliminary formation of the Agile Design Framework for testing in the subsequent stages of the research.

The use of surveys and questionnaires for gathering company data is commonplace in industrial research. Surveys can be administered in a variety of ways, the most common form of which is a questionnaire, usually distributed by mail. Machuca et al (2004) adopted a questionnaire-based methodology to gather data from 20 Spanish aerospace companies relating to their adoption of Advanced Manufacturing Technology. Yauch (2005) adopted a similar approach to gather data for a study of agility levels in the United States manufacturing sector. Both of these studies were carried out with mailed questionnaires.

Questionnaires have many benefits including:

- Inexpensive to produce and distribute compared to alternatives such as telephone interviews which can be time-consuming and costly,
- Allow for both quantitative and qualitative analysis depending on the way in which the questions are structured, and
- They can be piloted on a small sample to test the method before the full version is used.

However the validity of questionnaires has also come into question because of the frequent low response rates. To combat the first of these concerns there have been numerous studies carried out on the success of different response-improvement techniques. Monetary incentives, the colour of the form, the use of deadlines and the class of postage used for the outgoing and return mailing have all been cited as influencing the response rates to questionnaires (Duncan, 1979). The same study by

Duncan found that five factors had an influence on response rates: pre-notification, personalisation, the inclusion of monetary incentives, follow-up, and higher class return postage. Two further factors: source sponsorship, and the type of appeal in the cover letter, "appeared to increase response rates but in a situation specific manner". Other factors such as the colour and length of the form or the specification of a deadline appeared to have no effect on response rates. These influential factors were considered when generating the questionnaire to maximise the response rate.

4.2.2. Stage Two: Simulation and Protocol Study

The results of the earlier survey were used as the basis for developing a laboratory-based protocol study. The objective of the protocol study was to perform a preliminary test of the hypothesis which, if successful, would provide evidence for an industrial trial in the final stage of the research.

Protocol studies are an observation tool for gathering detailed data on procedures carried out by those being observed in a controlled environment (Cross et al, 1996). In design research this can be achieved by asking designers to "think aloud" during the design process or to record their thoughts on paper regularly. In order to record the "thinking aloud" audio and/or video recording equipment can be used. The advantages of video in a collaborative setting is that they can capture the interaction between designers as well as capturing the actual progress of the design on a computer screen or piece of paper at any given time.

Protocol studies also allow exactly the same problem to be solved by different groups which makes comparison between design projects more reliable than attempting to compare design projects with different objectives, parameters and influences. The environment can be controlled by the researcher which gives much better control than case study based research. Finally, the researcher is able to set up the experiment to capture the exact observations required for the study.

Protocol analysis has severe limitations in capturing the non-verbal thought processes going on in design work (Cross et al. 1996), no matter how much importance is placed on "thinking aloud". However for observing very specific actions and aspects of the design process protocol studies can be of significant use.

This ability to observe specific aspects of the process makes it particularly suitable at this stage of this research. It allows very detailed observation of the early implementation stages of the Agile Design Framework as well as the way in which the two teams of designers respond to artificially introduced unexpected events. Furthermore, their use of the tools and techniques which were specifically given to the experimental team, but which may also be used through personal experience by the control group can be observed in detail. The broader context of the design process where information may not be as obtainable is not of significant interest.

4.2.3. Stage Three: Insider Action Research

Finally, with the evidence of the laboratory-based experiment, the final hypothesis testing was conducted through an industrial trial. The Agile Design Framework was implemented into a real-life collaborative design project involving three companies.

In setting up an experiment of this nature it was important that, whilst maintaining a close relationship with the project team through regular observations, the outcome of the project was not directly affected by interference, either direct or indirect, from the observer.

Ottosson presents Insider Action Research (IAR) as a methodology for researching the domain of design and industrial engineering by participating in real-life projects in industry rather than less realistic lab-based settings. This can take the form of observations (IAR) or physical participation as a team member (Participation Action Research – PAR). It is proposed by Ottosson (2006) that only through one of these methods is it possible to obtain realistic information regarding the activities undertaken in such an environment. Additionally, the benefits of any suggested improvements can only be accurately understood through participation, or at the very least insider observation. These benefits support the use of this industry-based stage of the research as a valid method of testing the hypothesis which states that the application of the Agile Design Framework can have a positive effect on the agility of collaborative design projects, as measured with the Key Agility Index.

4.3. Justification of Design Research Methods

The three stage approach described includes only three of a large number of design research methods mentioned in the previous sections of this chapter. The rejected methods were experiential analysis, interviews and dialogues, observations and simulations and historical analysis, although elements of these approaches are evident as elements of the selected approaches.

The main reasons for rejecting interviews and dialogues were that they were highly time-consuming and significantly more invasive than the questionnaire approach. At the initial stages of the research the primary focus was on data collection from a broad range of sources and maximising the number of companies to whom there would be potential access for future aspects of the research. The questionnaire provided this more successfully than interviews and dialogues.

The objective of stage two was to test the hypothesis and refine the tools and techniques which formed the Agile Design Framework through a test implementation in a controlled environment. This can be described as a combination of alternative methods as the protocol study carried out in stage two was a combination of observations and simulation. The environment was a simulation of a collaborative design project where inputs and outputs could be controlled by the researcher. The observations, as defined by the protocol study methodology, were specific and targeted to the implementation of the Agile Design Framework and the responses to artificially introduced unexpected events. This combined approach enabled specific observations in a simulated and therefore controlled environment, the results of which were then sufficient to convince industrial participants of the benefits of the final stage of the approach.

Alternatives to the protocol study method include Ethnographic Analysis which has the same objectives but places the observation in a real-life setting. This was discounted at the second stage of the research because the theoretical model was not sufficiently well defined to test with so many variables as are found in a real-life environment. The Protocol Study provided a controlled setting for the testing of the theory where the inputs could be managed and prescribed to test specific elements of the Agile Design Framework.

Historical Analysis was rejected as it did not afford the opportunity to test the new Agile Design Framework as defined at the end of the first stage. Aspects of the framework which had previously been deployed could have potentially been tested with historical data, assuming such detailed data was available, however the opportunity to test the new framework as a whole was not provided by this method.

One alternative to stage three was a more detailed laboratory-based experiment similar to stage two but with a more complex and realistic simulation of the design environment. The benefits of this would have included the ability to plan the unexpected events to which the designers must respond; a shorter timescale to plan and implement; and more controlled observation techniques making results easier to identify. In contrast to these benefits of the more detailed laboratory-based experiment, testing the hypothesis in a real industrial environment meant that the results could be more conclusive, providing the techniques used for observing the project and taking appropriate measurements were rigorous. Unexpected events would be genuine along with real pressures to respond to them, allowing a realistic conclusion to the hypothesis test despite the longer duration and higher uncertainty.

4.4. Summary

The objective of the research is to test the hypothesis as defined in the previous chapter: that the application of a set of tools and techniques can improve the level of agility in a turbulent collaborative design environment. This chapter has introduced the concept of Insider Action Research as the most reliable method of conducting research in this field, whilst also recognising the challenges this approach brings in identifying willing companies.

In order to overcome the challenges whilst also providing a framework for fully defining the Agile Design Framework prior to industrial testing, a three-stage methodology has been described. The methodology consists of an industrial survey to gather evidence for any influence of the tools and techniques from the literature review impacting agility in industry. These tools and techniques then form the basis of the Agile Design Framework. This is followed by a controlled implementation in a lab-based environment which allows for very specific observations to be made through a protocol study of the implementation of the framework and its use in responding to unexpected events. These observations support further refinement of the Agile Design Framework before an industrial implementation through Insider Action Research using companies identified in the previous stages. Alternatives to the approach taken were discussed and rejected.

The next three chapters will describe each experimental stage of the research methodology in turn. The conclusions of each experimental stage form the basis of the subsequent experiment, linking the three stages coherently to develop the theoretical concept into an implementable framework. Each stage of the research tests the hypothesis using a different method in line with the multi-method triangulation approach deemed as necessary for this type of research.

Chapter 5. Industrial Survey

A three-staged research methodology was introduced in the previous chapter. The benefits of this approach are the increased contact with industry and the opportunity to develop and refine the Agile Design Framework throughout the stages leading to the industrial validation.

The literature review (Chapter 2) indicated tools and techniques, grouped into themes, which have been shown to have an influence on the agility of a design or collaborative project. The first stage of the research investigated the relationship between these tools and techniques and the agility of a collaborative design project in a turbulent environment through the use of an industrial survey.

This analysis provided the evidence for the basis of the formal Agile Design Framework through the adoption of the tools and techniques found to have a positive influence. This was then further tested and calibrated in the subsequent stages of the research.

As described in the previous chapter, a questionnaire was constructed for completion by design managers from industry. The questionnaire covered the adoption of the tools and techniques from the literature as well as questions related to recent collaborative projects in which the company had participated.

The remainder of this chapter presents the questionnaire methodology including population, structure, distribution and results analysis, along with some conclusions which support the next stages.

5.1. Population

Engineering Design takes places across the broadest range of engineering disciplines from chemical engineering through civil, mechanical and electrical to micro and even nano-scale electronics. Furthermore, there exist many industrial sectors in the UK undertaking Engineering Design regularly, particularly aerospace, defence, marine, IT, communications, automotive and pharmaceutical. Each of these industrial sectors combines many different engineering disciplines and each operates in a turbulent environment to varying degrees. It can therefore be argued that agility is important in each one of these fields; however an attempt to identify a design framework capable of benefitting every one of these disciplines or sectors represents too great a challenge for the scope and resources of this project.

Therefore a single industry sector was required to focus this research. In order to select the most appropriate the following list of criteria were used against each potential target sector:

- Accessible (established method of identifying/contacting companies),
- Companies work in collaboration within the sector,
- Environment can be described as turbulent, and
- Agility can bring benefits to the sector.

With this in mind a shortlist of companies were identified as being collaborative and having the potential to benefit from improved agility and operating in potentially turbulent environments. These sectors were defence/aerospace and automotive. An established link between Durham University School of Engineering and Northern Defence Industries (NDI) determined that defence/aerospace was selected for the purposes of the survey, as NDI has an accessible membership of suitable companies in this sector.

The defence and aerospace industries are characterised by large-scale products, typically with very long lead times, often running to decades. Budgets can stretch to billions of GB Pounds (Gow, 2007), and the projects endure a very turbulent external environment during their life-cycle. The environment is particularly vulnerable to technological, political, environmental, economic and other fluctuations over such long periods of time. Companies and entire industries can flourish and disappear during the life of many defence projects, and those participating in such projects are expected to offer support up to 25 years after a product is completed (Ministry of Defence, 2008).

These characteristics mean that an increased level of agility can be of significant benefit to any companies operating in this sector as they attempt to react to changes in their environment.

Northern Defence Industries (NDI) is a systems integrator and project manager for the defence and aerospace sector in the North of England. It has a membership of 178 companies, all of whom have some involvement in the defence and/or aerospace sectors. The companies range from prime contractors to single-person companies and have varying levels of involvement in design work.

There is no attempt by NDI to align the companies technologically to improve collaboration; all companies operate independently (although sometimes in collaboration with each other) despite their shared membership of NDI.

5.2. Questionnaire Structure

The questionnaire had a principal objective of gathering data from a broad number of companies to ascertain the relationship between the tools and techniques they use during collaborative design projects and the level of agility those projects achieve. In order to cover each of the necessary areas and gather sufficient information from the companies in a single attempt, the questionnaire was structured into three sections: Introduction; Research Themes and Recent Project Agility. These three sections provided a structure for gathering all of the necessary information, including peripheral information such as contact details of the person completing the form, and in addition to the data required for results analysis.

5.2.1. Introduction

The questionnaire began with factual questions regarding the company's contact details and the job title of the person completing the questionnaire. Also, the type of collaboration with which the company is involved was important. Therefore, at this stage the companies were asked to describe the type of projects with which they are involved:

1. Collaborating with other companies,
2. Collaborating within their own organisation only, or
3. No collaboration.

The purpose of this question was to identify companies who do not participate in any collaboration, even within their own companies, as this puts them outside the area of interest for this research. Companies responding with "no collaboration" were therefore excluded from the results.

The introduction required basic contact details to be completed so that in the event of any ambiguity to the answers provided, it would be possible to make follow-up contact with the person who completed the questionnaire.

The introduction also included a description of the terminology used throughout the questionnaire to ensure consistency of meaning between respondents. This introductory section can be seen with the rest of the questionnaire in Appendix A.

5.2.2. Research Themes

From the literature review six themes emerged as potentially influencing agility in this environment: Product Planning; Modularity and De-coupled Tasks; Cross-functional Teams; Integrated/Aligned Technology; Dynamic Planning throughout the Project; and Common Standards and Terminology (Section 2.4). The tools and techniques available within each of these themes were to be explored in this survey to establish the significance of each in affecting agility in the selected population.

In order to achieve this, the six themes were reframed into ten constructs for the questionnaire, using the literature review summary table (Table 2-2) and the sub-themes from each of the six themes as guidance. Each construct was made up of between three and six related questions which fitted into one or more of the themes from the literature. The 10 constructs were:

1. Project Setup Process: Dynamic Planning throughout the Project; Integrated Technology
2. Reaction Process to UEEs: Dynamic Planning throughout the Project
3. Data Sharing Systems: Integrated Technology; Cross-Functional/Multi-Company Teams; Common Standards and Terminology
4. Data Formats: Integrated Technology; Common Standards and Terminology
5. Terminology: Integrated Technology; Common Standards and Terminology
6. Measurement Units: Modularity/De-coupled Tasks;
7. Partnering: Cross-Functional/Multi-Company Teams
8. Turbulence Planning: Product Planning; Dynamic Planning
9. Design Techniques: Modularity/De-coupled Tasks
10. Design Change Negotiation: Cross-Functional/Multi-Company Teams

The constructs allow a more reliable questionnaire through the use of multiple questions to determine the same answer. For example, to find out if somebody is happy at work through a questionnaire, instead of simply having a single question: "Are you happy at work?", a construct might ask respondents to mark on a scale of 1-7 the extent to which they agree with the following statements: "I look forward to work in the morning", "I often have fun at work", "I am adequately challenged by my work".

Once the questionnaire is completed the questions in each construct can be analysed using the Cronbach's Alpha technique to give a score between 0 and 1. A score approaching 1 indicates a high level of internal consistency which means the questions are asking the same thing. Scores above 0.7 are considered acceptable although in some cases lower scores can also be adequate. The constructs created for the purposes of this questionnaire cannot be tested until after the responses have been received as it is not possible to find enough companies for the pilot study to reliably measure the Cronbach's Alpha values.

The construct questions were then arranged into sections of the questionnaire. However, in order to make the questionnaire as user-friendly and unintimidating as possible the themes, constructs and their components were combined and reorganised into 4 topics:

1. Project Setup (5 questions)

   This topic contained questions relating to identifying the correct partners quickly, and early integration of the partners through the formation of a core design/project management team (Project Setup Process, Reaction Process to UEEs and Partnering constructs).

2. Communication (25 questions in 5 sub-categories)

   Communication is the largest section of the questionnaire with questions relating to a standard data sharing method for all partners (Data Sharing Systems) including the aspects of the project managed using this method; the formats of electronic data to be shared (Data Formats); and the standards and terminology used by the project team including how widely known and used they are (Terminology). Additionally, the Measurement Units construct for the Modularity/De-coupled Tasks theme fits into this category as the Measurement Units relate to the ability to share and combine sub-components of a design.

3. Unexpected Events (17 questions in 2 sub-categories)

   The Unexpected Events section contained questions relating to the company's response to unexpected events and whether a time, quality or resource penalty was more common. Additionally, questions regarding future forecasting were posed (Turbulence Planning construct).

4. Design Techniques (7 questions)

   The final section related to Design techniques, specifically the use of Design for Manufacture/Assembly techniques and Modular Design/De-coupled tasks (Design Techniques construct), and the ability to effectively communicate design changes (Design Change Negotiation construct).

Of the questions in the first four sections, 39 determined the level of adoption of the tools and techniques in these areas such as the use of Design for Manufacture principles and the use of an electronic data sharing facility. The remaining 15 questions provided additional information which allowed further understanding of the company and projects, such as the different uses for their Product Data Management system.

5.2.3. Agility of Recent Projects

In addition to these 4 topics a fifth section asked for a brief description of the last three collaborative projects in which the company had taken part and the relevant timing information. It was highlighted that these projects should be ones for which their questionnaire responses were relevant. Specifically, the information requested was the number of partners in the project, the number of people collaborating, the original length of the project, the delay due to external events, and the delay because of other factors. There was also a space for additional information to describe the project and causes of delay.

5.3. Question Format

Respondents marked their responses on a 7-point Likert scale ranging from 1 (strongly agree) to 7 (strongly disagree). Likert scales are commonly used for indicating the respondents' agreement or attitude to a particular statement (Trochim, 2006). In this case the statements related to the extent of use of tools and techniques within each topic, recognising that they may not be used fully or every time and therefore a scale was appropriate. The use of a 7-point scale meant that a neutral option was available for "neither agree nor disagree".

5.4. Peer Review

The questionnaire was initially distributed to two experts in questionnaire design from Durham University Business School and Oklahoma State University. Both experts have conducted research by questionnaire in related fields. This process led to feedback which allowed the questionnaire to be refined, predominantly in the ancillary areas rather than in the main question sections.

Once the questionnaire had been completed a pilot study was carried out with four companies to test the usability. As a result of this pilot some questions were reworded to clarify their meaning and some questions were moved to alternative sections of the questionnaire.

5.4.1. Response Optimisation

The final questionnaire was then posted to the "Design Manager" at each of the 178 NDI member companies, using the Design Manager's name where it was known. The questionnaire was accompanied by a covering letter (Appendix B) from the NDI Director of Projects & Programmes, explaining the benefits of completing the questionnaire and asking that it be completed within two weeks. Additionally, a pre-paid return envelope was included in the mailing to eliminate any cost to the company completing the questionnaire and encourage a greater response rate. A feedback report was also offered for all respondents, benchmarking their responses against the other population mean and explaining the implications of the main findings of the study. An anonymised sample of the benchmarking report is included in Appendix C.

5.5. Respondents

Following a period of four weeks, 42 responses had been received as follows:

- 15 correctly completed responses;
- 2 incomplete responses;
- 25 companies indicated that the questionnaire was not applicable to their company as they did no collaborative work or no design work.

The initial mailing was then followed up after the four week period with 84 successful telephone calls to the non-responsive companies (successful is defined as making contact with a representative from the company and leaving a message as a minimum). This process resulted in identifying a number of reasons for non-responses:

- A further six companies indicated the questionnaire was not relevant;
- Some companies indicated they had not received the questionnaire so a replacement was sent by e-mail or post, whichever they requested;
- In some cases the contact person had left the company and therefore the questionnaire had not been opened;

- Some companies indicated an unwillingness to participate for a variety of reasons, principally because they were too busy;
- Nine companies had left the NDI organisation and did not wish to take part in the research.

This process of follow up phone calls and resending of questionnaires increased the number of usable responses to 19. It was also discovered that for at least 29 companies the questionnaire was not applicable in addition to the nine non-members of NDI, giving 38 companies to be removed from the population. Deducting this 38 companies from the number sent out the response rate as a percentage of the population to whom the questionnaire was sent and was applicable is at least 13.6%. This figure could be higher as it was not known how many of the companies did not respond because the questionnaire was not relevant, i.e. they undertook no collaboration or no design activity.

When compared to other recent studies in similar fields this response rate is high in comparison with 3.4% in a recent agility survey in the USA (Yauch, 2005). Machuca et al (2004) hand-picked 20 companies representing the aeronautical sector in a single region of Spain and so were able to claim a response rate of 100%. No data is given on the number of companies not considered and so it is difficult to draw any conclusions on the representation of this sector by the 20 companies, however twenty was considered a statistically significant number of companies for the purposes of data analysis.

5.6. Data Analysis

Although a response of 19 companies is considered adequate compared to other similar studies, the high number of variables in the study (39) dictate that a straight-forward correlation analysis is not possible. Principal Components Analysis is a recognised technique for the reduction of a high number of variables into a smaller number of factors in this situation (Daultrey 1996; Jolliffe, 2002). This technique was adopted and will be described in the following section.

5.6.1. Principal Components Analysis

Principal Components Analysis (PCA) is a factor analysis technique for analysing the variance of the variables in a study and creating a set of new factors which can represent the underlying variance of the dataset (Dualtrey, 1976; Jolliffe, 2002). This is done in such a way that the first factor describes the largest proportion of the variance, followed by the second factor which describes the second largest and so on. The new factors are orthogonal, therefore uncorrelated with any other factor, and there will be an equal number of factors as there were original variables. The benefit of this technique is that the first factors describe a large proportion of the variance, and therefore the later factors can be disregarded, leaving a more manageable and meaningful number of factors than variables.

Figure 5-1 illustrates the procedure graphically. In this example the data for responses to variables x_1 and x_2 are plotted for 12 respondents. The majority of the variance in the data can be described using one vector defined as $f_1=f(x_1, x_2)$, representing say 90% of the variation in the data. The second vector f_2 describes the remaining 10% variation, orthogonal to the first factor and summing to 100% of the variation.

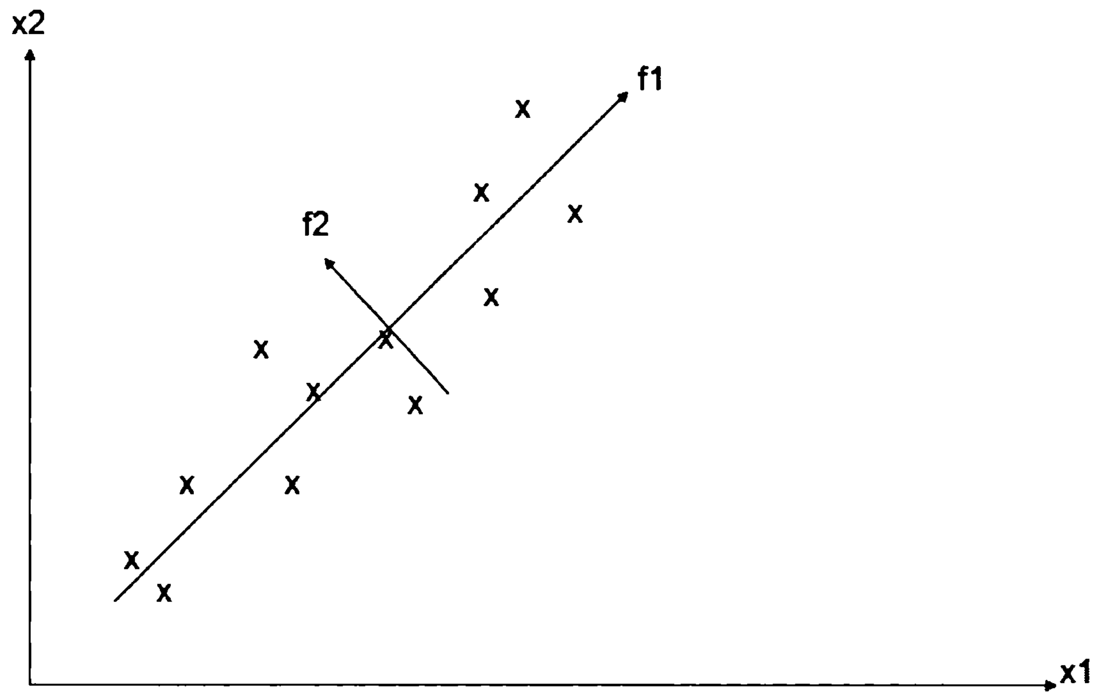

Figure 5-1. Example Results to Illustrate Principal Components Analysis

If 90% of the variance of the data is sufficient for analysis purposes then the two variables can be described for future analysis by the single factor f_1. However if 90% is not sufficient in this example then there has been little benefit to the PCA as two factors are still required to describe the variance of the data. The only benefit in this case would be the restructuring of the data which can aid interpretation. The addition to this example of a third variable x_3 with very little variance may mean that the three variables could be reduced to two factors f_1 and f_2 which illustrates the potential benefit of the technique.

