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Meta-design for agile concurrent product design in the virtual enterprise

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Abstract: The area of collaborative design is well-researched and many factors, including IT and other tools and techniques, which contribute to more effective collaboration, have been demonstrated. However, the implementation of these techniques in order to achieve a more agile collaborative environment is relatively under-researched, particularly at the design stage where agility is less well defined than at the manufacture stage. The article investigates the level of adoption of these factors in the defence and aerospace industry in Northern England, and their benefits to the level of agility in a collaborative design project. Furthermore, the article introduces meta-design as an early adoption technique for implementing agile tools and demonstrates the potential benefits of this method through data gathered by industrial questionnaire..

Key Words: Collaboration, Design, Agility, Project Planning

1. Introduction

In recent years collaboration between companies has become more widespread; co-operation with global partners or even with former competitors [1] is now increasingly common. This is due in part to a shift away from vertical integration, popular in the early 20th century, towards a more specialised set of core competences within individual organisations, allowing them to focus on developing these competences and develop partnerships with complementary businesses to satisfy their requirements for other aspects of the business [2]. These partnerships are referred to as Virtual Enterprises (VE) and have taken many forms depending on the circumstances, from long-term partnerships favoured in Japan, to very short-term and dynamic tactical partnerships to satisfy an immediate need, typically in response to a sudden business opportunity.

This collaborative approach has been adopted in more advanced markets such as aerospace, defence and automotive industries. The collaboration has also extended beyond the manufacture stage where the benefits are well documented [3], to include collaborative design, whereby the manufacturer of sub-assemblies/components becomes involved in the design stage rather than just making to plan.

One benefit of this method of collaborative product development is the emerging property of agility and the benefits that can be achieved in this area through the use of collaborative networks, especially of the short-term and dynamic variety. Agility is defined as the ability to respond to unpredictable events, particularly those external to the business environment, i.e. those out of the control of the businesses on which they impact [4]. Agility is increasingly important in global manufacturing with ever-changing customer demands, technological innovations, political and economic influences and many more factors creating a turbulent environment.

This research explores agility for the design stages of product development, achieved through the use of geographically distributed and collaborative virtual enterprises applying a concurrent engineering methodology. Specifically, the objective is to build on the widely adopted design process proposed by Pahl and Beitz in 1995 [5] and Concurrent Engineering techniques of Prasad [6], to look at ways in which these methodologies can be extended to reflect the collaborative nature of design with the goal of agility.

Section 1 reviews the literature dealing with the factors which are considered to have an influence on agility in a collaborative setting. This leads to the second part of the paper describing the methodology, the questionnaire design and the hypothesis for this research. The responses to the questionnaire will be presented, identifying the relationships between specific elements of the design process and the resulting agility of projects carried out using these elements. These relationships and their significance will be discussed before drawing conclusions and outlining planned future work based on the outcomes of this research.

2. Background

2.1.Collaboration

Collaboration between multiple companies or divisions within a company has been emerging for many years. Nagalingam et al [7] state that “Today's competitive and agility requirements of the global market can be only met by virtual enterprises”. This need for collaboration and the formation of virtual enterprises can take different forms depending on the circumstances. Martinez et al. [8] propose 3 types of VE:

Short-term VE – 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.

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, 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 [9], [10] [11]. Existing partners may be unable to satisfy new requirements and new partners may be brought in with the necessary expertise or resources.

2.2.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 [12]. Kidd in 1994 [13] suggested that in the future the market will face demand for higher product variety and lower production runs. In the following ten years there have been many varying definitions of agility, the most widely accepted of which states that agility is “the ability to operate profitably in a competitive environment of continually, and unpredictably changing customer opportunities” [9]. One theme running throughout the definitions is that of responsiveness to unpredictability in the external environment, i.e. an ability to deal with unexpected events.