The remaining stage requires the interpretation of the factors as they are now a combination of multiple variables, with each variable contributing to a different extent to that the factor. This means, a new factor may be strongly aligned with one or two variables, and therefore is more described by those variables than the ones which are less aligned. However a factor may be equally made up of many contributing variables, making interpretation difficult. At this stage manual interpretation of the variables making up the factor is required to determine a theme or descriptor of each factor.

5.6.2. Varimax Rotation

One barrier to reliable interpretation of the factors is that each variable can appear in multiple factors. Additionally, if too many variables contribute to a single factor then interpretation can be difficult. To combat this, a technique known as Rotation can be performed (Abdi, 2003). This technique allows the new axes to be rotated in order to identify an optimum alignment. The definition of optimum can vary depending on the desired outcome; however for the purposes of this research the optimum alignment allows for easier interpretation of the factors. Varimax rotation provides this desired outcome.

Varimax rotation is an orthogonal rotation technique which means the axes remain orthogonal to each other after optimisation has occurred. It focuses on determining factors accounting for the maximum variation possible, while each factor is made up of high loadings from as few variables as possible and each variable only contributes to a single or very few factors. Factors with few important variables can then more easily be interpreted or related to themes while the variance accounted for by the rotated factors is still a significant percentage.

5.6.3. Scree Method

Whether a rotation is required or not, Principal Components Analysis generates an equal number of factors to the original number of variables, but with the advantage of the early factors being more significant (representing a larger proportion of the variance of the data). However, it is still necessary to determine the appropriate number of factors to consider in the analysis of the results. The number of factors will always be equal to the number of variables, however the first factors will account for a much higher percentage of the variance than the later ones, meaning that a few factors can be taken to reasonably represent the entire result set. This provides the reduction to a manageable number of factors.

The most common technique for selecting the appropriate number of factors is the Scree Method (Cattell, 1966) which takes its name from the shape of the graph it generates. All the factors are plotted against their eigenvalue or the percentage of the variance for which they account. The technique then involves the visual inspection of the line joining each point on the graph, identifying a point at which the gradient is "steep" to the right and "not steep" to the left. A Scree plot illustrating this affect can be seen in Figure 5-2.

5.7. Results and Discussion

In order to process the questionnaire responses SPSS v.13 was used for statistical analysis. The responses to each question were entered into the software and the first stage was to confirm the reliability of the constructs in the questionnaire through calculation of the Cronbach's Alpha values. The results of this process can be seen in Appendix D. All Cronbach's Alpha values were above the acceptable level of 0.7 and therefore all 39 questions could be included in the next stage of analysis.

Principal Components Analysis was then performed on the results as described in the previous section. The variables fell into 8 dominant factors which accounted for 96% of the variance. A summary of the rotated factor matrix can be seen in Table 5-2.

Table 5-1. First 8 factors of Principal Components Analysis

	Factor							
	1	2	3	4	5	6	7	8
Terminology is agreed on by the whole project team	0.872							
All team members use the terminology agreed on for the project	0.840							
Document formats are agreed on at the beginning of the project	0.813							
Document Formats are agreed on by the whole team	0.775	-0.491						
New members to the project would easily understand how to use the system	0.764							
There is a standard method for sharing project data within the team	0.722	-0.452						
We have a procedure to follow when a change we make affects others	0.712		-0.410					
Everybody in the project knows who is coordinating the project	0.696		-0.428	-0.435				
Everybody in the project knows who they should report delays to	0.684	0.554						
Using standard 'off the shelf' parts is important	0.657			-0.453				
The meeting is attended by a representative from each company/division	0.647		-0.507					
Consideration is given to potential unexpected events prior to the project	0.630							
This method is electronic (i.e. not paper based)	0.626			-0.406	-0.512			
The nature of unexpected events is used when setting up subsequent projects	0.602					-0.438		
New members to the project could QUICKLY gain access to all the project data	0.589	-0.480						
If assistance is required there is a method of identifying the necessary skills/expertise/resources	0.554	0.451	0.537					
Reducing the number of parts/components in a design is important	0.546				0.450			
Document formats are independent of specific software applications	0.542		0.485		-0.456			
We always adhere to International Standards for designs	0.508		-0.405		0.441		-0.424	
All team members use the measurement units agree on for the project		0.757						
Team members never use different terminology to those agreed on		-0.751			0.447			
There is a meeting between companies/divisions at the start of the project	0.448	0.743						
Measurement units are agreed on by the whole project team	0.478	0.739						
Measurement units are agreed at the beginning of the project	0.513	0.701						
The response to unexpected events is recorded	0.530	0.697						
Problems never occur sharing files between project team members		-0.645		0.445				
The cause of unexpected events that require a response is recorded	0.587	0.599						
Training in responding to unexpected events is undertaken by all team members			0.894					
There are set procedures to follow if an unexpected event means that help is required	0.582		0.706					
Procedures are in place for responding to unexpected events that have occurred in previous projects	0.437		0.638		0.474			
Procedures for dealing with unexpected events are set before the project begins	0.545		0.603			0.432		
Making Manufacture/Assembly as easy as possible is important	0.428		-0.598					
All team members are aware of the procedures to follow in the event that assistance is required	0.488	0.419	0.573					
We are always aware of design changes by other members of the project team	0.588			0.739				
Team members never use different measurement units to those agreed				0.663				
All team members use the file formats specified for the project	0.443			0.551				
Finding the right companies/divisions for the project team is a quick process				0.446	-0.641			
Terminology is agreed on at the beginning of the project	0.504					0.601		
We re-use designs wherever possible	0.479		-0.410					0.557

Table 5-2. First 5 rotated factors after Varimax Rotation

	Factor				
	1	2	3	4	5
Measurement units are agreed on by the whole project team	0.954				
Measurement units are agreed at the beginning of the project	0.929				
All team members use the measurement units agree on for the project	0.906				
There is a meeting between companies/divisions at the start of the project	0.895				
Everybody in the project knows who they should report delays to	0.877				
The response to unexpected events is recorded	0.748				
Team members never use different terminology to those agreed on	0.696				
The cause of unexpected events that require a response is recorded	0.652				
The meeting is attended by a representative from each company/division	0.639				
There are set procedures to follow if an unexpected event means that help is required		0.884			
All team members are aware of the procedures to follow in the event that assistance is required		0.876			
Procedures for dealing with unexpected events are set before the project begins		0.823			
Training in responding to unexpected events is undertaken by all team members		0.807			
If assistance is required there is a method of identifying the necessary skills/expertise/resources		0.765			
Procedures are in place for responding to unexpected events that have occurred in previous projects		0.737			
Document formats are independent of specific software applications		0.602			
Reducing the number of parts/components in a design is important			0.907		
Everybody in the project knows who is coordinating the project			0.849		
Making Manufacture/Assembly as easy as possible is important			0.847		
All team members use the terminology agreed on for the project			0.681		
Terminology is agreed on by the whole project team			0.662		
Using standard 'off the shelf' parts is important			0.623		
Terminology is agreed on at the beginning of the project			0.580		
We are always aware of design changes by other members of the project team				0.869	
Team members never use different measurement units to those agreed				0.868	
We have a procedure to follow when a change we make affects others				0.814	
All team members use the file formats specified for the project				0.668	
Document formats are agreed on at the beginning of the project				0.633	
Problems never occur sharing files between project team members				0.564	
Document Formats are agreed on by the whole team				0.562	
We always adhere to International Standards for designs				0.455	
New members to the project could QUICKLY gain access to all the project data					0.865
Consideration is given to potential unexpected events prior to the project					0.809
There is a standard method for sharing project data within the team					0.771
New members to the project would easily understand how to use the system					0.702
This method is electronic (i.e. not paper based)					
The nature of unexpected events is used when setting up subsequent projects					
We re-use designs wherever possible					
Finding the right companies/divisions for the project team is a quick process					

From the rotated factor matrix it was evident that the factors were not well structured for interpretation as they were made up of a high number of variables and the variables were present in multiple factors. Therefore a Varimax rotation was performed in order to make the interpretation more manageable. The first 5 factors of the rotated factor matrix can be seen in Table 5-2.

When the factor matrix was rotated to identify a clearer underlying structure the resulting Scree plot showed five salient factors (Figure 5-2) accounting for 74.5% of the variance. This is compared to 82.2% for the five most significant factors before Varimax rotation. However, this drop in variance is acceptable in order to interpret the results for the purposes of the next stage of the research and formulating the Agile Design Framework.

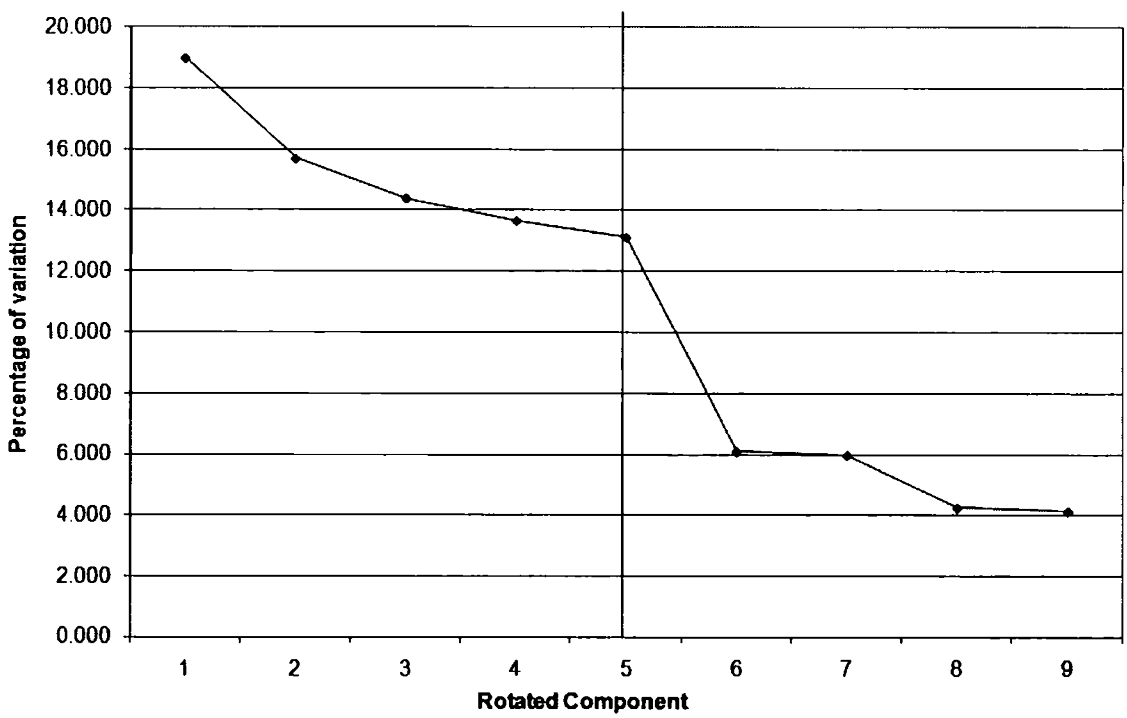

Figure 5-2. Scree plot showing 9 principal factors (components) after Varimax rotation and the percentage of the variation described by each factor

By reviewing the variables attributed to each of the five principal factors (Table 5-2) it was then possible to assign themes as follows:

Table 5-3. The 5 Salient Factors after Varimax Rotation incl. % Variance

Factor	Factor Theme	Variance
1	Project Setup and Measurement Units	19.0%

Theme identified from:

Measurement units are agreed on by the whole project team
Measurement units are agreed at the beginning of the project
All team members use the measurement units agree on for the project
There is a meeting between companies/divisions at the start of the project
Everybody in the project knows who they should report delays to
The response to unexpected events is recorded
Team members never use different terminology to those agreed on
The cause of unexpected events that require a response is recorded
The meeting is attended by a representative from each company/division

Factor	Factor Theme	Variance
2	Reaction Process to UEEs & Planning for UEEs	15.7%

Theme identified from:

There are set procedures to follow if an unexpected event means that help is required
All team members are aware of the procedures to follow in the event that assistance is required
Procedures for dealing with unexpected events are set before the project begins
Training in responding to unexpected events is undertaken by all team members
If assistance is required there is a method of identifying the necessary skills/expertise/resources
Procedures are in place for responding to unexpected events that have occurred in previous projects
Document formats are independent of specific software applications

Continued...

...continued from Table 5-3

Factor	Factor Theme	Variance
3	Terminology & Modular Design/Design for Manufacture	14.4%
Theme identified from:		
Reducing the number of parts/components in a design is important		
Everybody in the project knows who is coordinating the project		
Making Manufacture/Assembly as easy as possible is important		
All team members use the terminology agreed on for the project		
Terminology is agreed on by the whole project team		
Using standard 'off the shelf' parts is important		
Terminology is agreed on at the beginning of the project		
Factor	**Factor Theme**	**Variance**
4	Document Formats & International Standards	13.7%
Theme identified from:		
We are always aware of design changes by other members of the project team		
Team members never use different measurement units to those agreed		
We have a procedure to follow when a change we make affects others		
All team members use the file formats specified for the project		
Document formats are agreed on at the beginning of the project		
Problems never occur sharing files between project team members		
Document Formats are agreed on by the whole team		
We always adhere to International Standards for designs		
Factor	**Factor Theme**	**Variance**
5	Data Sharing & Consideration given to UEEs prior to the project	13.1%
Theme identified from:		
New members to the project could QUICKLY gain access to all the project data		
Consideration is given to potential unexpected events prior to the project		
There is a standard method for sharing project data within the team		
New members to the project would easily understand how to use the system		

5.7.1. Agility Analysis

As explained in Section 5.2, the third area of the questionnaire asked for data relating to the timings of recent collaborative projects the companies had undertaken and to which their responses applied. For each company the agility of their most recent project was then calculated using the Key Agility Index as described in Section 3.3.1.

The mean KAI for the population was 0.2, indicating that 20% of the overall project time was spent responding to unexpected external events. Observing the distribution of agility scores shown in Figure 5-3 a bi-modal distribution is evident with peaks either side of the 0.2 score. In the absence of a definitive value for what constitutes "an agile company", the value of 0.2 was adopted as a threshold, above which companies were considered not agile, and below which companies were considered agile. The hulls marked on Figure 5-4 indicate the groupings of "agile" companies (KAI $\leq$ 0.2) and "non-agile" companies (KAI $>$ 0.2).

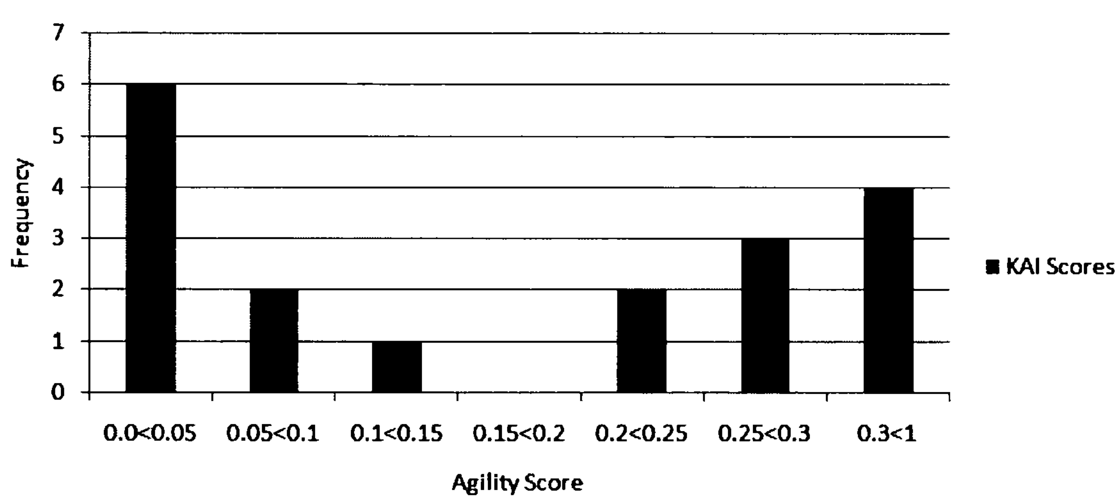

Figure 5-3. Distribution of KAI scores grouped into 0.05 brackets

5.7.2. Factor Interpretation

In order to show the relationship between the rotated factors and the agility of the projects, the values of each of the five most significant rotated factors were calculated for each company, grouped into agile and non-agile. "Project Setup and Measurement Units" accounted for 19% of the total variance in the data while "Reaction Process to UEEs & Planning for UEEs" accounted for a further 16% of the total variation, meaning that 35% of the variation in the data can be attributed to the two factors shown in Figure 5-4.

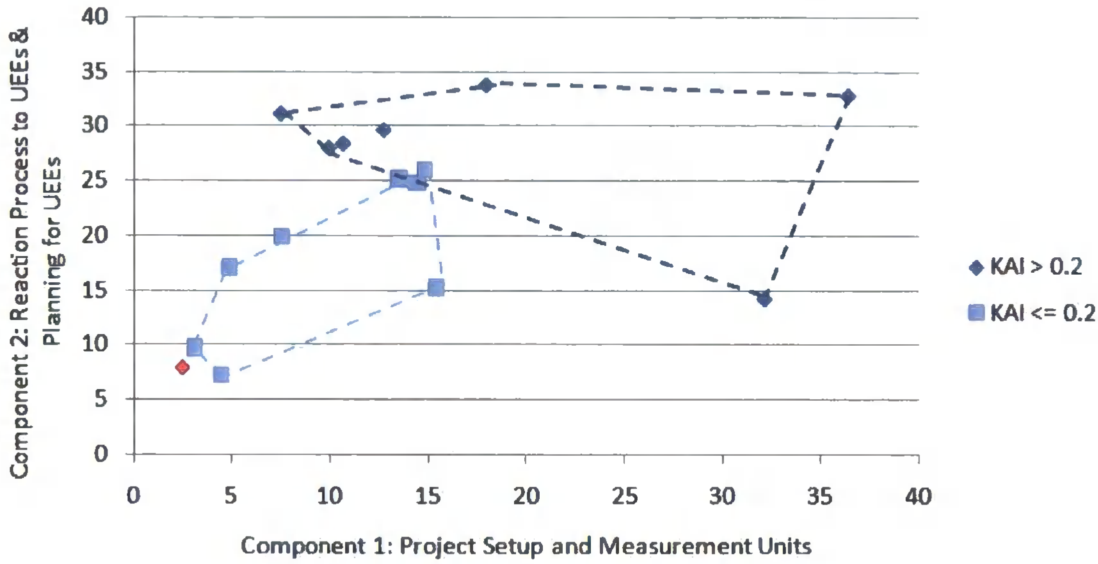

Figure 5-4. Chart of the calculated responses to the two most dominant factors

The groupings clearly indicate that the more agile projects were carried out by companies who scored lower on the two principal factors. Specifically, this means a lower score on the Likert scale (a high level of agreement to the questions posed) for the variables concerned with Project Setup, Measurement Units; Reaction Process to UEEs; and Planning for UEEs indicates a higher level of agility.

A single outlier belonging to a design and manufacturing company in Yorkshire (shown in red) scored low on both factors. The outlier company provided data for one collaborative project between four partners. In order to establish the nature of the delays and therefore whether the relatively poor score of KAI was appropriate an informal interview was held at the company premises with the Managing Director. The company were the smallest partner in a larger project which also involved two well-known large companies, for whom the project was not a priority. Despite having tools in place as indicated by their questionnaire responses, none of these were sufficient for countering the delays caused by the lack of co-operation from other partners. It could therefore be argued that the delays experienced by the company were internal to the project rather than external unexpected events, as at a project level it was the priorities of the partner organisation that were the cause.

On this basis the outlier can be accepted as an anomaly, however it remains in the dataset as the relationship between the responses given in the main section of the questionnaire are still of interest and relevance.

Table 5-4. Mean Company Responses to 5 principal Varimax rotated factors

Factor	Agile Companies	Non-agile Companies	Difference
1	9.77	17.1	7.33
2	19.27	25.4	6.13
3	13.89	14.9	1.01
4	16.49	18	1.51
5	8.95	10.1	1.06

Table 5-4 shows the mean company response to the five principal factors from the Varimax rotation. Companies considered being agile according to the definition of a KAI score below 0.2 clearly show a tendency towards lower scores across the five factors, although the difference is lower for the less significant factors.

Interestingly, four of the 39 variables did not feature at all in the first five Varimax rotated factors:

1. This method is electronic (i.e. not paper based)
2. The nature of unexpected events is used when setting up subsequent projects
3. We re-use designs wherever possible
4. Finding the right companies/divisions for the project team is a quick process

This suggests their values did not have any significant affect on the variance in the responses. Of these four, the most noteworthy is the use of an electronic data sharing method as it specifically includes the "electronic" differentiator from any of the other

Data Sharing questions. Of the other three, each was one variable within a construct whose other variables were clearly defined in the five principal factors.

5.8. Conclusions

The analysis of the questionnaire responses using Principal Components Analysis and Varimax rotation allows the high number of variables (relative to the number of respondents) to be analysed by identifying meanings for the rotated principal factors of the variance of the dataset. When compared to the agility levels of the respondents, the scores calculated for the companies for the rotated principal factors have identified a positive relationship between the adoption of the tools and techniques from within those factors and the level of agility experienced in collaborative projects.

The literature defined a set of themes that lead to better collaboration or improvements in the design process. However it is now possible to identify the themes from the literature which are more strongly linked with higher levels of agility, specifically the most dominant rotated principal factors.

The results suggest a strong relationship between the level of agility and the "Project Setup" which included such techniques as holding a meeting of all collaborating parties prior to the start of the project; having a representative from every one of those companies attend that setup meeting; team members knowing who was co-ordinating the collaborative project and to whom they should report any delays. Additionally, the use of common measurement units was prominent, as was the ability to plan for and have set responses to unexpected events.

Of the variables which did not feature in the five principal factors, perhaps the most interesting is the use of an electronic data sharing method. This perhaps suggests that the use of an agreed data sharing method is sufficient, not necessarily electronic, as other variables related to data sharing did feature in prominent factors.

From this research it is possible to determine that the implementation of certain tools and techniques from the literature can be linked to an increased level of agility. This supports the hypothesis presented in Chapter 3 as the agility level determined by the

Key Agility Index for agile companies (who have adopted the tools and techniques) can be shown to be higher than that of non-agile companies in the population.

The results of this chapter inform the next stage of the research through the development of an Agile Design Framework based on these results. The framework will first be described in detail as a series of steps to be undertaken by the collaborative design team. The framework will then be tested through implementation in a collaborative design project and compared with a control group to measure any explicit benefits to the level of agility.

Chapter 6. Protocol Study

The previous chapter described the relationship between design and collaboration tools and techniques, and the level of agility achieved by a company during design projects. The relationship was identified through analysis of questionnaire responses which also highlighted the more significant themes linked to agility. These findings will be used in this chapter to develop an Agile Design Framework to be tested using a protocol study as introduced in Chapter 4.

This chapter will describe the Agile Design Framework as it is to be implemented during the protocol study. It will also detail the protocol study methodology employed in running the experiment including the use of designers from industry, design brief, data capture techniques, unexpected events and data analysis.

The objective of this study is to provide a rigorous test of the hypothesis once the Agile Design Framework has been clearly defined. The protocol study will provide evidence for the test and the findings will be presented in the final sections of the chapter. Through thorough analysis of the data, the results will inform the refinement of the framework for implementation in industry in the final stage of this three-stage methodology.

6.1. Agile Design Framework

The hypothesis proposes that the implementation of a set of tools and techniques in a particular manner can have a positive effect on the agility of a collaborative design process. The Agile Design Framework describes the tools and techniques which have been identified from the literature and investigated through the questionnaire described in the previous chapter.

Based on those findings in the previous chapter it is now possible to refine the Agile Design Framework from a loose collection of methods into a more comprehensive model for testing at this stage of the research.

The evidence presented in the results of the previous stage suggested a relationship between all the themes included in the questionnaire, although some are more dominant than others. In particular, Project Setup appears strongly in the findings. This indicates a requirement of the Agile Design Framework is to ensure that the partners of the collaborating virtual enterprise meet at the outset of the project before any work is commenced. Therefore the initial implementation is carried out after the customer requirements have been gathered but before any design work is undertaken, ideally as soon as the design team partners have been identified. At this stage, it is then possible for other aspects of the themes to be addressed such as agreeing measurement units, defining data sharing procedures, planning for unexpected events and decomposing the tasks into independent modules.

In order to make this process as user-friendly as possible an implementation process was defined, comprising seven steps for the collaborating partners to follow during the setup process. Figure 6-1 illustrates the implementation process as defined for the protocol study. The seven steps within the process cover all aspects of the themes. The accompanying instructions, which can be seen in Appendix E, guide the partners in interpreting each step to ensure the themes are addressed. This is done through the use of example scenarios, questions and sample decisions and actions for the partners to take. The framework is not an explicit set of tools which must be adopted, but rather a set of guidelines for allowing companies to address specific areas which will lead to an increase in agility.

Although Figure 6-1 shows a concluding block stating "Agile Collaborative Team", the process of implementing this framework is continuous throughout the project, revisiting each step to revise it as necessary. This concept was introduced as Dynamic Planning and covered in the questionnaire in the Project Setup, Turbulence Planning and Reaction to UEEs sections which came out as dominant in the Principal Components Analysis. This dynamic approach was made explicit in the instructions to the team members and will be discussed in the next section which outlines the research methodology in more detail.

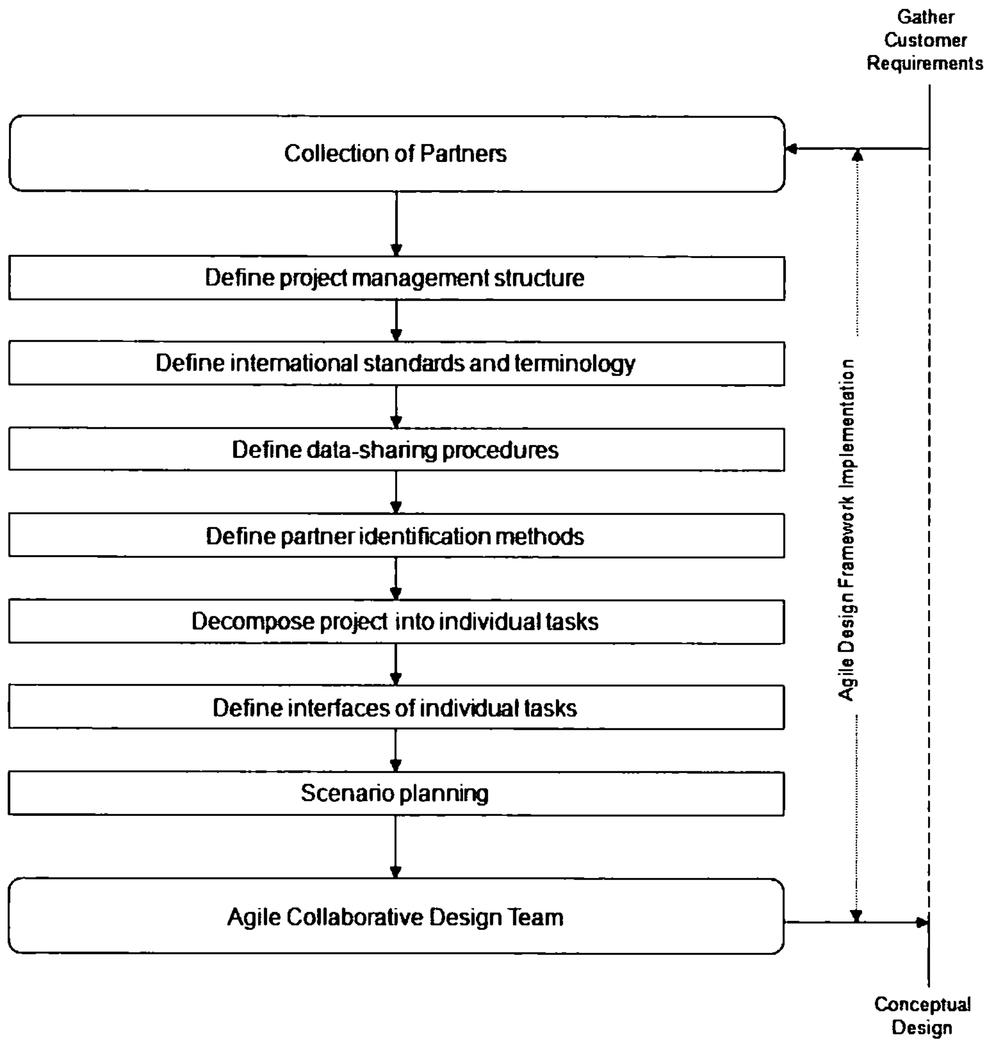

Figure 6-1. Agile Design Framework Implementation Stages

6.2. Experimental Setup

The protocol study was carried out in order to test the impact of the Agile Design Framework on the agility of the design teams taking part. The Agile Design Framework is defined as the early implementation of the steps illustrated in Figure 6-1.

The study was carried out at Durham University on a single day using three locations: an informal area for introducing the study; a computer-laboratory for the actual design work; and a classroom for debriefing the participants after the conclusion of the design work. Each participant had an e-mail account set up for the purposes of this study and a shared network drive had been created for the experiment team to exchange data should they wish. Additionally, each participant would have access to the CAD software with which they were familiar, which was either SolidWorks or CATIA V5.

6.2.1. Participants

The participants undertaking design work were all male Design Engineers or Design Managers from defence or aerospace related companies, most of whom were questionnaire respondents from the previous stage of the research. Originally nine companies were contacted who had indicated a desire in their questionnaire responses to become more involved in the research in this field. Of those nine companies five company visits were carried out following a brief telephone call to explain the potential nature of this study. The response to the site visits was positive and all five companies agreed to participate in the study day which was subsequently arranged. Once the date had been confirmed for the study two companies dropped out at short notice and so two further participants, both design engineers, were found to replace them from local engineering companies working with Durham University on other projects. Of the five participants one was not a designer and so was given an alternative role in the study.

The remaining four participants were split into two teams in advance of the study. One team would use the Agile Design Framework to guide them in their design, while the other team were to be the control group. The control group were to be given the design brief and asked to go about the design in the way they would normally undertake any design task in collaboration. They were asked to consider themselves geographically separated and not to collaborate as if they were sharing an office. One purpose of this geographic separation was to ensure that the unexpected events could be introduced to one partner without the other knowing. To facilitate the separation the team partners were located in different areas of the laboratory. The experiment group were given these same requirements to be geographically separated, but before they began the design or were given the design brief they were required to undertake an additional stage during which the Agile Design Framework would be set up as shown in Figure 6-1.

One of the benefits of protocol analysis is the ability to control the environment in a way that is not possible with case study based research. Nevertheless, all variability cannot be eliminated and the make-up of the teams is one area where variability is inevitable. Although the four participants involved in design during this study were all design engineers with an engineering background, their individual areas of expertise, experiences in both design and collaboration, and their personalities introduced variability into the experiment. This was mitigated with the design of the project brief which will be covered in Section 6.2.3 as well as by accommodating differences to ensure the participants could all operate in their normal manner. For example, different CAD software packages were made available to eliminate the disadvantage which would be caused by a participant having less experience with an unknown system. One participant chose to use CATIA V5 rather than SolidWorks which was used by the other participants.

A further option could have been to run the study multiple times; however the knowledge introduced by taking part in the Agile Design Framework implementation would have precluded those participants from being in a control group in a future experiment. This would have meant requiring new participants which reintroduces the same variability.

6.2.2. ADF Implementation Phase

The Agile Design Framework implementation stage was introduced in Section 6.1 as a series of seven steps which will take a virtual enterprise from a collection of collaborating partners to an agile collaborative design team. For the purposes of this study a guidance document was developed to explain each of the steps that the experiment group should go through, including examples of the decisions they must make. This full guidance document can be seen in Appendix E.

Prior to the study, this stage was piloted with three graduate engineers with some experience of engineering design. The objective of the pilot was to ensure that the steps were clear and the process could be followed. It also provided a useful insight into the time that should be allowed for this stage, as the process took longer than expected. If this was the case during the experiment then any potential benefits of the framework would be negated by the time taken to implement it. Therefore, the detail of the framework was reduced to make it relevant to the size of project the participants would undertake. This highlighted an important issue for this research, in that for every project there must exist a balance point at which the time taken to implement the framework outweighs any benefit it brings through increased agility. This balance point will be different for every project and industry sector, but is a useful observation for the next stage of the research during which the framework will be tested in industry.

6.2.3. Design Brief

A suitable design brief was required for the purposes of this study, which had to satisfy certain criteria. The design problem must be:

- achievable to a reasonable level within the time allowed,
- able to split into separate design tasks for collaboration,
- of sufficient scope for unexpected events to be introduced which will impact the design process,
- of sufficient relevance, interest and engineering challenge to engage the participants, and
- within the abilities/skills of the participants but not in their specialist fields.

These criteria provided a benchmark against which potential design briefs could be assessed. Many products were considered and rejected as the subject of the brief including examples from Pahl and Beitz (1995). The eventual design brief was a mechanical product for the health services sector.

The teams were required to design a mechanical, human-powered device for transferring a patient from one bed to another in a hospital with minimal assistance from other hospital staff. The benefit of the product was the reduction in labour required to transfer a patient, a process which is currently done manually and requires between 3 and 6 members of staff.

The mechanical, human-powered nature of the brief was a reflection of the background of the designers in mechanical engineering. One of the participants also had a background in electric motors, and so by insisting on a non-electrical solution any potential advantage was mitigated.

Detailed specifications were given in the design brief document at the beginning of the experiment (Appendix F) and any further information was available from the researcher acting as customer. Any additional information sought by a team was given to both teams if it was considered a part of the basic specification requirements.

6.2.4. Unexpected Events

The objective of the protocol study was to test the effect of the Agile Design Framework on the agility of a collaborative design process. The protocol study is well suited to this as it provides the ability to control the inputs and outputs to the experiment in a way that other approaches do not.

The Unexpected External Events, as classified in Section 3.1 form one element of the input to the experiment which specifically aims to facilitate measurement of the effects of using the ADF in this environment.

In order to achieve this, the events must fulfil certain criteria:

- They must be classified as either: trivial, minor or major. Fatal events cannot be resolved with this approach,
- They must not create such a delay that the project is no longer possible in the time available,
- The teams must have the resources/knowledge at their disposal to respond to the event, although additional resources/knowledge could be provided as if an additional partner were being introduced to the project,
- The time taken to respond to the event must be clearly measurable; therefore it must be evident when the team has returned to the same level of completed work as before the event was introduced, i.e. the event has been dealt with.

Two events were defined which would be introduced during the study. The first was a Trivial/Minor event which was a change in the customer requirements as shown below. Changes in customer requirements were frequently cited in the questionnaire reponses as events to which design teams must react. The nature of the event (Trivial or Minor) would depend on the design the teams had adopted and the way the teams had split the design work. The memo given to the teams stated:

> "It has been identified that that the most difficult patients to transfer between beds are the heavier patients, as it is difficult to get enough people around the body to lift it in a controlled manner. Therefore, the NHS would like the device to cater for up to 180Kg if possible, with a factor of safety of 2.5."

Changes in customer requirements were cited as the most frequent source of unexpected events in the questionnaire responses. This event also fulfilled the criteria of an event that can be handled by one or both of the partners in a team with a time-delay which still allows completion of the project. The event was introduced on a sheet of paper in the form of an "Urgent Memo" to each team.

The second event shown below was a legislative change regarding lifting equipment which would be classified as Major (the name John Smith has been substituted in to maintain the anonymity of the participants):

> "New legislation dictates that all new lifting devices used in hospitals must be subjected to a simple stress analysis test and the results submitted along with the design. In order to do this the teams must obtain the results of a stress analysis test from an approved FEA specialist.
>
> You can contact the FEA Specialist (John Smith) on john.smith@durham.ac.uk. He will require CAD models from you as well as a detailed explanation of how the device is to work."

Once again the event was issued on a sheet of paper as an "Urgent Memo", however this time the memo was given to only one member of each team, selected at random.

This was to explore the effect of communication between the geographically distributed team members. The nature of this event required that both team members take some part in responding to the event and also introduced a third party into the project with whom the partners had no experience. For the purposes of this study the third party was explicitly identified as it was not possible to simulate the New Partner Identification process in the time and with the resources available.

The third party in this case was the fifth participant in the study who had no experience as a designer or engineer but an interest in the field of research due to his professional position. The fifth participant spent the time prior to this direct involvement in the study learning to use a Finite Element Analysis software package which would then allow him to participate fully as an additional member of each team at the appropriate time.

6.2.5. Data Recording

Accurate testing of the hypothesis using the protocol study method requires reliable data recording methods from which timings of activities can be taken and interactions analysed. A multi-method approach was used to ensure that multiple opportunities for capturing the required data existed.

The principal data-capture method was video and audio recording using a set of video cameras. The cameras were initially used to capture the control group in the early design stages and the experiment group undertaking the ADF implementation stage in a separate room. Once this had been completed the two cameras were co-located in the same computer laboratory but covering different areas. The cameras were set up to be as unobtrusive as possible but while still allowing audio to be captured in addition to video. The cameras captured the computer monitors as well as the actions and interactions of the participants. The participants were asked to verbalise their decisions and in particular their design process as much as possible. The location of the cameras in the laboratory can be seen in Figure 6-2.

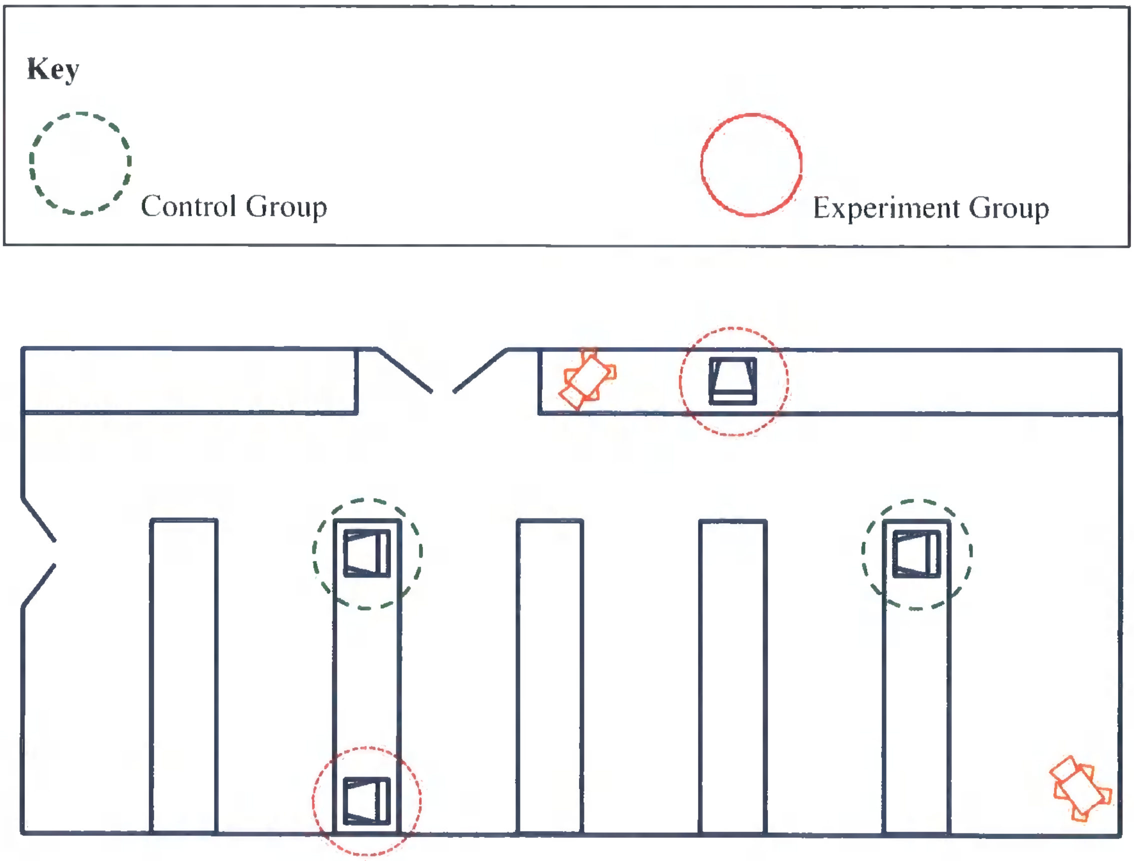

Figure 6-2. Layout of Computer Laboratory for Protocol Study

In addition to video and audio recording the participants were given notepads on which to write thoughts and sketch design ideas. The notepads were collected in at the end of the study. The participants were asked to keep a regular record of their progress on each task they were working on throughout the day. To assist with this process a timing sheet was supplied (Appendix G) which asked for the task they were currently working on and the percentage of the work done on that task at 15 minute intervals.

6.3. Results

There are two forms of result for the Protocol Study, both qualitative and quantitative. The qualitative analysis is in the form of a series of observations relating to the implementation process carried out by both the experimental group (guided by the Agile Design Framework Implementation Phase) and the control group (un-guided). Further observations were also made throughout the progress of the study. Quantitative analysis was carried out on the progress of the two groups in their design and specifically their responses to the artificially introduced external events. This timing data provides a measure in the form of the Key Agility Index by which the hypothesis can be tested. The table below shows the key events of the day on a timeline for reference:

Table 6-1. Event timeline for Protocol Study

Time	Event/Activity
09:30	Introduction to day
09:45	Control group begin conceptual design. Experiment Group begin ADF Implementation
10:17	Experiment Group complete ADF and begin conceptual design
11:05	Control Group completed Conceptual Design
11:25	Experiment Group completed Conceptual Design
11:30	Introduction of Event 1 – Change of factor of safety and specification
11:56	Lunch
12:49	Return from lunch
13:00	Introduction of Event 2 – Change in governing regulations
14:07	Control Group realise they don't have a copy of the Event 2 memo
14:12	Control Group begin response to Event 2 by trying to combine CAD models
14:17	Experiment Group begin responding to Event 2 by combining CAD models
14:26	Control Group receive rejection from 3rd party because of their use of SolidWorks file format
14:28	Experiment group receive completed FEA analysis (completed response to Event 2)
14:55	Control Group receive FEA analysis after combining models using a USB drive and neutral file format

6.3.1. Agile Design Framework Implementation

The Agile Design Framework implementation stage took 32 minutes at the beginning of the project from being handed the guidance notes to starting the conceptual design stage. During this time the steps outlined in the guidance notes (Appendix E) were discussed and the team made decisions on each step. These decisions were:

- Step 1: Define Project Management Structure
  - Immediately share information when it arrives with any of the partners in the organisation. This is to be done by e-mail. An automatic system would have been preferable whereby incoming e-mails are automatically routed to others as well.
- Step 2: Define International Standards and Terminology
  - Use Metric Units.
  - Use NHS (customer) own standards (assumed for this experiment).
  - Use relevant Governing Bodies such as MHRSA (Medical Health Regulatory Service Authority).
  - To develop a Bill of Materials style tree of parts terminology as the design develops.
- Step 3: Define Data Sharing Procedures
  - To save CAD files as STEP files.
  - To use .RTF for word processor files (.PDF considered but was not available).
  - To use .CSV instead of Excel file formats.
  - Use a shared directory to save files into.
- Step 4: Define Partner Identification Methods
  - N/A as any new partners required would be identified on their behalf.
- Step 5: Decompose Project into Individual Tasks
  - Once conceptual design stage has been completed they will divide the individual tasks up.
- Step 6: Define Interfaces of Individual Tasks
  - As for Step 5.
- Step 7: Scenario Planning
  - Supplier/Partner Failure – only use partners who have a proven track record and are well-known to them.
  - Use standard off-the-shelf parts wherever possible to prevent relying on single suppliers.

Observation 1

Participants had experience of some but not all of these areas. Anecdotal evidence given during the implementation stage illustrated that the participants had used some of these tools and techniques before, such as shared directories. However neither of the participants had experienced a formal setup process to explicitly cover these areas in this way.

In completing this stage of the process the participants showed experiences of where these steps had and had not been taken in previous projects they had been involved in. The use of automatic e-mail forwarding to multiple members of the team had been experienced by one of the designers but not the other. Problems arising from inconsistency of measurement units had been experienced where these had not been explicitly defined for a project. Therefore, one immediate benefit of this initial collaborative project setup approach was the combination of experiences and techniques in considering the different aspects of the framework. This would be of particular benefit when partners have experience of different sectors or sizes of project.

Observation 2

Not all of the steps were applicable at this early stage of the project and so some steps were deferred until later in the project. For some steps the need to revisit the step at a later stage to enhance the decisions was identified by the participants. This supports the use of a dynamic framework rather than a single closed process conducted at the start of the project which then sets firm rules.

Observation 3

The team decided to adopt the terminology of the ultimate customer, in this case the NHS, and generic terminology from the medical profession, for their design. This decision had not been picked up in the pilot study where it was decided to define part names and terminology as it arose during the project. However the decision raises an interesting point regarding the dominance of the customer, especially where it is a big organisation such as the NHS. In this case adopting the terminology of the customer (where standard terminology exists) is easier than adopting or defining new terminology.

An alternative to dominant customer terminology is where industry-specific terminology is already established as a de-facto standard. For example, the automotive industry refers to "left-hand" and "right-hand" sides of the vehicle. An alternative to this is the "near-side" and "off-side" of the vehicle which is relative to the pavement next to the vehicle. However, with vehicles being designed and manufactured in multiple countries where the side of the road on which the vehicle is driven can be different, the "near-side" and "off-side" can change, but the "left-hand" and "right-hand" will always be the same. Therefore, this adoption of industry or customer standard terminology can be integrated into the Agile Design Framework implementation guidelines.

Observation 4

The guidelines for the implementation encouraged a discussion regarding file formats for interchanging data. This highlighted that each of the designers would be using different CAD software, and therefore would need to use a neutral file format for exchanging data between themselves. Had this not been a part of the implementation there would have been potential for difficulties in exchanging data when it came to assembling the final design.

Observation 5

The experiment team spent 68 minutes discussing concepts following the agile design implementation which is a similar amount of time to the control team (80 minutes). Following their discussion regarding concepts the team revisited the agile design framework implementation to split the final concept into discrete modules of work which were functionally independent, allowing both designers to operate independently with a clear definition of how the two sections of the design would fit together later.

Observation 6

Although the decision was made during the ADF implementation phase to revisit the decisions and add to them/adjust them as necessary, the two partners of the experiment team failed to do this explicitly once they each began their individual aspects of the design. For example, the team identified the potential to have a bill-of-materials style list of terminology as the design developed, which could easily have been implemented through a single text file on the shared server. However this was never mentioned again after the initial implementation stage. This focus on the individual problem to the exclusion of the "bigger picture" became more evident during the introduction of the Unexpected Events as discussed in Section 6.3.3. Having a dedicated project manager responsible for the agile design framework may reduce this problem as there is explicit instead of shared responsibility for the framework and its implementation/update throughout the duration of the project. Additionally, having a review of the framework and the decisions that have been made as part of regular review meetings would provide a further opportunity to update the framework.

6.3.2. Control Group Project Setup Process

The control group were not party to the Agile Design Framework implementation but their activities throughout the experiment were analysed for elements of the process which were carried out in a less structured approach.

The team initially discussed concepts but did attempt to plan their working day by assigning timescales to each of the Concept, Embodiment and Details Design stages of the project. SolidWorks CAD software was discussed in terms of its built-in parts library which could be of use, meaning that the partners understood each was using SolidWorks software for their design. However the use of independent file formats was not discussed at this stage, nor was data sharing in general.