Until recently the goal of achieving agility has been focussed on the manufacturing stage of product development. This is at the organisational level down to the individual agility of factory configuration, machine versatility [14] and material handling techniques [15], [16]. There have been many methodologies developed for increasing agility at both ends of this spectrum.

Although it has been identified that agility is a necessary attribute of any successful company in the modern climate, and that "collaboration" can be a means of achieving a certain level of agility, the area of agility applied to the design process is relatively unexplored, particularly in the collaborative environment of virtual enterprises and when dealing with Small and Medium sized Enterprises(SMEs).

2.3.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. A review of the literature has identified the need for many ICT systems, procedures and standards to be implemented within a virtual enterprise in order to increase the effectiveness of collaboration. 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 [17], [18].

There have been numerous projects investigating this area, from independent cases to Europe-wide research programs which have attracted large amounts of funding. iViP [19] succeeded in creating a single software environment for virtual product creation through the use of "wrappers" to convert data as it exited and entered different legacy systems used by the partners of the Virtual Enterprise. PRODNET [20] 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. Not least is the unwillingness to co-operate from the software vendors/manufacturers. In recent years there has been a consolidation of software companies encroaching into each others territory. CAD vendors have developed PDM systems which interface directly with the CAD software, 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. There is no perceived benefit to the vendor to have their software able to communicate with other systems, rather they hope to provide a single-instance software solution for a whole organisation (from enquiry and requirements capture through design and manufacture to after-sales support), and then all their partners too.

The use of translators (also known as "wrappers" or "parsers") 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. i.e. ten partners, each with their own PDM systems, would require 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.

One solution is for all companies within the VE to use the same systems, which has clear benefits because the inter-operability issue is removed. This was the subject of a trial by the Global Digital Enterprise Laboratory of Durham (UK) and Oregon State (USA) Universities [21] who carried out a re-design project using the SmarTeam PDM system from Dassault Systeme. The project concluded that although there were significant benefits to this approach, there still remain problems of inter-operability between the other software systems – for example CAD software – whose files are shared in this way.

An alternative method to both of these is an independent web-based system such as 4ProjectsTM. The cost of this system in particular 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 end-user. Another example of this web-based approach utilising the independent VRML format and Web Computer Supported Cooperative Work presented by Eynard et al. [22], which concludes that an asynchronous web-based system can significantly improve project management and sharing of information between partners. International standards and data formats

2.4.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. In addition to standards of units, there are also independent file formats for digital data, such as the FRML mentioned in the previous section and 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 save files in this way, but rather using the native file formats of the particular software. The same is true of common-place software programs such as Microsoft Office products, where an assumption is made that recipients can access the software specific files.

In the cases where external companies are brought into a project part-way through, it is important that they can be integrated as easily as possible in order to minimise the delay caused by their inexperience with the project [23]. One well-established methodology for achieving this is through the application of Design for Manufacture (DFM) and Assembly (DFA) techniques [24]. These techniques advocate the use of standard components, interfaces and connectors in product designs, making it easier for new partners to identify, work with and interface with existing designs. Additionally, DFM/A techniques suggest a modular approach to design, decomposing the design into a number of sub-designs connected through standard interfaces. This technique increases re-usability of individual sub-designs and increases ease of distribution for a collaborative concurrent engineering approach. This principle is also referred to as de-coupling tasks [25] and Modular Architecture [26].

2.5.Identifying Partners

As discussed previously 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 [27]. 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. propose a "breeding ground" structure for creating virtual enterprises where by a diverse group of companies all work 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 [27].

Armoutis & Bal [28] have developed a system of "competence profiling" where by 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 state: "people are the competence carriers" [29]. 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.