After 80 minutes of concepts research and discussion the team split the conceptual design into tasks, but did not specify clear interfaces between the tasks, leaving the two aspects of the design interlinked in an undefined way.

6.3.3. Response to Unexpected Events

The main benefit of a Protocol Study is the control over the environment. For the purposes of testing the hypothesis two specific events were introduced to the two groups of designers and the responses, both quantitative and qualitative, were observed as follows.

Change in Customer Requirements

The first event was a change in customer requirements as described in Section 6.2.4. The event was implemented in the form of a memo on a sheet of paper with the change of requirements on it.

The control group were co-located at the time of the event and at the stage of finalising the concept for their product. The event initiated a discussion about the suitability of the materials selected in light of the additional strength requirements. The additional discussion lasted 150 seconds before the group agreed on the changes required and returned to the stage they were previously at.

The experimental group were also co-located when the event was introduced and at the same stage of the process at the end of the conceptual design. The event also initiated a discussion about the materials for 58 seconds during which time the chosen materials were confirmed as being adequate to satisfy the new requirements. Although the experimental group responded more quickly to the event, it cannot be determined that this was a direct result of the Agile Design Framework.

Change in Legislation Requiring Finite Element Analysis

The second event was also introduced as a memo to just one member of each team after approximately 4 hours and 15 minutes of the project. At this stage both teams were sufficiently far advanced with their designs for the event to have an impact on the design, but there was still sufficient time for them to respond to the event and complete the brief. The team members were not told that the event was only given to one member of their team, meaning the team members not receiving the memo were unaware of the event until they were informed by their colleague.

Neither team acted upon the event information immediately as if they were not at a stage where the additional information was relevant to their activities. Once the teams reached that stage the time taken to complete the additional activities (compile the design into a single model and send it to the Finite Element Analyst for assessment) was recorded to assess the difference between the control and experimental groups. At this stage, particular attention was given in the video analysis to steps taken, specifically where there was a direct benefit of any aspects of the Agile Design Framework implementation.

The control group completed the additional tasks in a time of 43 minutes while the experimental group took 11 minutes. Both had very similar activities to undertake with two separate CAD designs to combine into a single model before sending to the FEA specialist. However the experimental group had the additional complication of using two different CAD software packages, as these were the packages each designer was familiar with. For this reason, they had agreed as part of the ADF implementation that they would store all their files in neutral STEP format in order to share files with each other.

The experimental group took 11 minutes to bring both parts of the design together onto a single computer and join them before sending them to the FEA analyst for processing. The control group began the process of combining the separate models nine minutes earlier than the experiment group and succeeded in sending an assembled model by e-mail to the FEA analyst after 18 minutes. However the assembly was in the native SolidWorks format which was not acceptable for FEA analysis as the FEA software could only import IGES and STEP files. The control group were notified of this by e-mail and began converting the necessary files into IGES files before bringing them back together for resubmitting to the FEA analyst after a total of 43 minutes.

From the video analysis of the activities, the time savings demonstrated by the experimental group can be clearly attributed to the following factors:

- A clear interface for the modules of the design, making assembly more straightforward. A like-for-like comparison of the assembly between the two sets of working files shows the experimental group assembling and submitting their design in 11 minutes against 18 minutes for the control group. A further benefit of the clarity of the individual design modules was the reduction in communication between the partners which will be explored further.
- The 11 minute time to submit the assembly for FEA analysis was also aided by a common data storage folder. This allowed the components to be assembled quickly without the need for clumsy data interchange such as e-mail with

which the control group had difficulties with the relations between individual CAD parts.

- The use of independent file formats meant that integrating the FEA analyst into the project was streamlined because the software used was compatible with the software used by the analyst. Only one attempt was needed to share the required information and get back the expected results, with no additional processing of data.

Although Protocol Studies provide a more controlled environment than real-life experiments or observations, additional and unplanned inputs to the experiment are always a possibility. During the experiment one of the Experimental Group members had to leave for a period of 45 minutes for business reasons. However, the other member of the team was able to continue their design work independently of the member who had left, as their designs were independent except for a single pre-agreed interface as prescribed by the Agile Design Framework.

6.3.4. Agility Scores

The total project completion times for the control group and experimental group were 360 (N_1) and 331 (N_2) minutes respectively. Importantly, the total project completion time for the experimental group includes the 31 minutes taken to undertake the Agile Design Framework implementation. The total delays caused by unexpected external events are the sums of the delays from both unexpected external events: 45.5 minutes (δ_1) for the control group and 12 minutes (δ_2) for the experimental group.

Based on the timing data from this study it is possible to calculate the Key Agility index of the control group as:

$$\kappa_1 = \frac{\delta_1}{N_1 + \delta_1} = \frac{45.5}{360} = 0.13 \qquad \textbf{Equation 4}$$

And for the experimental group as:

$$\kappa_2 = \frac{\delta_2}{N_2 + \delta_2} = \frac{12}{331} = 0.04 \qquad \textbf{Equation 5}$$

It is clear from these calculations that the experimental group has a better agility score than the control group, primarily as a result of its response to the second external event. It is of interest to note that by the benchmark determined from the industrial participants in the questionnaire in the previous chapter, both teams would be considered agile with KAI scores below 0.2. However in this controlled environment this can be attributed to a reduced number of unexpected events.

6.4. Discussion

The results of the experiment indicate that there are significant benefits to be made from the application of the Agile Design Framework, although showing these during such a short and artificially controlled experiment in the lab is difficult. Nevertheless the experiment highlighted several areas of interest, specifically:

1. Certain aspects of the framework cannot be fully defined prior to the conceptual design work being carried out, specifically: the division of tasks which is dependent on the conceptual design; and the definition of the interfaces between individual partners' aspects of the design.
2. The framework decisions must be fluid, being referred to and updated as the project develops. The terminology is a good example of this, because it was evident from the study that although preliminary steps can be taken to define terminology, as the experiment group did with adopting the customers' standard terminology, other terms will only be defined as the design develops.
3. That good project management and training is required if the decisions made during the implementation of the framework are to be adhered to and function as anticipated. If the decisions are not adhered to and the tools and techniques are not used then the benefits in terms of agility cannot be realised.

The first of the two events introduced to the teams was designed to be trivial and was managed in a relatively short time by both teams, 58 and 150 seconds respectively. The timing of the event as the teams completed the conceptual design stage and the fact that the teams were co-located contributed to the minimal delay.

The second event was considered as Major in the four-level classification scale defined in Chapter 3, because it dictated that external assistance was required in order to manage the impact of the event and continue the design. The control group had a response time of 43 minutes while the experimental group responded in 11 minutes to this event, primarily due to the effect of three aspects of their Agile Design Framework: Common Data Sharing method, Modular design with explicit interfaces, and the use of neutral file formats for the exchange of data.

One significant observation from the study is the contrast in the contact between partners of the two groups. The control group spent an initial 80 minutes in direct contact during the conceptual design stage, after which they separated to work independently. The two partners came together a further 10 times during the remaining 4 hours and 10 minutes of the project for a total of 49 minutes. In contrast the experimental group came together only 4 times during the same period, spending less than 3 minutes together in total. The majority of the discussion between the members of the control group concerned aspects of each other's design, or aspects of their own design affecting the other partner. It is suggested therefore that the significantly reduced contact between the experimental group partners was a consequence of the emphasis on modularity in the design process, meaning the two partners had less need to discuss matters affecting both parties.

The contribution of the specific data sharing method appears to contradict the findings from the previous section which suggested that an electronic data sharing method may not influence the agility of a collaborative project. However the findings here, particularly from the video observation of the two contrasting approaches, appear to support the assertion that the data sharing need not be electronic, but that it must be defined prior to the project commencement and tested for that use. It is possible to observe from this study that a data sharing method requiring data to be saved onto a disk and manually transferred could have been as effective in this case as a shared directory on a network. The control group eventually decided on this solution only after other attempts, including e-mail had failed.

6.5. Conclusions

This chapter has described a protocol study during which the design activities of a control group and an experimental group have been observed through video analysis. The objective was to identify the ways in which the implementation of the Agile Design Framework at the outset of a collaborative design project can influence a project team's ability to respond to unexpected events.

The results suggest that the Agile Design Framework had a positive influence on the agility level of the experimental group, with them achieving a Key Agility Index score of 0.04 compared with 0.13 for the control group. Three aspects of the framework were identified as significant in this instance: Modular design with clearly defined interfaces; the use of neutral file formats for shared data; and the use of a formal data sharing procedure which is defined and agreed at the outset of the project. It should also be noted that some aspects of the Agile Design Process could not be tested in this setting such as the identification process for potential new or replacement partners.

Further observations for the refinement of the Agile Design Framework were that the framework cannot be fully defined at the outset of the project. Some of the steps defined in the framework implementation process were well suited to early definition, such as data sharing, while others such as definition of interface cannot be completed until later in the design process. Furthermore, other steps such as the definition of terminology can be started during the initial implementation but must be revisited throughout the project as the product develops. This transforms the Agile Design Framework implementation from a process carried out before design, to a continual process begun before the design work and running alongside for the duration of the project.

The Protocol Study as a research method has limitations which mean that the results from a single study cannot be taken as conclusive evidence. Factors such as the experience and even the personalities of the designers, non-verbalised information which is difficult to capture, the lack of commercial pressures, unfamiliar surroundings and facilities, the time available and the number of participants all influence the outcome of the study in some way. In order to mitigate these known limitations, steps were taken to minimise the effects such as providing familiar software, balancing the experience of the designers in each team, and the use of multiple data recording methods.

The Agile Design Framework has been shown to be of benefit to the agility of collaborative design projects. A Key Agility Index score of 0.04 was achieved by the team who undertook the Agile Design Framework implementation, in comparison with a score of 0.13 for the control group. In addition, from this experiment there have been significant developments in terms of the implementation of the Agile Design Framework. The next chapter presents the final stage of the research methodology, namely the industrial validation of the Agile Design Framework.

Chapter 7. Industrial Trial

The previous chapter described the lab-based experiment during which the Agile Design Framework was implemented and critically assessed in a controlled environment. While advantages of the framework were measured during the experiment, further potential benefits were suggested by the industrialists taking part in the experiment. The participants suggested these benefits could not be seen during such a short and controlled experiment as that carried out in a laboratory setting. Furthermore, the observation of the implementation of the framework during both the pilot and actual lab-based experiment highlighted areas for improvement, in particular the need for a more dynamic and ongoing process with planned reviews.

This chapter will describe the final stage of the research methodology during which the Agile Design Framework was implemented in industry within a genuine collaborative design project. Some changes were made to the implementation process and these are described in detail along with the metrics for performance and the results of the experiment.

7.1. Experimental Setup

The objective of the experiment was to validate the Agile Design Framework as a suitable method by which the agility of a collaborative design project can be improved. In order to achieve this objective the design of this final stage of the research is justified here.

7.1.1. Project Requirements

In order to meet the objectives of this stage of the research there were certain criteria to which the project must conform if it was to be used as the subject of the industrial trial.

The project had to be collaborative in nature, because this research is specifically concerned with collaborative design projects. The collaboration could be either between multiple companies or multiple sites and divisions of a single large organisation, as geographical distribution and heterogeneous cultures and management systems were important. A project between designers sitting in the same office would not have provided sufficient scope for improvement using these techniques, because too many problems can be overcome simply by immediate interaction within the office. This is supported by Dekel (2005) who shows that despite methods such as video-conferencing and data-sharing procedures available for collaborative design, designers still favour face-to-face meetings.

The project had to involve product design work, and should preferably be at the stage that no design work had yet been undertaken. The project should be one that is in its infancy and will involve people from every aspect of the product life cycle from conceptual design to manufacturing. This is important as all of these departments have the potential to impact on the product design due to unexpected external events affecting their areas or responsibility. Additionally, a project in its infancy has a greater potential for unexpected events than a project that is almost completed, and the Agile Design Framework has been developed for implementation at the beginning of the project, not part way through.

Because of the limited timeframe available for conducting the trial, the project should also be one that would make sufficient progress during the three month observation period that was available. Therefore, at least the initial design work should be completed in this time so that observations could be made and the handling of numerous unexpected events could be reasonably expected during that period.

It was important that the market sector in which the project was conducted was a volatile one with many external influences. The project should also be a complete design and not simply a re-design of an existing product where only minimal adjustments are required.

7.1.2. Industrial Participation

The previous section described the requirements for the project to be used in the industrial experiment in order to meet the experiment objectives. Six companies had indicated a willingness to take further part in the research on Agile Design when they had completed the Industrial Questionnaire described in Chapter 5 and of these four had been visited with regard to the lab-based experiment. During the visits an enquiry was made as to their willingness to implement the Agile Design Framework in one of their forthcoming collaborative projects.

Four companies did not have suitable projects and two responded positively, offering their company as a test-bed. Of the two, one company was an electronic and communications systems integrator and the other was a first-tier automotive sub-assembly supplier. Following the lab-based experiment further discussion took place with both companies and it was decided that the automotive company satisfied the criteria better than the systems integrator, and so the company was chosen as the host of this industrial trial.

Prior to the implementation of the Agile Design Framework a number of visits were made to the lead partner involved in the project. During these meetings the objectives of the trial were discussed, as were the methods and outcomes, both expected in terms of increased agility, and also guaranteed in terms of feedback reports for the companies involved.

Appendix H shows the implementation plan which specified the approach to be taken, the metrics to be defined and the requirements for the project to be used for the experiment.

7.1.3. Project Description

The project itself was the design and manufacture of a hood (bonnet) release cable assembly for a well-established automotive manufacturer. The estimated project duration was 18 months, however it was anticipated that the majority of the design work would be carried out in the first three months, with prototyping, process design, testing and manufacturing validation taking up the rest of the 18 months to full-scale production. This made the project an ideal candidate for the industrial trial as the timescales fitted well. The project was also a good fit as it initially involved two different companies on three sites from within the same group, but with other partners to be identified and brought on-board as the project progressed. Some of the benefits of the Agile Design Framework are realised during the partner identification and integration process, again making the project a good fit to satisfy the objectives.

7.2. Data Collection

In order to establish whether an improvement in the agility of the company had been made, it was necessary to consider multiple metrics and observation techniques. Specifically, burn-down data, an Issues Tracker, and regular team meetings were used, and each is described in this section. The combination of these metrics and techniques provided the necessary data to then establish whether or not an improvement had been made, and to what extent any improvement could be attributed to the Agile Design Framework.

7.2.1. Burn-down rate

Work burn-down is the day-level tracking of effort left within a work iteration and has previously been used to monitor the progress of projects by plotting the data on a burn-down chart, illustrating the rate at which the project is nearing completion (Green, 2007). However in applying the burn-down metric to this experiment it has the additional benefit of visualising the impact of external events on the project.

Figure 7-1 shows the burn-down chart for a hypothetical project. The number of hours remaining at t_0 is an estimate by the person responsible for completing the task(s) represented by this chart. This does not have to be completely accurate, but should be considered carefully, as though the cost of a project was being based on this number of hours work involved.

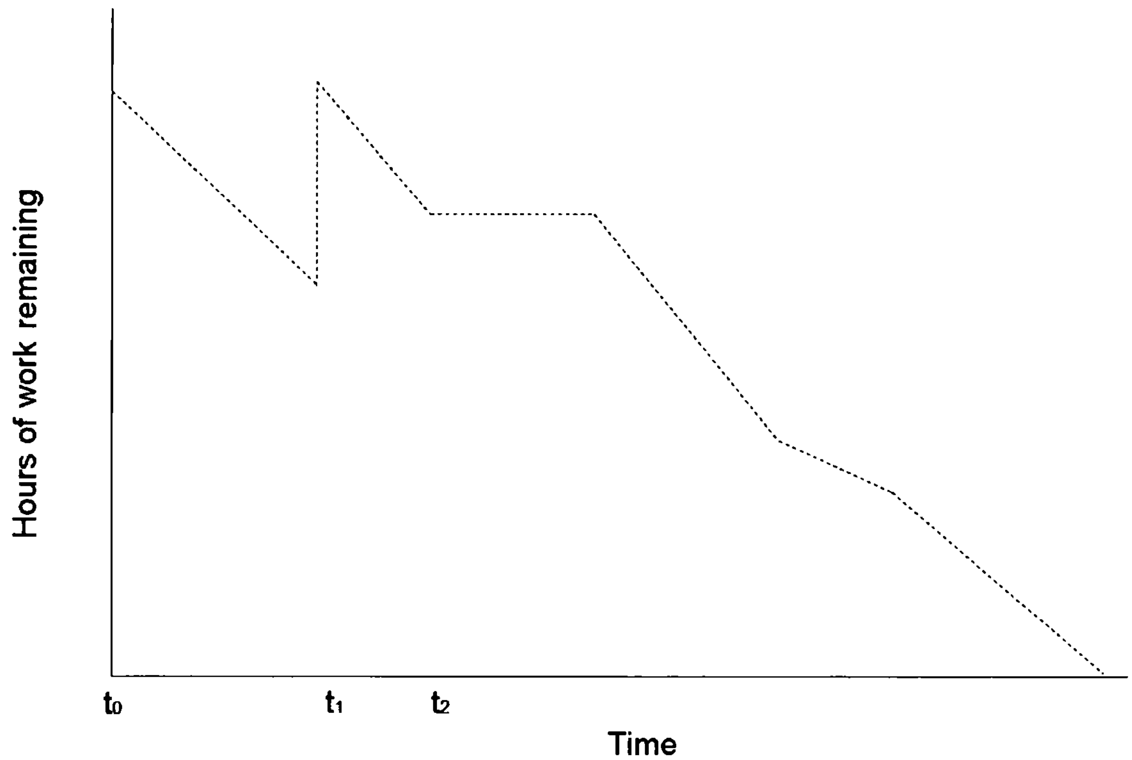

Figure 7-1. Work burn-down chart for a hypothetical project, illustrating the impact of unexpected events at t_1 and t_2

As time progresses the number of hours remaining on the project decreases in general, with two forms of exception. At t_1 the number of hours remaining rises sharply and by a considerable amount. There are two explanations for this rise:

- The original estimate for the number of hours to complete the project was wrong. This is a valid reason for increasing the number of hours remaining at any given time to give a true representation of how the task is progressing.
- Alternatively, an unexpected event may give rise to a sharp increase in the number of hours remaining, because of additional work which must now be completed. For example, a customer demanding that a design must now use a new type of cable terminator for a car door-handle assembly will increase the number of hours of work remaining.

The other exception to the falling number of hours is a period where the burn-down chart runs flat. Again, two reasons can be given for this:

- No work has been done on the project during this time, perhaps because of resource allocation issues (e.g. the person was working on another project).
- An unexpected event has meant that no work could be done in this time because, for example, more information or a resource with specific capability is needed before the task can be progressed.

The data from the burn-down charts was collected regularly through automated e-mails to all the team members. The e-mail contained 3 questions requiring a response:

- Time remaining on the individuals tasks,
- Hours worked on their tasks, and
- Activities/events that have contributed to a decrease/increase in hours remaining.

This data was compiled daily and used to create the individual burn-down charts for each team member. By creating burn-down charts for the industrial trial it was possible to create a profile of the progress on the project and combine these charts with two other forms of metric.

7.2.2. Issues Tracker

Throughout any project there are inevitably issues which become apparent which impact on progress. Some of these issues can be classified as Unexpected External Events as discussed earlier, and their source and magnitude can vary greatly.

In order to determine whether or not the Agile Design Framework is of benefit to the collaborative design project in this experiment, it was necessary to identify and monitor any issues that arose which had the potential to impact on the design of the product. To do this an Issues Tracker was used to record any issues arising during the project.

The Issues Tracker comprised a text document located on a shared drive which each member of the collaborative team had access to. Whenever any issues arose they were added to the document, along with the person responsible and the date on which the issue arose. An example of the Issues Tracker can be seen below.

Table 7-1. Sample Issues Tracker for tracking unexpected events

Open Issues Tracker		**PROJECT X**	REVISION DATE:	31-Aug-08				
			REVISED BY:	Chris Lomas				
ITEM	**ITEM DESCRIPTION**	**ISSUE STATUS**	**RESPONSIBILITY**		**DATE RAISED:**	**ORIGINAL DUE DATE:**	**REVISED DUE DATE:**	**DATE CLOSED:**
			NAME	**DEPT**				
1	Customer has reissued interfacing CAD data with slight amendments	Have placed the revised data on the shared drive and informed team members	CL	Design	n/a			
2	JF is on long term sick leave, expected back in Jan 08	TR selected to undertake JFs design work, but due date revised by 7 days to reflect delays	CL	Design	22-Oct-07	21-Nov-07	28-Nov-07	
3	Supplier X has indicated they will no longer be supplying R654 fasteners	KF has identified another supplier already	KF	Purchasing	n/a			
4	New software to be introduced for sharing data online similar to video conferences	All team members to undergo 2 hour training session at next team meeting in 2 weeks	CL	Project	22-Oct-07			

7.2.3. Team Meetings

Regular team meetings were used as a forum for empirical data gathering. The Issues Tracker was combined with the Burn-Down chart data to build a picture of how the project was progressing and what unexpected events had occurred which had impacted on the hours remaining on the project.

Individual team members were asked to discuss the issues they had documented on the issues tracker and a cross-check was made that the impact of any events was properly reflected in the burn-down charts.

7.3. Project Execution

The results of the industrial experiment can be decomposed into two forms: observations and decisions related to the initial implementation of the Agile Design Framework, and analysis of the unexpected events which occurred during the project and to which the partners had to respond.

7.3.1. Agile Design Framework Implementation

Project launch meetings at the company typically last half an hour, during which a brief overview of the product is given and the team are introduced to each other. The interfacing CAD data from the customer is shown if it is available at that point, showing where the product will sit within the vehicle and any specific constraints such as areas to route around or mounting points to be used.

As outlined in the implementation plan agreed with the company prior to launch (Appendix H), the launch meeting was extended to 3 hours for the purposes of implementing the Agile Design Framework for this project. The implementation meeting was attended by the following people:

- Team Leader & Chief Designer,
- Group Project Manager,
- Project & Design Support,
- Purchasing,

- Purchasing Support,
- Group Quality Director,
- Quality,
- Commercial / Managing Director,
- Purchasing Director,
- Manufacturing Process,
- Production,
- Logistics, and
- Logistics Support

A brief introduction to the framework was given, followed by a guided discussion of the seven steps:

1. Project Management and Reporting Structure
2. International Standards and Terminology
3. Data Sharing Procedures
4. Define Partner Identification Procedures
5. Decompose Project into Individual Tasks
6. Define interface between modules of the design
7. Scenario Planning

During the discussion decisions were made based on the project team's knowledge of the tools and systems they had available and their prior experiences. These decisions made by the group were noted down by the team members and are detailed below:

Step 1 – Project Management and Reporting Structure

A Team Leader had already been appointed to manage the project and ensure that deadlines were met. For the purposes of this experiment the Team Leader was given the additional responsibility of ensuring that people adhered to the decisions regarding the Agile Design Framework. The decision was made to appoint a deputy team (project) leader, as well as a main team leader, in case the appointed team leader was incapacitated for any reason.

Regular meetings of the project team were to be held, fortnightly at first, perhaps moving to weekly when necessary. Major issues were to be raised immediately with the Team Leader if help from outside of the team was needed, or raised at the regular meetings if they are not urgent. Issues and external events were also to be added to the Issues Tracker. The Issues Tracker was to be reviewed at each regular meeting and the issues discussed to find solutions and make the rest of the team aware.

The project team was to comprise a Core Team of four members and a peripheral team made up of the people present at this meeting. The benefit of this model was that each position had backup in the form of somebody else in the necessary department/role that had knowledge of the project. However the size of the day-to-day project team remained manageable, with the whole team only coming together when necessary. The four core team members were from Design, Quality, Purchasing and Customer Support departments within the same group, although based on three different sites and employed by two different companies.

Step 2 – International Standards and Terminology

It was agreed that all designs would be done in metric in keeping with existing company policy and that of the customer. Customer terminology was already well documented. Therefore this was to be shared with all team members through the shared drive system. The terminology used on the project timing plan was to be combined with the terminology of the customer to make external communication with the customer easier. The decision was taken to place more detailed descriptions on the Bill of Materials and always use those descriptions when referring to parts of the design to avoid ambiguity.

The use of standard components wherever possible was discussed and it was agreed that this should be done where possible, recognising the commercial pressures to deliver the project while also fulfilling the requirements of this experiment. Additionally a customer specification already exists which the design must adhere to.

In terms of standards for electronic data a previous problem concerning the sharing of project plans was discussed and it was agreed that all Microsoft Project files would be saved as pdf files. This was to mitigate problems with existing team members not having the necessary software, and to recognise that potential new partners may also not have Microsoft project software but would require access to the project plan. Similarly, all 3D CAD files were to be saved as IGES in case they were required by anyone who cannot view native CATIA files. 2D CAD files were saved as de-facto standard .dwg files which can be viewed with a free viewer where necessary.

Step 3 – Data Sharing Procedures

Shared access to a data repository for CAD files which has version control was to be set up for sharing CAD files between team members. CAD data was to be controlled by the team leader who is also chief designer, but stored centrally on this CAD data repository to be accessed by everyone. Additionally, a shared drive was to be created for the project files which are not CAD files. A folder structure was to be implemented on the drive which can be reviewed and changed in future as necessary. At the next meeting there was to be a demonstration of how to use the shared folder structure.

Step 4 – Define Partner Identification Procedures

The existing Approved Supplier List was to be modified to include multiple suppliers for common products to protect against one of the existing preferred suppliers being unable to satisfy any future requirements. There already existed a backup in place for the cable assembly plant where the final products were expected to be manufactured. The Purchasing Representative was to identify a backup manufacturer of the other parts once the design has been developed and more detail is known.

In order to protect against failure (for example through illness, other work commitments, or departure from the company), it was agreed that designers could typically be replaced in-house from within the design department of one of the collaborating companies. However, a source of design contractors was also identified if absolutely necessary.

Step 5 – Decompose Project into Individual Tasks

The CAD elements of the design were to be undertaken by a single designer with support from two other project team members where necessary, while the additional aspects of the design process such as supplier identification, manufacturing process planning etc. were to be carried out by other members of the team. The individual areas of responsibility were divided among the partners present at the meeting; however the individual tasks for each team member were to be published on a more detailed project plan along with timings which link to the overall timeline presented at this meeting. This detailed task allocation was to be carried out by the Team Leader and was placed as a job outstanding on the Issues Tracker.

Step 6 – Define interface between modules of the design

As it was not possible at this early stage to decompose the conceptual design into individual parts, there was no possibility to define interfaces between different aspects. This will be reviewed in future meetings and amended if necessary.

Step 7 – Scenario Planning

A scenario planning exercise was carried out which led to some of the decisions which have already been documented: the use of neutral file formats for Microsoft Project files, the need to identify multiple manufacturing sites for production of component parts. In addition, each individual area of responsibility was covered by more than one person so that if any individual could not fulfil their responsibilities for any reason, another person with the necessary skills and knowledge could be used.

7.3.2. Observations of the Initial Implementation Process

The implementation process took two hours to complete which was less than the three hours allowed. The large number of participants and broad range of experiences led to useful discussions, particularly when discussing prior unexpected events for scenario planning. For example, one participant remarked that they had never been able to open the project plan in Microsoft Project format, and so had never known if the project was on time or delayed. Nor had they known when the relevant deadlines were. To counter this, a neutral format (Portable Document Format - pdf) was agreed so that in future participants would be more engaged with the project.

Additionally, data sharing has been a source of delay in the future when incorrect versions of documents have been used or the necessary files are located on the computer of somebody who is not available. There was a strong desire to address these problems by setting up communal space on a server which could be accessed from multiple sites and by any of the partners, simply with the necessary permissions.

The decision to identify alternatives to the suppliers was driven by the collapse of two established suppliers during the previous two weeks. This also supported the discussion regarding the use of common parts where possible to allow a much broader range of suppliers. There was currently a problem with another project involving some of the same partners where a pin which had been designed could not be sourced from a supplier "because it is not standard". This was causing a delay in producing prototypes which could be avoided through using common parts, although it was recognised this is not always possible.

7.3.3. Continual Revision of the Agile Design Framework

In light of the results from Chapter 6 the implementation of the Agile Design Framework was developed from a single pre-design stage to an ongoing process to be revisited throughout a project. Therefore, for this case study the requirement to revisit the decisions made at the outset of the project was stressed to the project team. It was agreed at the project launch that this revision could be done at any time by contacting both the team leader and their deputy to raise any suggestions for additions or amendments to the decisions already made. Additionally, a review of the Agile Design Framework was to be carried out at each full team meeting, providing a formal opportunity for updating the framework and notifying all key personnel of any changes.

7.3.4. Project Progress

The project was observed over a period of 27 weeks through regular e-mails with the project team, attendance at team meetings and telephone conversations with the team leader. The principal area of collaboration was between the designer and the customer which introduced an international element to the project as the customer was based in Germany while the designer was based in the UK. The majority of the time spent on the project was by the Chief Designer (177 hours) with other work being carried out by the other partners including Purchasing (8 hours), Quality (8 hours) and Design (1 hour).

Core Team meetings were held every two weeks initially and then only every two months after the first 8 weeks, whenever there was sufficient progress to report. A regularly postponed deadline from the customer meant that resources were diverted elsewhere and progress on the project was not at the speed originally anticipated. During the team meetings the Agile Design framework was reviewed as agreed.

The two principal revisions to the framework both concerned the exchange of data between team members. The team had agreed in the initial implementation that a barrier to responding to unexpected events previously had been a lack of access to the most up-to-date information which had been stored on team members' own computers. Therefore, a shared directory system was to be set up, however this tool 3 weeks to complete and was therefore introduced at a later team meeting. At this stage the protocol for use of the shared directory was agreed between all members, including a directory structure and set of rules for the creation of new directories, and the content which should be stored on this central system. Secondly, new web-based CAD collaboration software was introduced to assist in the reviewing of CAD models between partners in the team who were geographically separated. This was of particular use to the designers working in the team and reduced the number of hours travelling required.

The Chief Designer's progress during the 27 weeks of observation can be seen in Figure 7-2. The turbulence of the project can be seen by the high number of spikes during the project, each of which relates to an increase in the work which must be done as a result of an unexpected event. In the case of the designer each event was a change in requirements from the customer which required a re-design of all or part of the product. Obtaining details on the reason for the change from the customer was not possible. The flat sections of the chart between weeks 8 and 12, and between 16 and 18 represent the Christmas and personal holidays respectively.

Of the 177 hours spent on the project by the Chief Designer, the data from the issues tracker and automated e-mail responses indicate that 87 hours were in response to unexpected events, primarily changes in requirements from the customer, which dictates that the time to complete this project without the delays was 90 hours.

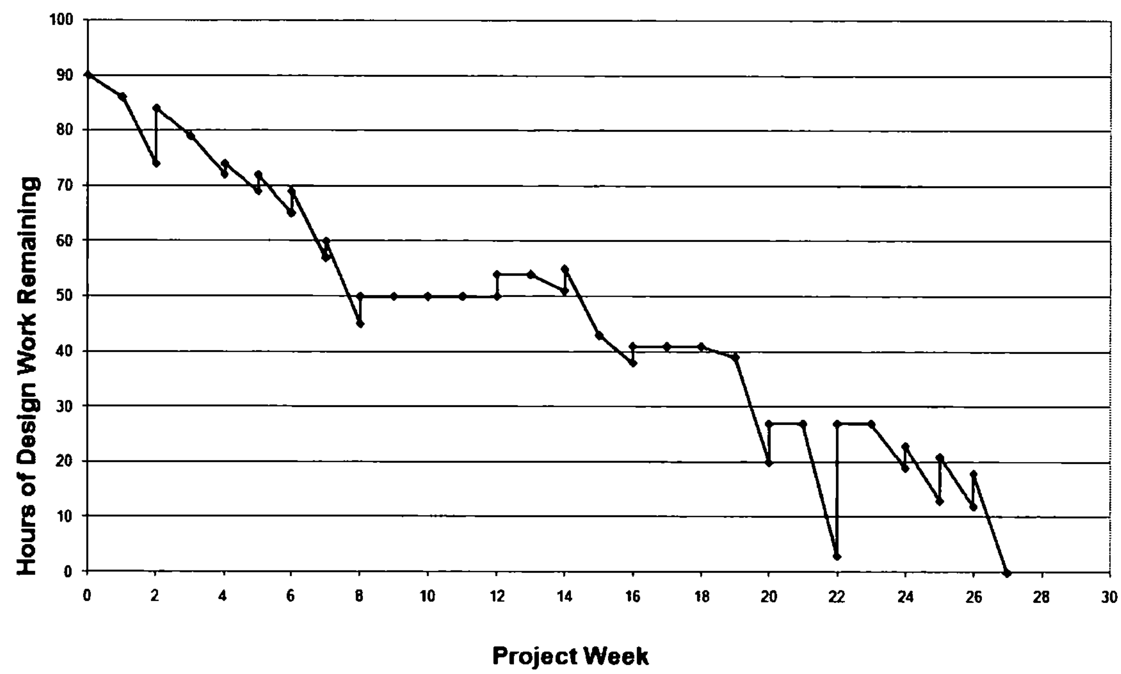

Figure 7-2. Project Progress of Chief Designer Shown as a Burn-Down Chart

The Results section will discuss the causes of the delays show in Figure 7-2 as well as those experienced by the other team members, and the responses to those delays in terms of the impact of the Agile Design Framework on any responses.

7.4. Results

The following two sections discuss the qualitative and quantitative results of the industrial trial. A Qualitative measure of any improvements will be described by addressing the two principal areas of turbulence and the effects on the project as described by the affected team member. Quantitative analysis of the benefit of the Agile Design Framework is difficult as a direct comparison between two identical projects is not possible. However, through the use of semi-formal interviews with the team members on completion of the project it is possible to obtain their interpretations of the benefits realised through this approach. These can be used to produce a quantitative measure of any improvement in agility demonstrated.

7.4.1. Qualitative Analysis

Despite the turbulent nature of the automotive industry the UEEs experienced during the project were limited to two even types, although one type occurred multiple times. These events were: changes in customer requirements (although their causes are unknown); and partner failure resulting in the introduction of a new and geographically separated partner into the collaborative team. Informal interviews with the project team were used to understand the delays and the benefits of any of the ADF tools and techniques.

Requirements Changes

During the project there were more than ten changes in customer requirements, each of varying magnitude. These ranged from minor routing adjustments for the cable to complete redesigns of the handle assembly including materials changes. The requirements changes were the major cause of delays to the project. Each of these events was classified as Trivial or Minor on the four-level classification scheme (Section 3.1.2) as they could be managed within the existing project team, often with no assistance (Trivial) and occasionally with assistance from within the project team (Minor).

Through informal interviews with the project staff it has been possible to establish a link between the implementation of the Agile Design Framework and a more rapid response to these requirements changes. In particular, as outlined in the previous section, the use of collaboration IT tools such as CAD data sharing software and a shared document folder (ADF Implementation Step 3) both provided significant time-savings through immediate access to the most up-to-date information without disrupting other team members.

Partner Failure

The second major source of turbulence was the failure of one of the project partners which was caused by their unexpected departure from their employer. In this case an alternative suitable partner was required who could deliver the work which was required. The requirement for external assistance and integration of a new partner classifies the event as Major on the four-level classification scheme introduced previously.

During the Agile Design Implementation a secondary partner for each of the principal roles had been present. This provided a reliable Partner Identification Method (ADF Implementation Steps 1 and 4) in cases such as the one which arose, as it meant they were fully conversant with the project details and management procedures. The process for integrating the new partner to the project team was therefore much simpler than it would have been if a completely new partner had to be identified. Time savings purely on the integration of the new partner were estimated at twelve man-hours by the Project Manager who facilitated the integration, six for the Project Manager and six hours for the replacement partner.

Further savings can be seen because the process of identifying the new partner would have been sufficiently longer if the secondary partner had not been in place. If a new partner had to be employed then the delay could have run to months, although the activities were not on the critical path and therefore the project delay would not have been affected by months. Nevertheless, the Project Manager's involvement in the process would have caused a further delay of as much as 4 hours.

Finally, the time savings in this event could have been greater if the partner who left the organisation had made proper use of the data sharing facilities as agreed during the ADF implementation (Step 3). The lack of legacy information from the departing partner caused an additional two hours of work for the Purchasing Replacement which could have been reduced to as little as 30 minutes if the agreed procedures had been followed.

7.4.2. Quantitative Analysis

Table 7-2 shows the hours worked by each team member on the project, the amount of that time which was spent responding to unexpected events, and the hours they believe were saved through different aspects of the Agile Design Framework, based on their previous experience.

Table 7-2. Project hours of the team members

Partner	Total project hours	Of which were due to delays	Savings due to Agile Design Framework
Chief Designer	177	87	38
Assistant Designer	1	0	0
Purchasing	8	0	0
Quality	8	0	2
Purchasing Replacement	16	4	6
TOTAL	**210**	**91**	**46**

Table 7-3. Observed time savings for Chief Designer due to Agile Design Framework

Use of web-based collaboration software	24 hours
This was through savings on travel times to discuss design requirements changes from the customer	
Partner Identification procedures	10 hours
When a partner failed and was replaced the replacement was already familiar with the background to the project and the working procedures which resulted in a 6 hour time saving. The process of identifying a new partner would have taken up to 4 hours in addition to the integration time.	
Use of shared directory system for data sharing	2 hours
The previous method of data sharing had required distractions to the Chief Designer to find the necessary information and send it to other partners. This was removed during this project causing a minimum of two hours time savings.	
Use of neutral file formats for shared data	2 hours

> During the lessons learnt process it had been identified that the project plans had not been accessible to all partners, causing delays while the Project Manager gave the information to others. This delay was removed through the use of neutral file formats for shared data.

The savings observed by the Chief Designer/Project Manager (in hours) during unexpected events were achieved through the following activities which formed part of the agile design framework implementation and are shown in Table 7-3.

The Purchasing Replacement spent a total of 16 hours on the project during the same period, with four hours being due to unexpected events. These four hours are broken up as two hours spent with the Project Manager getting up-to-speed with the project, and two hours collecting the data from the previous Purchasing Manager who had since left the company unexpectedly. Interviews with the Project Manager and Purchasing Replacement indicate that six hours was saved through the inclusion of the Purchasing Replacement at the beginning of the project and their understanding of the project management procedures, including the use of the data sharing practices.

The Quality Manager spent eight hours on the design project, none of which were due to unexpected delays. However it is suggested by the Quality Manager that up to two hours would have been spent responding to unexpected changes if the Agile Design Framework had not been implemented. These savings relate to the ability to access shared data immediately rather than wait for other partners to provide it. The use of neutral file formats also assisted in this process as previously the inability to access the required data due to incompatible software had been a cause of delays.

From Table 7-2 the timings for calculation of the Key Agility Index can be calculated:

With Agile Design Framework

$\delta_I = 91$ Total delays to project with ADF

$N_I = 210 - 91 = 119$ Original project duration (total duration – total delays)

Without Agile Design Framework

$\delta_2 = 91 + 46 = 137$ Total delays to project without ADF

$N_2 = 210 - 91 = 119$ Original project duration is the same as with the ADF

From this data a score for the Key Agility Index of this project can be calculated as:

$$\kappa_1 = \frac{\delta_1}{N_1 + \delta_1} = \frac{91}{119 + 91} = 0.43$$ **Equation 5**

The savings achieved from the ADF implementation, based on the evidence provided by the team members, indicate this score would have been 0.54 if the ADF had not been adopted for this project:

$$\kappa_2 = \frac{\delta_2}{N_2 + \delta_2} = \frac{137}{119 + 137} = 0.54$$ **Equation 6**

Although 43% of the time spent on the project was in responding to unexpected events, it has been shown that this figure would have been 54% if the Agile Design Framework had not been implemented for this project. Furthermore, as well as a reduction in the proportion of time spent responding to unexpected events, a real-world time saving of 46 man-hours has been achieved.

7.5. Conclusions

Ottosson (2004) proposes Insider Action Research as a reliable method for research in this field of engineering design, the principal benefits being the realistic environment and the proximity of the observer to the subject of the study. This chapter has described an industrial implementation of the Agile Design Framework in a collaborative design environment. The framework as it was implemented in this experiment was developed from the version in the previous chapter to place greater emphasis on the need for explicit and dynamic project management. This development was to ensure that the decisions were adhered to throughout the life of the project, and to ensure that the framework was revisited regularly to update and add to it.

The project ran for 27 weeks during which time the majority of the design work was carried out by the Chief Designer, with additional elements contributed by the Quality and Purchasing Managers, the Assistant Designer and the Purchasing Replacement.

There were two main causes of unexpected event during the project: Customer requirements changes which caused in excess of ten events; and partner failure which caused one event. Each of the customer requirements changes were classified as Trivial or Minor on the four-level classification scheme (Section 3.1.2) because they could be managed and rectified without external assistance. The partner failure was classified as Major because an additional partner was required from outside the immediate project team to continue the outstanding work.

Through regular observations of the project by the researcher, as well as project documentation and post-project interviews, elements of the Agile Design Framework were identified as having reduced the impact of these events significantly. In particular the use of clearly defined data sharing techniques, an established method for replacing partners internally, and the use of neutral file formats all contributed in this instance to increased agility through a reduction in the time taken to respond to unexpected events.

The Key Agility Index was agreed prior to the start of the project as a suitable metric for testing the hypothesis through this experiment. The Key Agility Index illustrates that the agility score of the project was 0.43, but this figure would have been 0.54 had the Agile Design Framework not been implemented for this project. This represents a real-world time-saving of 46 man-hours for this design project.

Some aspects of the Agile Design Framework have not been of benefit during this project, principally because unexpected events which would require their use did not occur during the observed period of the project. However, other elements have played a significant role in the reduction of delays caused by unexpected events, demonstrating the benefits of the framework as a whole.

In terms of testing the hypothesis of this research the results of this third stage of the research, quantified by the Key Agility Index, clearly illustrated that the agility of a collaborative design project can be increased through the structured implementation of a set of tools and techniques defined in this research as the Agile Design Framework.

Chapter 8. Conclusions

The hypothesis presented in this research is that a specific set of tools and techniques can be implemented to increase agility in a collaborative design environment. In order to test this hypothesis, this thesis has described a novel framework for the increase of agility levels in collaborative design environments. The framework, referred to as the Agile Design Framework, is founded on a set of core tools and techniques which have been shown to be of benefit to engineering design or collaboration. These tools have been combined with a novel implementation process defined by seven steps at the initial stages of any collaborative design project. These seven steps are subsequently supported by frequent revisions to the implementation throughout the project to further define the tools and techniques with a view to further increasing agility.

8.1. Empirical Evidence

The Agile Design Framework has been developed through the use of a three-stage methodology, which has also facilitated testing of the hypothesis using a number of methods. A literature review identified tools and techniques currently in use in industry or under research in academia. These tools were considered to be of benefit to areas related to the field of collaborative agile design such as multi-company collaboration, engineering design and agile manufacturing. The results and conclusions of each stage of the methodology are discussed here.

8.1.1. Methodology Stage One

The first stage of the methodology was an Industrial Survey, the objective of which was to identify the relationship between the many tools and techniques identified in the literature and the level of agility achieved in collaborative design projects adopting these tools and techniques. The level of agility was measured using the Key Agility

Index which allows a numerical score of agility to be calculated at the project or departmental level rather than the overall organisational level.

The survey received 19 correctly completed responses from suitable companies and the data was analysed using Principal Components Analysis and Varimax rotation to identify the underlying themes to the responses. The use of Principal Components Analysis allowed the relatively high number of variables (39) to be reduced into a smaller number of meaningful factors (5). The Varimax Rotation of the principal components then allowed themes to be assigned to those factors by reducing the number of variables in each factor.

The most significant themes found to be associated with high levels of agility were those of formal "Project Setup" which included such techniques as holding a meeting of all collaborating parties prior to the start of the project; having a representative from every one of those companies attend the meeting; team members knowing who was co-ordinating the collaborative project and to whom they should report any delays. Additionally, the use of common measurement units was prominent, as was the ability to plan for and have set responses to unexpected events.

This stage of the methodology identified the significant themes associated with high agility levels and so informed the initial definition of the Agile Design Framework. The framework was initially conceived as a process to be undertaken principally at the outset of the project once the customer requirements had been gathered, but prior to any design work taking place.

8.1.2. Methodology Stage Two

The second stage of the methodology involved the implementation of the Agile Design Framework in a controlled laboratory environment. Two collaborative teams of two designers were given a design brief to undertake during the course of one day. One team undertook the Agile Design Framework implementation process while the second control group were asked to undertake the brief with no further guidance.

The experiment was observed and video and audio recording equipment was used for post-experiment analysis. During the experiment two unexpected events were introduced to the environment, and the response to those events was analysed.

The results concluded that the Agile Design Framework had a positive influence on the agility level of the Experiment Group, with them achieving a Key Agility Index score of 0.04 compared with 0.13 for the Control Group. Three aspects of the Framework were identified as significant in influencing the Experiment Groups ability to respond more quickly: Modular design with clearly defined interfaces; the use of neutral file formats for shared data; and the use of a formal data sharing procedure which is defined and agreed at the outset of the project.

In addition to demonstrating a benefit of the Agile Design Framework in increasing agility levels, further observations were made which allowed the framework to be developed further for the final stage of the methodology. Specifically, the framework cannot be fully defined at the outset of the project. For example, steps such as the definition of Terminology can be started during the initial implementation but must be revisited throughout the project as the product develops. Also, steps such as definition of interfaces between tasks or sub-designs cannot be completed until later in the design process. These observations transformed the Agile Design Framework implementation from a process carried out before design, to a continual process revisited throughout the project in addition to an initial implementation stage.

8.1.3. Methodology Stage Three

The final stage of the methodology was the industrial implementation of the Agile Design Framework. During this stage the Agile Design Framework was implemented in a real-life collaborative design project involving multiple companies and geographic locations over a period of 27 weeks. The initial project launch meeting was extended to accommodate the Agile Design Framework implementation process which was guided by the Project Manager and the researcher. The decisions made during the implementation were documented and, in line with the findings of the previous stage of research, these were revisited at regular intervals as part of the frequent project team meetings.

During the project there were two significant sources of unexpected event to which the project team had to respond. These were regular customer requirements changes and the complete failure one of the team partners. The failure of the partner was a team member leaving the company immediately which meant a replacement partner had to be found. This event would be classified as Major on the four-level classification scheme which has been defined by the researcher as part of this research, as assistance from outside the collaboration team was required. The frequent requirements changes were classified as Trivial or Minor meaning that they could be dealt with by the affected party or with the assistance of existing members of the project team.

The summation of each of these events caused delays to the project of 91 man hours in a total of 210 project hours. Therefore, the Key Agility Index for this project has been calculated as 0.43. Data recording techniques used throughout the project, combined with informal post-project interviews, indicate that the Agile Design Framework reduced the impact of these delays by 46 man hours. This indicates the agility level would have been 0.54 if the Key Agility Index had not been implemented for this project. These figures illustrate quantitatively a decisive improvement in the agility level as a direct result of the Agile Design Framework.

8.2. Hypothesis Testing

The objective of this research was to test the hypothesis that the specific implementation of a set of tools and techniques could improve the agility of a collaborative design project. The hypothesis has been tested using a three stage methodology which has tested the methodology at each stage with an alternative method, while also refining the set of tools and techniques and the implementation process.