2.6.Summary

This review of the literature leads to the definition of an Agile Design Framework [4] comprising a set of Core Areas which are considered to be the most influential on collaborative design:

- Effective Data Sharing – potentially through an independent web-based system
- Adoption of International Standards
- Application of Design for Manufacture and Assembly techniques
- Rapid and Appropriate Partner Identification

The benefits of these Core Areas is fourfold: (1) to increase the effectiveness of collaboration efforts; (2) to minimise disruption to the existing internal activities of each partner; (3) to reduce product development time through seamless data transfer; and (4) to increase agility through the adoption of a set of tools which facilitate rapid re-configuration of the virtual enterprise in responding to unpredicted external events.

3. Hypothesis

The objective of this research is to explore ways in which the impact on a project of an unexpected event in the external environment can be minimised. Specifically, when a design project is de-composed into a number of concurrent tasks and distributed to a number of partners, unpredictable events can cause penalties in terms of time, resource allocation or quality to the project. This is illustrated in terms of time in Figure 1.

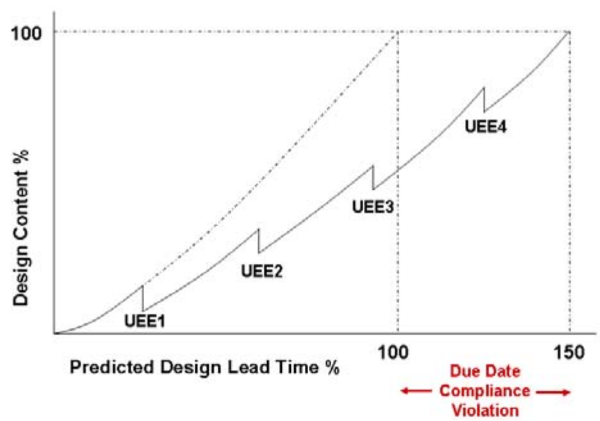

Figure 1 - (Time) Penalty Incurred as a Result of Unpredictable External Events

Although the Core Areas have been defined and have each been proven independently to have benefits to collaboration, one aspect of collaborative product development which has been under-addressed is the process of "setting up" the virtual enterprise to achieve the goal of agile product development. The classical product development process of Pahl and Beitz [5] is described for single companies, and while there has been research into the tools required to allow the same process to apply for the collaborative environment, there has been no change to the stages of the process itself. Therefore, in order that the Core Areas can be effective throughout the product development process, and in particular their agile benefits exploited in the face of unexpected events, the hypothesis states that a novel meta-design stage, during which time the details of the Core Areas are discussed and tools implemented, can be effective at increasing the agility of the product development process.

The meta-design stage is a process of designing the design process; including defining any data sharing system and the international standards to be used, providing training on any new ICT systems and ensuring procedures are in place and clear for responding to unpredicted events. If carried out before the early stages of product development (Figure 2), as soon as the virtual enterprise (potential) partners are assembled and before the embodiment or detailed design takes place, it is proposed that the Core Areas will be more effective in realising an agile product design process. This research seeks to identify any direct correlation between the extent to which meta-design is already used, the extent to which the Core Areas are already considered, and the level of agility experienced in existing design projects.

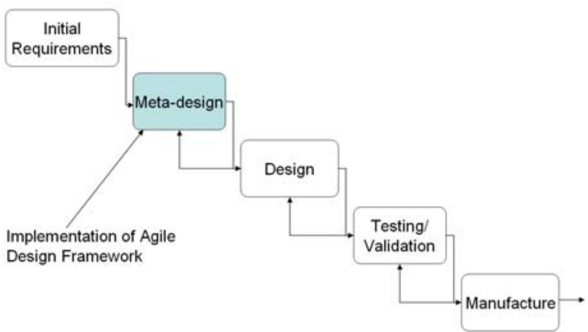

Figure 2 - Meta-Design stage for the agreement of the design process tools and meta-data

In summary, the hypothesis is that the adoption of techniques and tools covered by the four Core Areas, known as the Agile Design Framework, will have a positive effect on the agility of a company. Additionally, the early definition of these tools and techniques has a further positive effect, thus supporting the concept of meta-design.