The results of the industrial survey indicated a correlation between the tools and techniques and increased levels of agility as measured with the Key Agility Index (Section 5.7). In particular the themes of Project Setup and Measurement Units and Reaction Process to UEEs & Planning for UEEs were identified as significantly correlated with increased levels of agility. The second stage of the methodology took the prominent themes from the survey and developed the Agile Design Framework to retest the hypothesis with a specific implementation in a controlled and laboratory-based protocol study. Increases in the agility level were measured for the experimental group using the Agile Design Framework, with an agility score of 0.04 compared with a score of 0.13 for the control group. Finally, the industrial implementation has tested the hypothesis using a refined Agile Design Framework in an uncontrolled industrial environment (Chapter 7). Increased agility levels have been measured, with a combination of both qualitative and quantitative evidence suggesting an increase in agility level from 0.54 to 0.43 using the Key Agility Index (Section 3.3.1). Furthermore, industry participants have supported the assertion that the framework has assisted in responding to unexpected events.

8.3. Contribution to Knowledge

As a result of the activities undertaken in this research for the development of the Agile Design Framework, this research has made contributions to knowledge in three complementary areas related to agility, design and collaboration. These areas of novelty are presented here.

8.3.1. Agile Design Framework

Through a multi-method approach this research has developed a novel design framework which can be adopted in a collaborative design environment to increase agility levels in response to turbulence.

The novel implementation process coupled with a specific combination of existing tools and techniques have been shown to have a positive influence on agility in this environment using multiple testing methods in both controlled laboratory settings (Chapter 6) and industrial implementation (Chapter 7).

8.3.2. Event Classification

In addition to the novelty of the Agile Design Framework this research has also presented a novel four-level classification scheme for unexpected events, categorising them as Trivial, Minor, Major or Fatal (Section 3.1). This classification scheme is of benefit in the planning of unexpected events in a research environment and the discussion and analysis of events in an industrial setting.

8.3.3. Agility Measurement

Finally, the Key Agility Index has been shown to be a valid metric for agility at the project or departmental level. The Key Agility Index (Section 3.3.1) has benefits over other agility metrics as it operates at this project level with easily obtainable data.

By contrast, other measures presented in this research operate at the organisational level to provide a quantitative score or use the attainment/presence of a set of characteristics to define agility, rather than a quantitative measure based on specific performance.

8.4. Future Work

This work has focussed specifically on the collaborative design environment to develop a framework which increases agility in this setting. As a result, some areas of interest have not been fully explored as they were outside the scope of this research topic. Nevertheless, they represent interesting areas for future exploration and are described in this section.

The implementation of the framework in different sizes and sectors of organisation and with different sizes of project has not been explored in depth. This area of research could be further enhanced with the exploration of the trade-off between the time spent on the ADF implementation stages and the benefit realised through its use. It is anticipated that for different sectors of industry which experience different levels of turbulence, there exists a balance point at which the benefits will be outweighed by the time taken to implement the ADF. In this scenario it may be that a priority can be placed on the different aspects of the ADF depending on the source of UEEs or the level of turbulence experienced in that sector.

The tools and techniques identified in the literature are not exhaustive and an exploration of the additional features which could be incorporated into the framework would provide an interesting extension to this research. For example knowledge management, although partially addressed through prior experiences during the ADF implementation, is a large area of research in its own right. The use of knowledge management tools could provide additional opportunities for increasing agility.

Furthermore the eventual Agile Design Framework can be classed as a project management tool for engineering design. Therefore, the application of the Agile Design Framework in fields other than engineering design could be of significant interest. The challenges face by other industries where collaboration is a central part, can be similar to those faced in engineering. An example might be the National Health Service or the many government departments whose offices are geographically separated. "Projects" similar in structure to those in engineering design are regularly carried out in these sectors and there certainly exists a turbulent environment in which these sectors operate. Therefore, an industrial implementation into one of these sectors may illustrate a realisation of the same benefits: increased responsiveness to changes to which the organisation must react to minimise the penalty.

The limitations of the Key Agility Index as described in Section 3.3.3 could be the subject of an interesting area of future research. The inclusion of the quantity and magnitude of unexpected events into the equation would allow the comparison of agility between different industries, projects and companies because the score would be normalised against the turbulence experienced. To achieve this a more detailed study of the nature of "events" would be required to allow a numerical value to be placed on the events and their total potential impact.

It could be that the 4-Level event classification proposed in this research provides a sound starting point for this work which would inevitably involve significant case-based research as a minimum, and potentially industry based experimental work to understand the impact of these events on different projects.

Finally, further validation of the Agile Design Framework could be carried out with more in-depth protocol study work. This could be used to test different implementations of the framework, test the response to a wider variety of events in terms of both magnitude and frequency, and investigate the human influences on the ADF in terms of the affect on response times with different people operating in the same way to the same implementation of the ADF.

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Appendices

Appendix A. Industrial Questionnaire

Appendix B. Covering Letter from NDI

Appendix C. Anonymised Sample Benchmarking Report

Appendix D. Cronbach's Alpha Values for Questionnaire Constructs

Appendix E. Agile Design Framework Implementation Explanation Document

Appendix F. Protocol Study Design Brief

Appendix G. Timings Crib Sheet for Protocol Study

Appendix H. Industrial Experiment Implementation Plan

Appendix A

Industrial Questionnaire

Northern Defence Industries

Agile Design Survey

In conjunction with Durham University School of Engineering.

Introduction

The purpose of this questionnaire is to investigate the current trends in *product design*, the disruption caused by unexpected external events, and the extent to which companies are equipped and prepared to deal with such events.

Your participation in this survey is greatly appreciated and will contribute to the advancement of knowledge in the field of Agile Design. To conclude the study a report on the findings and Agile Design will be made available to all companies, and you will receive an individual 16-page feedback report for your company with details of your agility level and a bench-marking report against the NDI membership.

The questionnaire is split into the following 5 sections focusing on different aspects of your product development process, in particular the design stages of new product introduction.

1. Project Setup
2. Communication
3. Unexpected Events
4. Design Techniques
5. Recent Projects

Wherever possible we will use only the information supplied in this questionnaire, however we would be very grateful if you could supply a contact telephone number and/or e-mail address in the Company Details section in case any answers are unclear or further information is required.

Contact

Chris Lomas
School of Engineering
Durham University Science Site
Stockton Road
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DH1 3LE

Tel: 0191 334 2487
E-mail: c.d.w.lomas@dur.ac.uk

Company Details

Company Name: ____________________

Questionnaire Completed by: ____________________

Job Title: ____________________

Contact Phone Number: ____________________

Contact E-mail: ____________________

All reasonable efforts will be made to preserve anonymity when using the data provided in this questionnaire. However, your company name, not relating to any specific information given, may be published as evidence of the companies taking part in the study. If you do not wish to have your company name published then please indicate this by ticking this box. ☐

If you would be interested in improving your company's design agility by taking part in further research or experiments then please tick this box. ☐

Terminology

Division: refers to a section of a company. For example a department (design, marketing etc.) or a geographical site (UK branch, USA branch, London office, Newcastle Office etc.).

Project: refers to a project carried out in collaboration between companies or *divisions.*

Team members: refers to any member of any company or *division* involved in the *project,* **not** just within a particular company/*division*

Project team: refers to all *team members*

Unexpected Event: refers to an event which is ***external*** to your division and was not planned for in the project schedule.

Your Projects

Please tick one box.

If your company operates some design projects as part of a collaborative team with other companies, then please tick the box and answer the questions with regard to this type of collaborative project. **Go to Section 1.** ☐

If your company does not operate design projects as part of a collaborative team with other companies but does use multi-department/disciplinary teams, then please tick the box and answer all questions with regard to projects carried out in this manner. **Go to Section 1.** ☐

If your company carries out design projects without interaction between departments/disciplines, then please tick the box and answer all questions with regard to projects carried out in this manner. **Go to Section 1.** ☐

1 Project Setup

1.1 Please indicate to what extent you agree with the following statements:

	Strongly agree						Strongly disagree
1. Finding the right companies/divisions for the project team is a quick process	1	2	3	4	5	6	7
2. There is a meeting between companies/divisions at the start of the project	1	2	3	4	5	6	7
3. The meeting is attended by a representative of each company/division	1	2	3	4	5	6	7
4. Everybody in the project knows who is co-ordinating the project	1	2	3	4	5	6	7
5. Everybody in the project knows who they should report delays to	1	2	3	4	5	6	7

2 Communication

2.1 With regard to your Project Data Management system, please indicate to what extent you agree with the following statements: (NB: New team members may be from companies that are also new to the project)

	Strongly agree						Strongly disagree
1. There is a standard method for sharing project data within the project team	1	2	3	4	5	6	7
2. This method is electronic (i.e. not paper based)	1	2	3	4	5	6	7
3. New members to the project would easily understand how to use the system	1	2	3	4	5	6	7
4. New members to the project could quickly gain access to all the project data	1	2	3	4	5	6	7

2.2 What proportion of the following activities are done through the Project Data Management system?

	None						All
1. Document Sharing	1	2	3	4	5	6	7
2. Document Revision Control	1	2	3	4	5	6	7
3. Project Planning (timelines, milestones etc.)	1	2	3	4	5	6	7
4. Project Calendar (scheduling meetings etc.)	1	2	3	4	5	6	7
5. Issuing Tasks to groups or individuals	1	2	3	4	5	6	7
6. Project related discussions/suggestions	1	2	3	4	5	6	7
7. Document mark-up	1	2	3	4	5	6	7
8. Contact details for team members	1	2	3	4	5	6	7

9. Give details of any other uses of your Project Data Management system

Other ______________________	1	2	3	4	5	6	7
Other ______________________	1	2	3	4	5	6	7

2.3 With regard to the electronic document formats for project data (CAD files, Spreadsheets etc.), please indicate to what extent you agree with the following statements:

	Strongly agree						Strongly disagree
1. Document formats are agreed on by the whole project team	1	2	3	4	5	6	7
2. Document formats are agreed on at the beginning of the project	1	2	3	4	5	6	7
3. Document formats are independent of specific software applications (e.g. Microsoft Word, AutoCad etc.)	1	2	3	4	5	6	7
4. Problems never occur sharing files between project team members	1	2	3	4	5	6	7
5. All team members use the file formats specified for the project	1	2	3	4	5	6	7

2.4 With regard to terminology (jargon, acronyms, descriptions for products, people, places etc.), please indicate to what extent you agree with the following statements:

	Strongly agree						Strongly disagree
1. Terminology is agreed on by the whole project team	1	2	3	4	5	6	7
2. Terminology is agreed on at the beginning of the project	1	2	3	4	5	6	7
3. All team members use the terminology agreed on for the project	1	2	3	4	5	6	7
4. Team members never use different terminology to those agreed on	1	2	3	4	5	6	7

2.5 With regard to units (centimetres, gallons, mph/kph etc.), please indicate to what extent you agree with the following statements:

1. Measurement units are agreed by the whole project team	1	2	3	4	5	6	7
2. Measurement units are agreed at the beginning of the project	1	2	3	4	5	6	7
3. All team members use the measurement units agreed for the project	1	2	3	4	5	6	7
4. Team members never use different measurement units to those agreed	1	2	3	4	5	6	7

3 Unexpected Events

3.1 With regard to unexpected events, how often are the following statements true?

	Never						Always
1. Unexpected events cause projects to be completed late	1	2	3	4	5	6	7
2. In responding to an unexpected event, the quality is sacrificed in order to meet the completion date	1	2	3	4	5	6	7
3. Unexpected events require an increase in resources to meet the deadline	1	2	3	4	5	6	7
4. Unexpected events cause help to be needed from within the affected company/division	1	2	3	4	5	6	7
5. Unexpected events cause help to be needed from another company/division already in the project team	1	2	3	4	5	6	7

6. Unexpected events cause help to be needed from a company not already in the project team	1 2 3 4 5 6 7
7. Unexpected events mean the project cannot be completed	1 2 3 4 5 6 7

3.2 With regard to unexpected events, please indicate to what extent you agree with the following statements:

	Strongly agree						Strongly disagree
1. There are set procedures to follow if an unexpected event means that assistance is required	1	2	3	4	5	6	7
2. All team members are aware of the procedures to follow in the event that assistance is required	1	2	3	4	5	6	7
3. Procedures for dealing with unexpected events are set before the project begins	1	2	3	4	5	6	7
4. If assistance is required, there is a method of identifying the necessary skills/expertise/resources	1	2	3	4	5	6	7
5. Consideration is given to potential unexpected events prior to the project	1	2	3	4	5	6	7
6. Procedures are in place for responding to unexpected events that have occurred in previous projects	1	2	3	4	5	6	7
7. Training in responding to unexpected events is undertaken by all team members	1	2	3	4	5	6	7
8. The cause of unexpected events that require a response is recorded	1	2	3	4	5	6	7
9. The response to unexpected events is recorded	1	2	3	4	5	6	7
10. The nature of unexpected events is used when setting up subsequent projects	1	2	3	4	5	6	7

4 Design Techniques

4.1 Please indicate to what extent you agree with the following statements:

	Strongly agree						Strongly disagree
1. We always adhere to international standards for designs (i.e. connectors, protocols, dimensions etc.)	1	2	3	4	5	6	7
2. We re-use previous designs wherever possible	1	2	3	4	5	6	7
3. We are always aware of design changes by other members of the project team	1	2	3	4	5	6	7
4. We have a procedure to follow when a change we make affects others	1	2	3	4	5	6	7
5. Reducing the number of parts/components in a design is important	1	2	3	4	5	6	7
6. Making manufacture/assembly as easy as possible is important	1	2	3	4	5	6	7
7. Using standard *off-the-shelf* parts is important	1	2	3	4	5	6	7

5 Recent Projects

5.1 For the 3 most recent collaborative projects in which you took part and the answers to this questionnaire apply, please provide the following information: (See example below for explanation)

No of divisions collaborating	Total no. of people in project	Original length of project	Delay due to unexpected external events	Delay due to other reasons
1. ______	1. ______	1. ______	1. ______	1. ______
2. ______	2. ______	2. ______	2. ______	2. ______
3. ______	3. ______	3. ______	3. ______	3. ______

Please give a brief description of each project. Any details you can give of the unexpected events causing delays would be most useful:

1. ______

2. ______

3. ______

Thank you very much for your collaboration in this survey

Appendix B

Questionnaire Cover Letter from Northern Defence Industries

Dear Colleagues,

Please find enclosed a short (approximately 20 minutes) survey which we have put together in collaboration with Durham University to explore the extent to which NDI members are prepared for collaborating on future design projects.

The output from this Questionnaire will play a significant role in the development of our design collaboration strategy and I would be grateful if you could give it your support. The questionnaire itself should only take 20-30 minutes to complete and we would appreciate it if you could find the time to complete it in the next two weeks. The benefit to your company is two-fold. Firstly, each company will receive a tailored 23-page feedback report based on their responses. Considering areas such as Software Systems, and Design for Manufacture; the report will identify strengths and weaknesses within the business and suggest solutions. In other words you will obtain a very useful "health check" on your design capability that would ordinarily cost several hundred pounds from a consultant in return for your time. The report will also show how you scored compared to the other NDI members (although scores from individual companies will not be divulged). Secondly, the output from the questionnaire will help ensure that the new NDI Marine Design Centre concept is on target and will help to ensure that the areas which require the most attention and development are addresses by the Design Centre.

You can return the Questionnaire in the FREEPOST envelope provided.

Many thanks for your support and time,

Director of Projects & Programmes

Appendix C

Anonymised Sample Benchmarking Report and Cover Letter

Northern Defence Industries

Agile Design Survey Feedback

In conjunction with Durham University School of Engineering

Company
Contact

Introduction

Firstly, we would like to thank you for taking the time to complete the NDI Agile Design Survey. Your contribution to the study was invaluable and here we present the findings along with some feedback for your company.

The purpose of this questionnaire was to investigate the current trends in collaborative product design, the disruption caused by unexpected events, and the extent to which companies are equipped and prepared to deal with such events. This is in contrast to previous research which has focused on the agility of the manufacturing stages of product development. Additionally, previous research has only dealt with manufacturing within a single company. The purpose of this research is to identify ways in which 'virtual enterprises' consisting of multiple collaborating companies can be configured to be more agile. This represents a development in the way design and manufacture is now carried out.

The objective was to identify relationships between the extent to which certain tools and processes have been adopted in industry and the level of design agility demonstrated by those companies.

Methodology

The questionnaire was sent out to all 178 member companies of Northern Defence Industries, all operating in the defence or aerospace sectors. The questionnaire consisted of 54 questions in five categories of Project Setup, Communication, Unexpected Events, Design Techniques and Recent Projects.

For the purposes of data analysis these five categories were further reduced into 14 sub-categories as illustrated in the rest of this report. Of these 14 sub-categories, 11 were related to tools and procedures used by each company for collaborative projects. The remaining three were used for data gathering, specifically: the agility level of projects, the consequences of Unexpected External Events (UEEs) and the features of any product data sharing system.

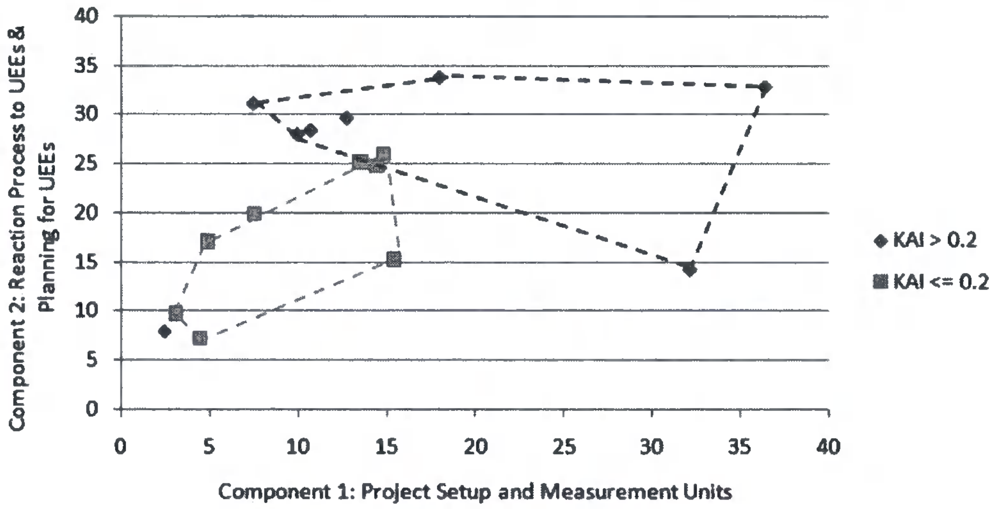
The majority of questions were answered on a 7-point Likert scale (scale of agreement from 1 (strongly agree) through to 7 (strongly disagree)), with the remaining questions requiring numerical or descriptive answers.

In order to analyse the agility of the companies taking part the Key Agility Index (KAI) was used. This is a measure of the time spent on activities caused by UEEs as a proportion of the eventual project time. Therefore, companies experiencing no delay would record a KAI of 0, where as companies spending more time on UEEs related tasks would have a KAI tending towards 1.

Results

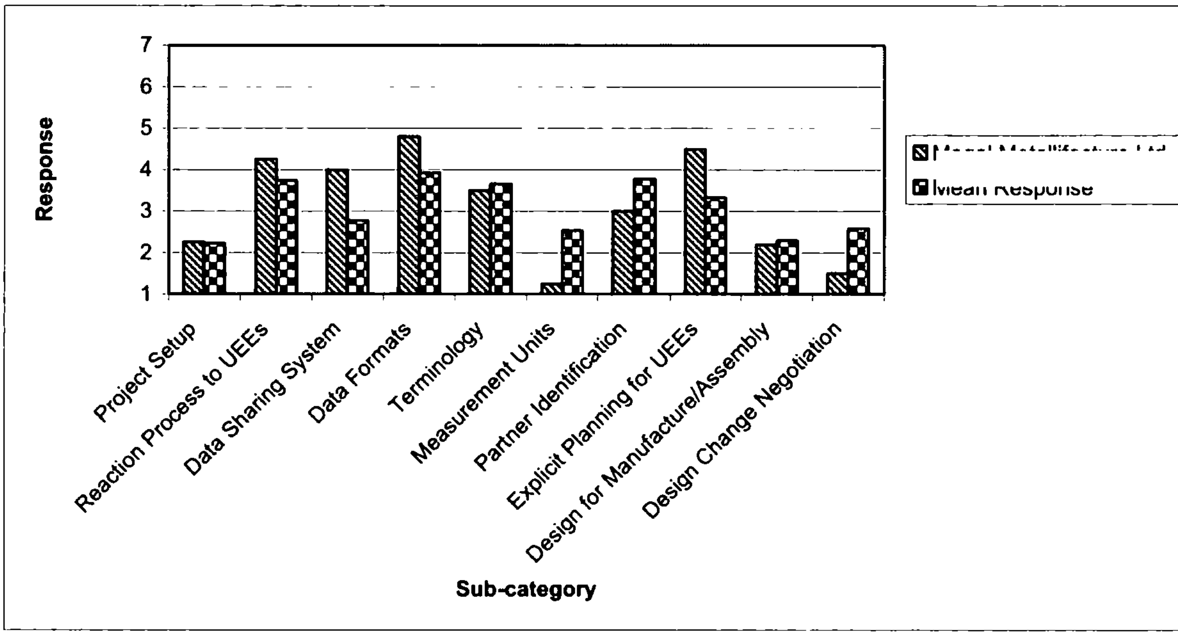
In order to analyse the results the questions from each of the 11 sub-categories mentioned were reduced to five "Principal Components" based on their influence on the results (See Appendix 2 for a detailed explanation of the analysis using Principal Components Analysis). The graph below shows the response to the first two components of each company who responded to the survey. The Pink Squares show companies whose Recent Project Data resulted in a Key Agility Index score of greater than 0.2 (above average), and the blue diamonds show companies who scored less than 0.2 (below average) on the Key Agility Index.

The graph demonstrates a significant relationship between the first two principal components from the questionnaire and the level of agility. Specifically, Principal Component 1 was made of primarily Project Setup and Measurement Unit questions. Principal Component 2 was made up of questions relating to Reacting to UEEs and Planning for UEEs. The graph shows that the more agile companies have scores tending towards the bottom left of the graph, i.e. lower scores on these questions, than the less agile companies. Low scores indicate an agreement with the statements in the questionnaire or a stronger implementation of the techniques asked about in the questionnaire. See the rest of the report for details of those questions asked under each heading. The exact questions making up each Principal Component are listed in Appendix 1.



The following sections provide greater detail on your responses to the questions in each area of the questionnaire, including how your score compared to the average response of the population, how the responses correlated to the level of design agility, and how your company might be able to move towards a greater level of agility through changing your activities in this area. The 'average' score for the population is the mean.

Response Summary



The chart above shows your responses to each area of the questionnaire against the average response from the population. The average in this case is the mean value of response to the questions under each heading (see full report for details of which questions fit into which headings).

For the sections which were fully completed your responses were below the average, which indicates a higher level of agreement or adoption for each question. The results of the survey indicate that this relates to a higher level of agility.

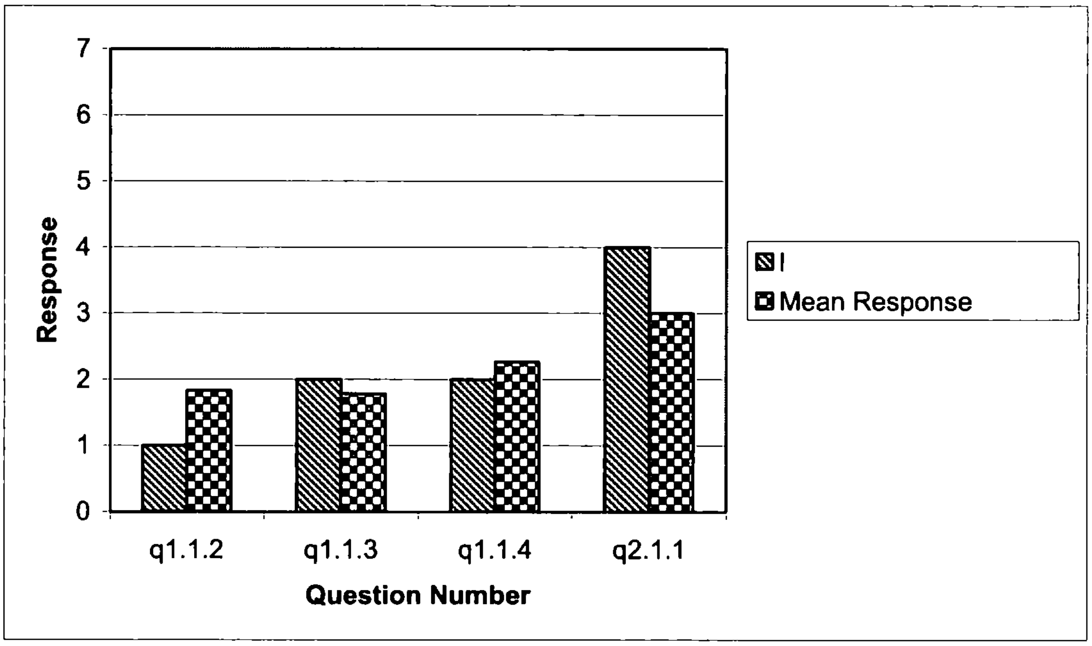
Your Key Agility Index (KAI) was 0.0, which means that during your recent projects none of your time was spent on activities relating to Unexpected External Events (UEEs). The mean KAI score was 0.2, meaning 20% of activities carried out during recent projects were related to UEEs. Although it appears that your company is therefore perfectly agile, you may still find it useful to review the responses to individual sections of this report and follow the recommendations.

In order to improve your agility further it is recommended that you review any areas for which you did not supply full data. In addition, the results suggest that the lower the response, the higher the level of agility, and therefore you can review each section individually to identify individual areas of improvement. Suggestions of how to so this are included in the report.

The research has shown a correlation between lower scores in certain areas and an increased level of design agility. In these areas you scored below the population average. Therefore it is these areas you should concentrate on in order to increase your design agility.

The rest of this report will give more detail for each area.

Project Setup



The chart above shows the average responses for the following questions:

1.1.2 There is a meeting between companies/departments at the start of the project

1.1.3 The meeting is attended by a representative of each company/division

1.1.4 The meeting is attended by all members of the project team

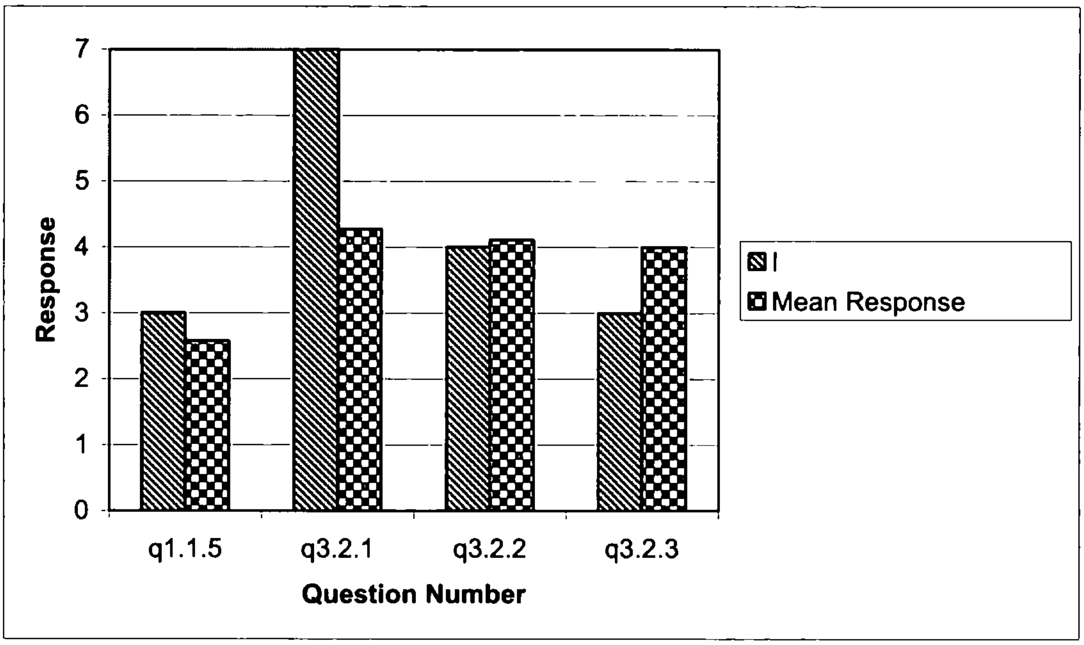
2.1.1 There is a standard method for sharing project data within the project team

YOUR COMPANY Ltd. responded with an average of 2.3 for the questions relating to the setup process for a project. The population as a whole responded with an average of 2.2, meaning that YOUR COMPANY Ltd. places slightly less importance than the population on project setup techniques. The results of the questionnaire analysis show a positive correlation between the adoption of these techniques and the level of Design Agility shown during projects. Therefore, a lower average response in this section suggests a higher level of agility.

In order to increase your adoption of these techniques, consider the following activities:

- Ensuring that all members of a project have the opportunity to meet together at the beginning of a project.
- Adopting a standard method of data sharing between all partners for any work involving collaboration, be it between employees or with external companies/organisations.

Reaction Process to Unpredictable External Events



The chart above shows the average responses for the following questions:

1.1.5 Everybody in the project knows who is co-ordinating the project

3.2.1 There are set procedures to follow if an unexpected event means that assistance is required

3.2.2 All team members are aware of the procedures to follow in the event that assistance is required

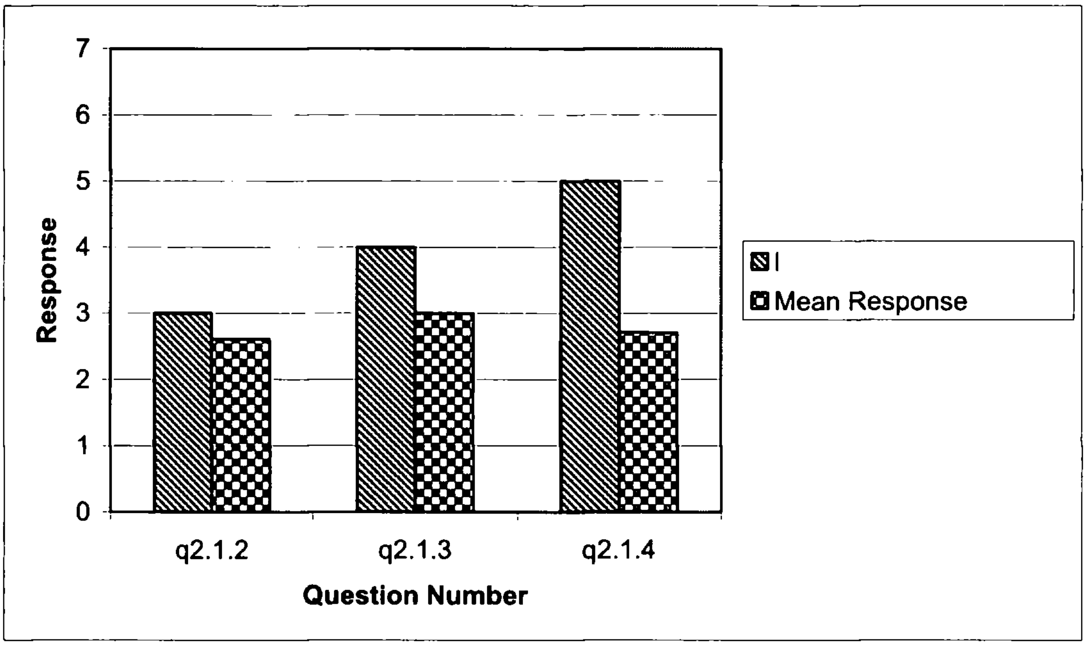
3.2.3 Procedures for dealing with unexpected events are set before the project begins

YOUR COMPANY Ltd. responded with an average of 4.3 this section of the questionnaire, indicating a low level of agreement/adoption in this area. The population as a whole responded with an average of 3.7, indicating a slight weighting towards adoption of these techniques on a range of 1-7.

The following activities may have a positive affect on your responses to this section:

- A meeting at the outset of the project, attended by everyone, can be used to identify key personnel within the project, making them more approachable and giving contact details.
- Clear procedures for dealing with unexpected events, including the chain of command for notification of such events, should be set prior to the start of the project.
- All members of the project team should be made aware of such procedures at the beginning of the project.

Data Sharing System



The chart above shows the average responses for the following questions:

2.1.2 This method is electronic (i.e. not paper based)

2.1.3 New members to the project would easily understand how to use the system

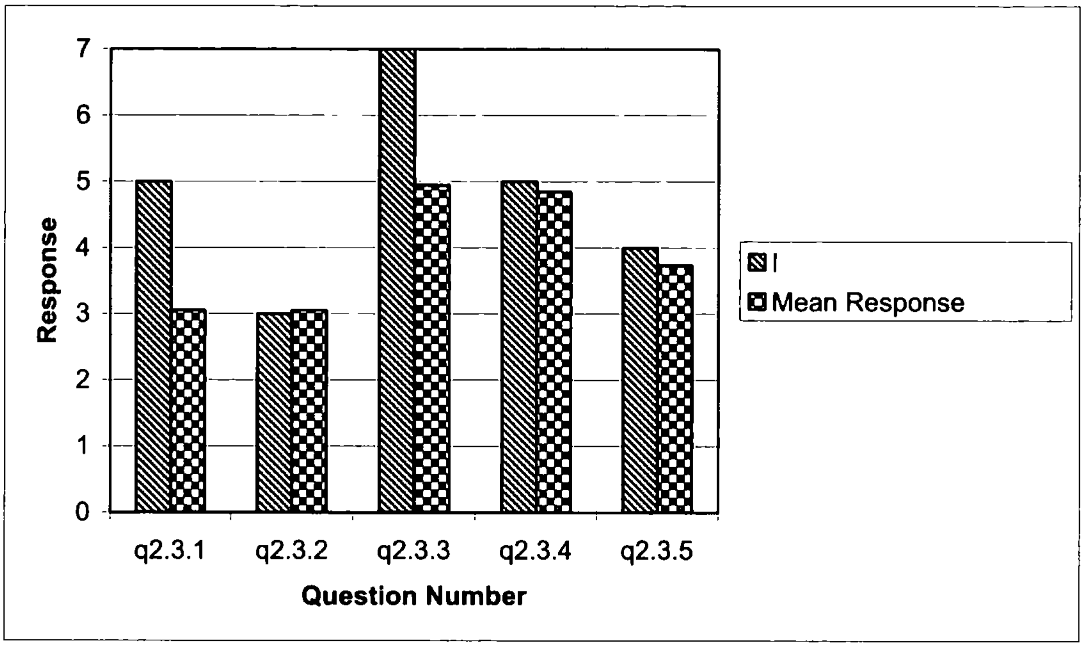
2.1.4 New members to the project could quickly gain access to all the project data

YOUR COMPANY Ltd. responded with an average of 4.0 to this section of the questionnaire, indicating a low level of agreement/adoption in this area and a worse than average response. The population as a whole responded with an average of 2.8 which indicates a reasonable level of agreement across the NDI membership.

In order to increase your agreement with the questions above, consider the following activities:

- Where a paper based data sharing system is used, could any of this be done more easily on-line? i.e. obtaining files (drawings?) from other companies; or informing people of updates to plans, schedules, products etc.
- Undertake a review of what is required to give a new person access to the data sharing system in use for your project. They could be from within or outside your company. Could this process be made easier? i.e. more people trained/authorised to give access to new people, a web-based system instead of software on a single computer etc.
- Undertake a review of how easy a new person finds your data sharing system to use. Are there any simple improvements or tutorials that people could undertake which would make the familiarisation process easier? Perhaps get somebody who has never used the system to try using it under observation. Make a note of any difficulties they have and try to find changes which will eliminate these difficulties.

Data Formats



The chart above shows the average responses for the following questions:

2.3.1	Document formats are agreed by the whole project team
2.3.2	Document formats are agreed at the beginning of the project
2.3.3	Document formats are independent of specific software applications (e.g. Microsoft Word, AutoCad etc.)
2.3.4	Problems never occur sharing files between project team members
2.3.5	All team members use file formats agreed for the project

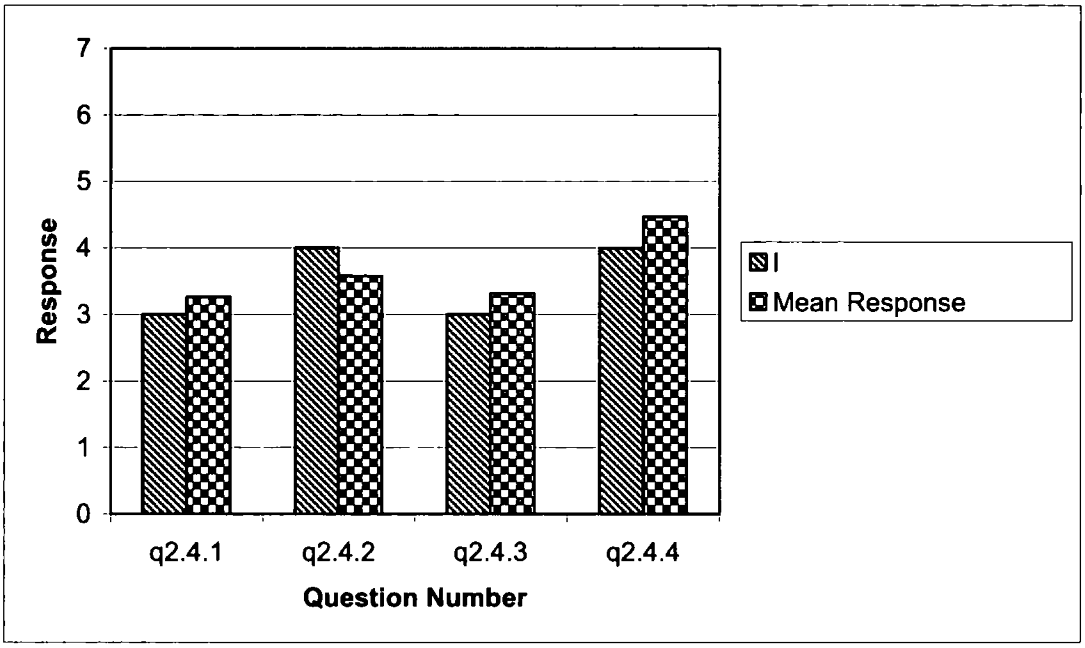
YOUR COMPANY Ltd. responded with an average of 4.8 for the questions relating to Data Formats. The population as a whole responded with an average of 3.9, meaning that YOUR COMPANY Ltd. tends to agree with these statements on average less than NDI membership.

The one exception to this is the statement in question 2.3.3 where YOUR COMPANY Ltd. Disagrees that files are independent of software applications. The research suggests that a lower score on this sub-category relates to a higher level of agility, and therefore an average of 3.0, while being below the average, still allows much scope for potential benefits:

- Consider doing a quick poll around the company to find out what people do if they can't open a file somebody sends them. Can they all open common files such as Microsoft Project? What about your partners in other companies?

- You may find that people just manage without the information when they can't open a file, rather than asking for it again in a different format. Either way, time is lost. Therefore you could consider agreeing all these document formats before the start of the project. Ideally, independent file formats can be used, so that it doesn't matter which CAD or word processor software you use. If this isn't possible, at the very least try to agree which software the different collaborating partners all have. You can give these details to new partners as they join, so they know what to expect and can get the software if necessary.

Terminology



The chart above shows the average responses for the following questions:

2.4.1 Terminology is agreed by the whole project team

2.4.2 Terminology is agreed at the beginning of the project

2.4.3 All team members use the terminology agreed for the project

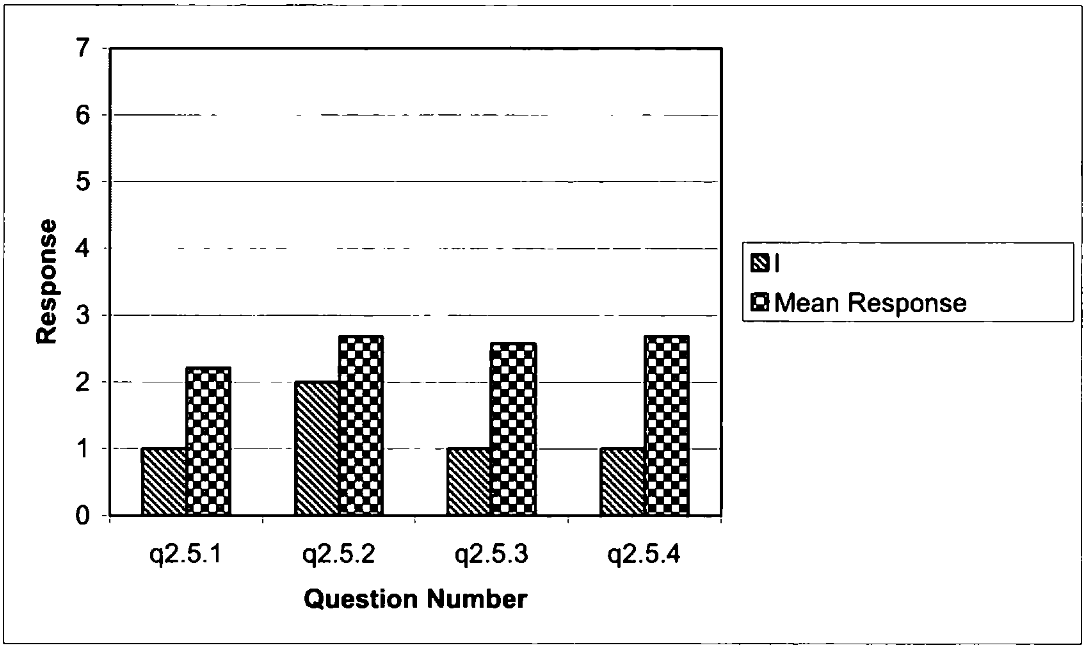
2.4.4 Team members never use different terminology to those agreed

YOUR COMPANY Ltd. responded with an average of 3.5 for the questions relating to importance of Terminology in collaborative design. The population as a whole responded with an average of 3.7, meaning that YOUR COMPANY Ltd. agrees slightly more than the population with the statements relating to Terminology.

In order to obtain a better score in this sub-category you should consider the following activities:

- As part of your pre-project meeting you should identify any terminology which is key to the project, or which may be different to that used by partners. This could be because of geographical differences, different technical backgrounds or any other reason.
- Create a glossary of terminology which can be shared with all members of the project team. This will help to reduce ambiguity.
- Encourage team members to question any terminology which they are not sure of the meaning of, and to correct any terminology which is different to that agreed at the beginning of the project.

Units

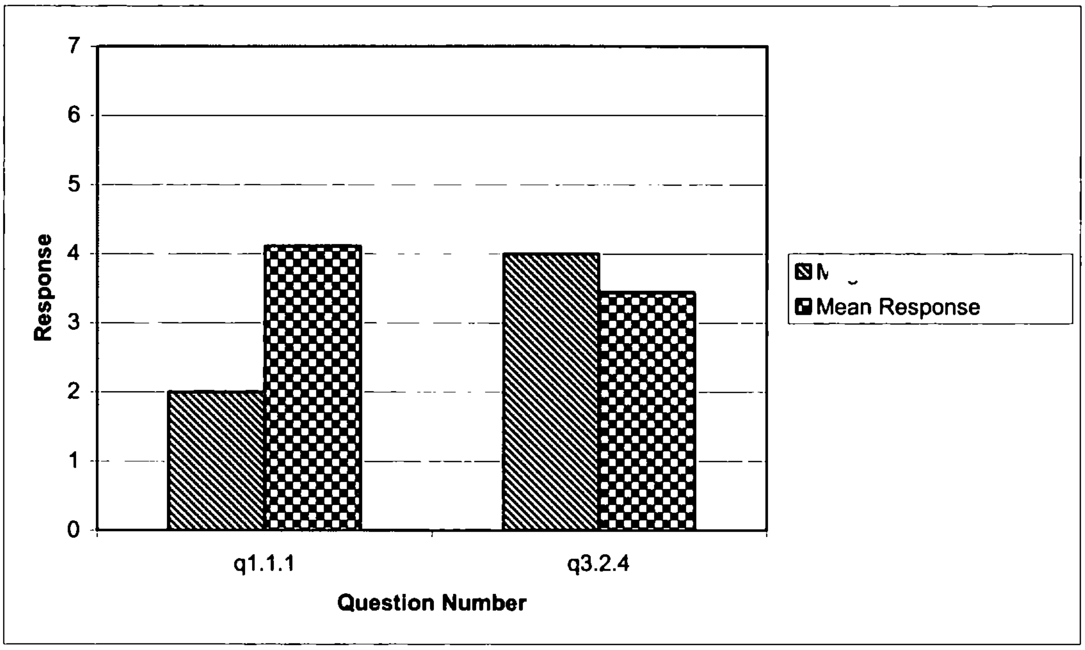


The chart above shows the average responses for the following questions:

2.5.1	Measurement units are agreed by the whole project team
2.5.2	Measurement units are agreed at the beginning of the project
2.5.3	All team members use the measurement units agreed for the project
2.5.4	Team members never use different measurement units to those agreed

YOUR COMPANY Ltd. responded with an average of 1.3 for the questions relating to Measurement Units. The population as a whole responded with an average of 2.5, meaning that YOUR COMPANY Ltd. Agrees more strongly than the population on Measurement Unit questions. 1.3 is a very strong positive response and little can be done to improve this further. It is important to identify the reasons for this positive response and review your procedures regularly to maintain this level.

Partner Identification



The chart above shows the average responses for the following questions:

1.1.1 Finding the right companies/divisions for the project team is a quick process

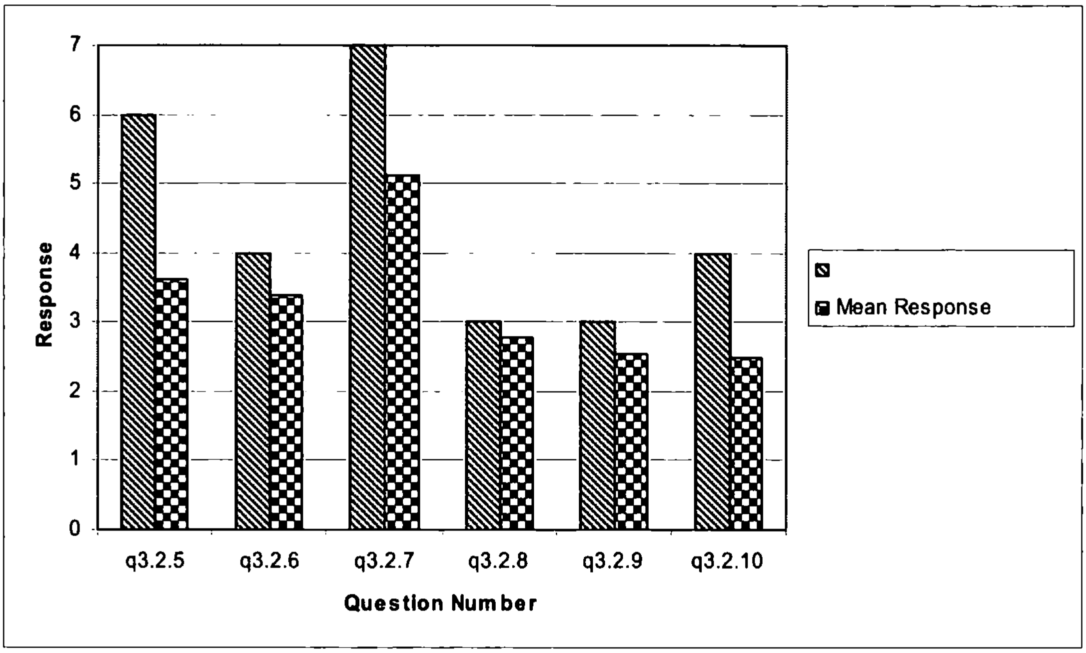
3.2.4 If assistance is required, there is a method of identifying the necessary skills/expertise/resources

YOUR COMPANY Ltd. gave an average response of 3.0 to this section and the mean response was 3.8.

In order to improve the response to this sub-category, consider the following activities:

- Review your procedures for identifying companies to work with, both before and during the design process.
  - Do you rely on companies you know about already or could you access a broader set of companies through other organisations, trade associations or directories?
  - How much information can you find out about the companies before you approach them? Finding searchable databases with lots of detailed information about each company may make it easier to identify the right companies quickly, rather than having to approach lots of companies individually.
  - Do you advertise your capabilities and skills/expertise in any way? If a company needed your skills, could they find you easily? Think about where you might advertise/sell your skills, and try looking there for potential partners.

Explicit Planning for Unexpected Events



The chart above shows the average responses for the following questions:

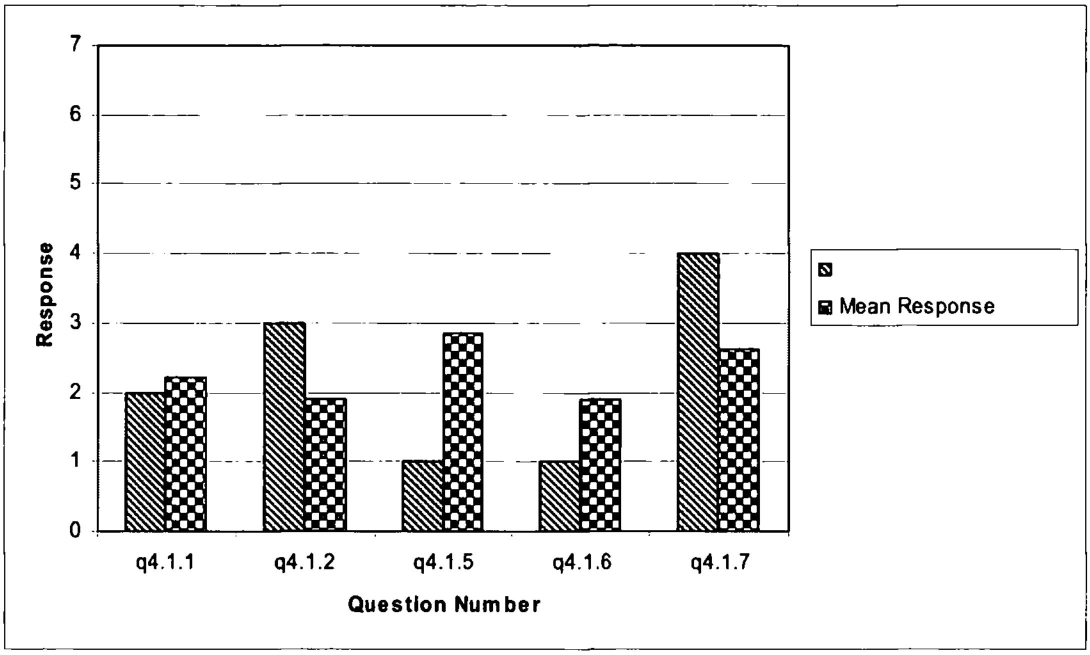
3.2.5	Consideration is given to potential unexpected events prior to the project
3.2.6	Procedures are in place for responding to unexpected events that have occurred in previous projects
3.2.7	Training in responding to unexpected events is undertaken by all team members
3.2.8	The cause of unexpected events that require a response is recorded
3.2.9	The response to unexpected events is recorded
3.2.10	The nature of unexpected events is used when setting up subsequent projects

YOUR COMPANY Ltd. responded with an average of 4.5 to this sub-category, while the mean response was 3.3. The research results suggest that 4.5 is a poor score, related to a low level of agility.

In order to increase your adoption of Design for Manufacture and Assembly techniques, consider the following activities:

- Consider recording Unexpected Events and your response to them.
- Did the response work? Could you have responded better with different preparation or facilities?
- When planning the project consider previous UEEs and also any others that could occur. Have a plan for how to respond, and make sure everyone knows what the plans are.
- Is there anything you could do before the project which makes it easier to respond to UEEs when they occur, such as knowing where to go to find new partners and how to do it, or how to integrate new partners quickly?

Design for Manufacture and Assembly



The chart above shows the average responses for the following questions:

4.1.1 We always adhere to international standards for designs (i.e. connectors, protocols, dimensions etc.)

4.1.2 We re-use previous designs wherever possible

4.1.5 Reducing the number of parts/components in a design is important

4.1.6 Making manufacture/assembly as easy as possible is important

4.1.7 Using standard *off-the-shelf* parts is important

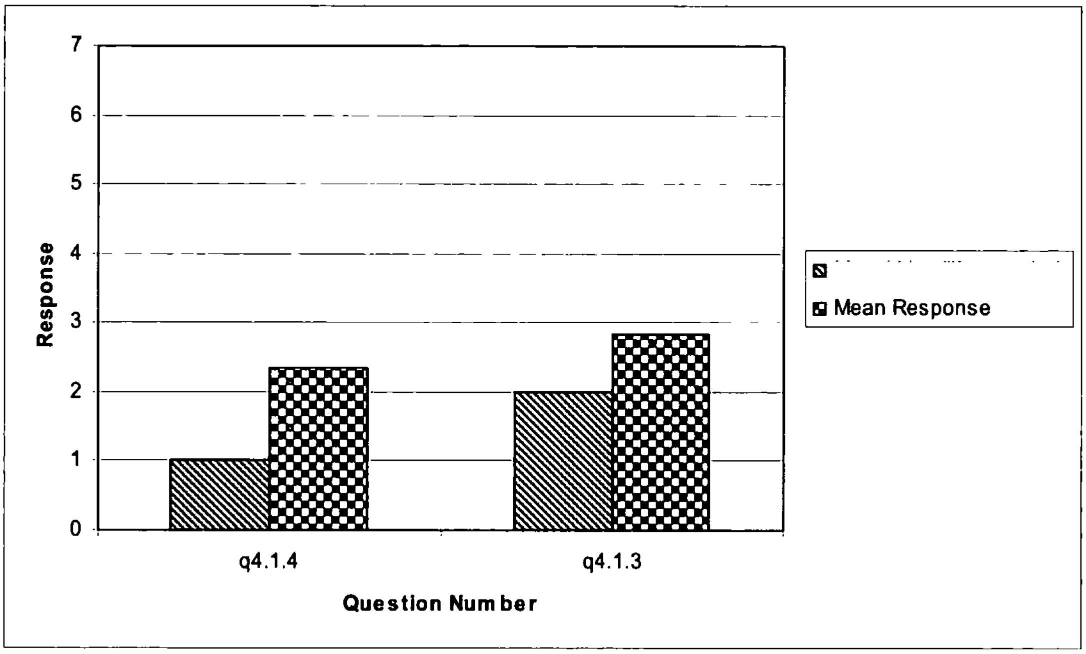
YOUR COMPANY Ltd. responded with an average of 2.2 for the questions relating to importance of Design for Manufacture and Assembly techniques. The population as a whole responded with an average of 2.3, meaning that YOUR COMPANY Ltd. places slightly more importance than the population on Design for Manufacture and Assembly.

The results of the questionnaire analysis suggest a positive relationship between the adoption of Design for Manufacture Techniques and the level of Design Agility shown during projects. Therefore, a better (lower) average response in this section means a potentially higher level of agility.

In order to increase your adoption of Design for Manufacture and Assembly techniques, consider the following activities:

- Use standard parts conforming to International Standards wherever possible
- Re-use previous designs to save time and maintain best practise
- Carry out a DFMA assessment which looks at how necessary each part of a product is (See Appendix 1).

Design Change Negotiation



The chart above shows the average responses for the following questions:

4.1.3 We are always aware of design changes by other members of the project team

4.1.4 We have a procedure to follow when a change we make affects others

YOUR COMPANY Ltd. had an average response of 1.5 for this sub-category which relates to a high level of agility. The mean response was 2.6.

In order to improve your response in this section, consider the following activities:

- Set out clear procedures for when designers make changes which affect other parts of a design
- Everybody should be aware of the team members whose work interfaces with their own
- Everybody should be aware of who is overseeing their part of the design

Discussion

By increasing your level of design agility your company will gain a competitive advantage in an increasingly turbulent market place. New technologies are regularly becoming available, political and economic factors are playing more of a role as the marketplace becomes more global, and even meteorological factors such as more extreme seasons can impact on your ability to develop designs that meet the ever-changing needs of your customer.

The objective of this research is to identify ways in which the design process can be configured, tools that can be used and procedures that can be put in place to ensure that the effect of these factors on the design process is minimised.

Through carrying out this research we have been able to conduct a comprehensive analysis of the tools and techniques employed already by NDI member companies, and their current level of agility. The results suggest that companies with a higher level of adoption or agreement in the following areas were more agile than the average.

- Project Setup & Measurement Units
- Reaction Process to UEEs & Planning for UEEs
- Terminology & Design for Manufacture/Assembly
- Document Formats & International Standards
- Web-based PDM & Consideration given to UEEs prior to the project

By identifying training opportunities and technologies which can enhance these factors it may be possible to increase the design agility of your company. Some of these recommendations are included in each section of the report; however there will inevitably be additional steps your company can take to increase its level of design agility.

Conclusions

Using the findings of this research the next stage will be to identify a framework which companies can adopt when beginning a design project to assist them in being more agile, through the use of the tools, procedures and techniques identified in this questionnaire.

Many thanks once again for your cooperation with this research

Appendix 1 – Design for Manufacture and Assembly Survey

You can use this check sheet to analyse existing designs and improve their manufacturability/assemblability.

For each component of a design, ask the following questions:

1. Does the part move with respect to other parts already assembled?
2. Must the part be made of a different material or be isolated from all other parts already assembled? (Only fundamental reasons concerned with material properties may be considered here.)
3. Must the part be separate from all other parts already assembled because necessary assembly or disassembly would otherwise be impossible?

This will establish whether or not a part/component is necessary at all. If you answered no to all the above questions, then the part can probably be replaced by combining it with another part, and therefore reducing assembly steps, manufacturing costs and inventory.

References / Useful Reading

"Product Design For Manufacture and Assembly", Boothroyd, Dewhurst & Knight (1994). Published by Marcel Decker Inc., New York

Appendix 2 – Principal Components Analysis

Principal Components Analysis is a technique used to ascertain the groups of variables (questions) which contribute the most variation in the dataset. That means, that for multivariate data such as the responses to a 50 question survey, Principal Components Analysis will allow the data to be represented by a number of "Principal Components" which are a combination of the many variables.

Additionally, the first Principal Component represents the largest variance within the dataset, and the other components represent decreasing proportions of the total variance. Variables which contribute very little to the overall variance will not be included in any of the significant Principal Components.

Once the principal components have been determined, a "score" for each company can be obtained for each of the principal components, by looking at which variables (questions) contribute to those principal components and "how much" each variable contributes.

For example - Principal Component 1 is the sum of:

Response to this question	**multiplied by this number**
Measurement units are agreed on by the whole team	x 0.954
Measurement Units are agreed at the beginning of the project	x 0.929
All the team members use the measurement units agreed on for the project	x 0.906
There is a meeting between companies/divisions at the start of the project	x 0.895
Everybody in the project knows who they should report delays to	x 0.877
The response to unexpected events is recorded	x 0.748
Team members never use different terminology to those agreed on	x -0.696
The cause of unexpected events that require a response is recorded	x 0.652
The meeting is attended by a representative from each company/division	x 0.639

The same procedure is carried out for the other four Principal Components and graph 1 shows the "scores" for the first two Principal Components plotted on a graph, grouped into "Agile" and "Unagile" companies based on their agility level as measured using the Key Agility Index.

Appendix D

Cronbach's Alpha Analysis for Questionnaire Constructs

Reliability analysis for Questionnaire Responses

Construct: Project Setup

Case Processing Summary

		N	%
Cases	Valid	18	94.7
	Excluded(a)	1	5.3
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.663	4

Construct: Reaction Process to UEEs

Case Processing Summary

		N	%
Cases	Valid	18	94.7
	Excluded(a)	1	5.3
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.832	4

Construct: Data Sharing System

Case Processing Summary

		N	%
Cases	Valid	16	84.2
	Excluded(a)	3	15.8
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.808	3

Construct: Data Formats

Case Processing Summary

		N	%
Cases	Valid	19	100.0
	Excluded(a)	0	.0
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.826	5

Construct: Terminology

Case Processing Summary

		N	%
Cases	Valid	19	100.0
	Excluded(a)	0	.0
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.751	4

Construct: Measurement Units

Case Processing Summary

		N	%
Cases	Valid	19	100.0
	Excluded(a)	0	.0
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.898	4

Construct: Rapid Partner Identification

Case Processing Summary

		N	%
Cases	Valid	17	89.5
	Excluded(a)	2	10.5
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.726	2

Construct: Explicit Planning fo UEEs

Case Processing Summary

		N	%
Cases	Valid	18	94.7
	Excluded(a)	1	5.3
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.845	6

Construct: DFMA

Case Processing Summary

		N	%
Cases	Valid	19	100.0
	Excluded(a)	0	.0
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.806	5

Construct: Design Change Negotiation

Case Processing Summary

		N	%
Cases	Valid	17	89.5
	Excluded(a)	2	10.5
	Total	19	100.0

Reliability Statistics

Cronbach's Alpha	N of Items
0.763	2

Appendix E

Agile Design Framework Implementation Explanation Document

Meta-Design Process

Meta-design is a phase of the design process which is additional to those traditionally considered, with particular importance in a collaborative setting. The objective of the meta-design stage is the definition of key tools and procedures known as an Agile Design Framework, which will be of importance as the collaborative design project is carried out. Specifically, the definition of these tools and procedures will allow a more rapid response in the face of Unpredictable External Events (UEEs) which occur during the project and have an impact upon it. Meta-design *designs the collaborative design process*.

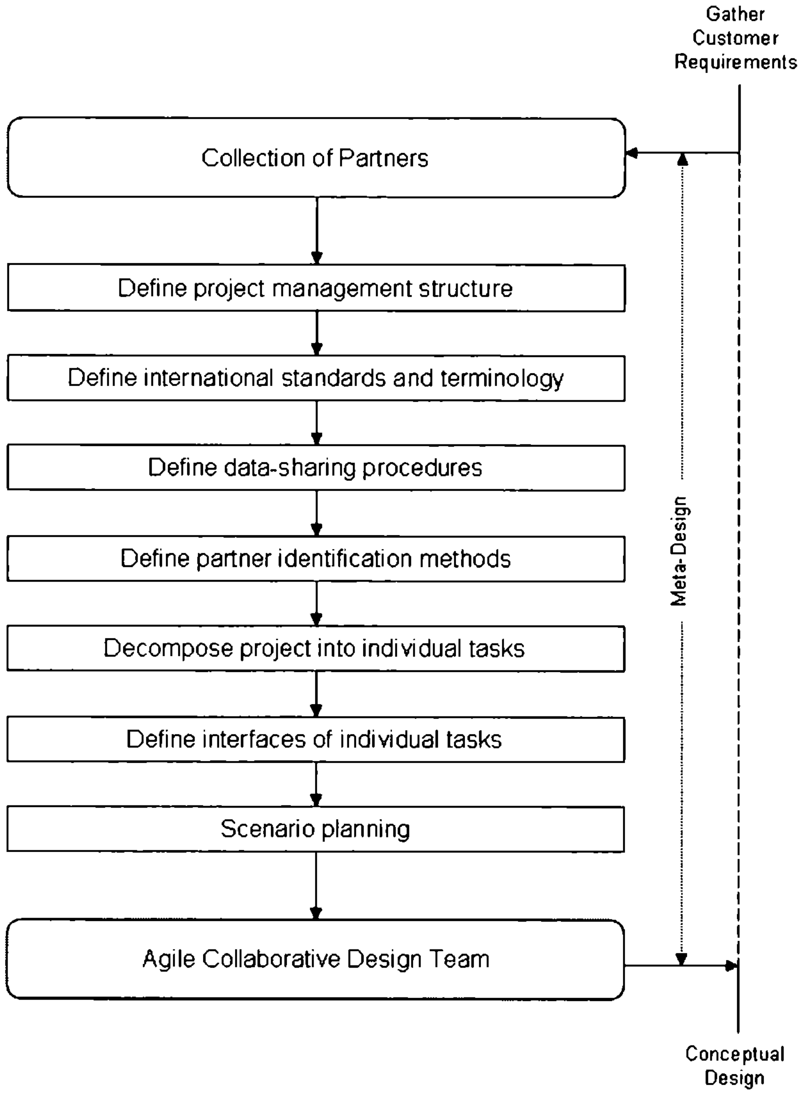


Figure 1: Steps of meta-design

Step 1: Define Project Management Structure

The aim of the first step in the meta-design stage is to define a management/reporting structure so that in the event of a UEE, everybody knows exactly who they should report the event to, and how. This will allow an overall view of the potential impact of the UEE to be taken, and somebody with that knowledge can then take a decision on the best course of action. You should agree within your team who you report UEEs to,

Step 2: Define International Standards and Terminology

Although it may seem obvious, defining International Standards is not always done by project teams, which can lead to confusion later on. You should agree the standards you will use, for both obvious areas such as distances, and also any other areas in which standards may be ambiguous.

The same principal applies for Terminology. Often companies or departments use different terminology for the same thing. If there are any aspects of this project where you think differing terminology may be used then clarify it during this process.

Step 3: Define Data Sharing Procedures

There are different ways in which you can choose to share data between the members of your team. In order to respond to UEEs, some methods may be better than others. For example, what happens if a member of the team goes bust and leaves, could the others access their data? What about if a new member to the team needs access to all the files? You should make this as easy as possible.

You should also consider the file formats you will use. Does everyone use the same software – i.e. Microsoft Word/Excel, or SolidWorks? If you need to introduce a new member to the team, can you guarantee they will also use the same software? If not, then you should try to use independent or 'standard' file formats rather than ones linked to specific software.

Step 4: Define Partner Identification Methods

This step is not applicable for the purposes of this experiment, but would involve identifying methods of finding new companies/experts who can assist with the project if required. If you need to introduce new partners today they will be identified for you.

Step 5: Decompose Project into Individual Tasks

It may be more appropriate to address this step of the process during or after the Conceptual Design Stage. The design should be divided into modules in such a way that each partner is clear on their responsibilities within that particular module of the design. The word module is important here, as each person's tasks/module should be as independent as possible, i.e. interlinking between the modules should be kept to a minimum.

Step 6: Define Interfaces of Individual Tasks

This step relates to the previous one and involves clearly defining the boundary between modules. Each designer should not only be clear on what is their responsibility, but also on how their design interfaces with that of the other partners. Where possible the interfaces should be based on simple standards-based connectors/interfaces.

Step 7: Scenario Planning

Based on your expertise, spend a short amount of time considering some of the events which might occur during the design of this project which would affect the design. Is there anything else you could decide/define now which would make it easier to deal with those events if they occur? If so, and you think the time trade-off would be worthwhile then you should take some time to prepare in case these events occur.

For example, if a new company becomes part of your design team, who would introduce them to the project, give them access to all your project data and explain to them how you work?

And finally...

Now that you have been through the meta-design process you should write down what you have decided so that everyone has a clear understanding of the things you have agreed, and each take a copy.

It is important to refer to this document throughout the design process. Remember that you can make changes to the document throughout the design if it is necessary, and you should certainly go through it with any new partners so that they also understand the way you work as a team.

Appendix F

Protocol Study Design Brief

Design Brief

The NHS has identified that the use of up to 8 staff members to move a hospital patient from one bed to another is often time-consuming and poor use of qualified and skilled personnel in non-urgent situations. Therefore, they have identified a potential need for a mechanical device which can perform the task of moving a patient from one bed, perhaps a surgery or ambulance trolley, to a ward bed in cases where time is not critical and the patient's condition allows.

The mechanical device must be operable by one trained member of staff, it must be transportable between wards, and it should be storable in as small a space as possible when not in use.

Patient safety and comfort is paramount, so the device should not apply large amounts of pressure to any one area of the body, and it should not induce any more movement or deflection in the patient's body than would normally be experienced when moving them with 8 staff.

The two beds may not necessarily be of the same height, and the typical height of a hospital bed mattress is 1metre from the floor, although this is not always the case. The device should be able to handle a patient up to 150Kg in weight. Wards have a minimum ceiling height of 2.4m and doorways are at least 1m wide and 1.8m tall.

It is required to present a detailed design at the end of the exercise including 2D drawings and a 3D representation. You should also present the design process including concepts and the way in which the concepts evolved to produce the final design.

Appendix G

Timings Crib Sheet for Protocol Study

Progress Report **Name**______________________________

Please complete a row of this every 15 minutes.

Time	Task	% of task completed	Expected finish time of task
09:30			
09:45			
10:00			
10:15			
10:30			
10:45			
11:00			
11:15			
11:30			
11:45			
12:00			
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14:00			
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14:30			
14:45			
15:00			
15:15			
15:30			
15:45			
16:00			

Appendix H

Industrial Experiment Implementation Plan

Meta Design Project
Planning Meeting

AGENDA

1. Define Objectives

2. Define Project Requirements
   - No. People
   - People Involved

3. Define Implementation Plan
   i.e. - Launch meeting agenda
   - Ensuring Meta Design Understanding (Training?)
   - Execution of Meta Design Steps (Incl. Supporting documents?)

4. Define how the project will be managed
   - CFT Leader or Project Manager?
   - Define role

5. Define and agree measures

6. Define Output/Deliverable (Company Report? When? Who?)

Initial Thought

- We already have a stage-gate process (APQP) therefore we would follow our current process, meta design would mean including different activities at Project Launch and Weekly CFT meetings, with the exception of the option to redefine project management and reporting procedures.

- As I understand it we are focusing on investigating the benefit/Importance of the 7 Meta Design Steps for minimising the impact of UEE's and the benefit/importance of agreeing at the start of the project a method of work based around the 7 steps. We're not really focusing on the detail behind each step, rather the consideration of each step???

Agile Design Project

Objectives

Establish whether using the Agile Design Process allow the team to better respond to unexpected events during the project.

Project Requirements

Collaborative project:
- Multiple people from same company, preferably different departments
- Multiple people and companies.

Implementation

Part of current APQP launch meeting. Include 2+ hours to define principles of Meta Design.
- Presentation introducing Agile Design concept, including examples of UEEs.
- Launch Agile Design Process

Step 1: Define Project Management Structure.

Same as current with additional activities at weekly meetings and the introduction of burn-down charts.

Introduce CFT deputy leader to cope with additional requirements and step in if CFT leader is unavailable.

Step 3: Define Data Sharing Procedures

Setup shared drive for Agile Design project – demonstrate and agree at launch meeting. Agree process for setting up new folders.

Step 4: Define Partner Identification Methods

Introduce procedure of using pre-identified methods for finding competences/facilities that may be required during the project. Will mean identifying (or developing) a database of useful contacts.

Step 5: Decompose Project into individual tasks

Identify all tasks, responsibilities and define total duration (hours) of tasks allocated to each team member.

Step 7: Scenario Planning

Conduct a formal lessons learnt review, document and implement results where reasonable.

Project Management

Project reporting:

- Weekly meeting:
    - Update issues tracker
    - Understand how issues relate to burn-down charts
    - Determine use of agile-design process.
    - Update Agile design reference document.
- Issues Tracker: as current
- Burn-down metrics: updated daily to illustrate progress.
    - Team will report via email on following three areas:
        - Time remaining on tasks
        - Hours worked on tasks
        - Activities/events that have contributed to decrease/increase in hours remaining.

CFT Leader:

- As current and ensure team are completing burn-down metrics.

Measures

Qualitative, based on discussions during and at the end of the project.

Output / Deliverables

Report outlining benefits or otherwise of Agile Design process:

- Background of Agile design Process
- Methodology
- Results
- Conclusions