4. Methodology

4.1.Population

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, and the projects must endure a very turbulent external environment during their life-cycle, which is particularly vulnerable to technological, political, environmental, economic and other fluctuations over such a long period of time. Companies and entire industries can come and go 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.

Because of these characteristics there can be great benefits to be realised from a design and manufacturing process which ensures that the best partners are always chosen, based on their individual expertise, knowledge and competence, and that can ride the external events to ensure that the project is able to keep to time and budget. For these reasons, the population to be considered for this research will be companies in the defence and aerospace industries.

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 170 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. The companies all operate independently of each other and so there is no attempt between them to align their systems for collaboration.

4.2.Data Gathering

In order to gather the required data on current tools and techniques in use, a questionnaire was developed based on the 4 Core Areas influencing collaborative design. In addition data was gathered to allow a calculation of the agility of their most recent collaborative projects (up to 3) using the Key Agility Index (KAI) [30].

Initially a pilot study was developed and it was submitted to experts and a selection of 8 companies with whom the authors had good contacts. The final questionnaire was then mailed to the “Design Manager” at each of the NDI member companies. The questionnaire was accompanied by a covering letter from the NDI Director of Projects & Programmes, explaining the benefits of completing the questionnaire and asking that it be completed within 2 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 respondents and explaining the implications of the main findings of the study.

Following a period of four weeks, the initial mailing was followed up with telephone calls to the non-responsive companies. This process resulted in identifying a number of companies for whom the questionnaire was not relevant (no design work); companies who had not received the questionnaire; and companies where the contact person had left the company and therefore the questionnaire had not been opened. A number of questionnaires were re-sent by post or e-mail and this generated further responses.

4.3.Questionnaire Structure

The questionnaire began with factual questions regarding the companies contact details, the job title of the person completing the questionnaire and the type of projects with which they are involved: collaborating with other companies; collaborating within their own organisation only; or no-collaboration. Companies responding with “no collaboration” were excluded from the results because the scope of the study covered collaborative design projects only. The introduction also included a description of the terminology used throughout the questionnaire to ensure consistency of meaning between respondents.

The questions were based on the four Core Areas previously identified from the literature and organised into 10 categories:

- Project Setup
- Reaction Process to UEEs
- Data Sharing Methods
- Data Formats
- Terminology
- Units of Measurement
- Partner Identification
- Planning for UEEs
- Design for Manufacture/Assembly
- Design Change Negotiation

Each factor contained between 2 and 6 questions on that theme giving a total of 39 questions which determined the level of adoption of techniques in these areas when collaborating with other companies or divisions. Respondents marked their opinions on a 7-point Likert scale ranging from 1 (strongly agree) to 7 (strongly disagree).

4.4.Data Analysis

In order to reduce the high number of variables (39) the results were factor analysed using Principal Components Analysis (PCA). PCA is a widely-used technique for identifying the underlying structure of the responses and the factors (variables) contributing the most variance [31]. The resulting component matrix was rotated using a varimax rotation with Kaizer normalisation to more clearly identify the patterns of adoption of the different variables and make labelling the factors less ambiguous. The Rotated Component matrix can be seen in Appendix 1. From the rotated component matrix it was possible to identify the number of significant factors using the Scree method (REF) which were then analysed for reliability using Cronbach’s alpha and the theme of each component was identified.

4.5.Results and Discussion

Data from the questionnaire were factor analysed in order to reduce the 39 variables into a smaller number of factors to reveal patterns among the variation of characteristics. The factors fell into 9 factors which accounted for 96% of the variance. When the component matrix was rotated to identify a clearer underlying structure the resulting Scree plot showed 5 salient factors (Figure 3).

The 5 factors accounted for “Project Setup and Measurement Units” ($\alpha = 0.879$), “Reaction Process to UEEs & Planning for UEEs” ($\alpha = 0.928$), “Terminology & Design for Manufacture/Assembly” ($\alpha = 0.867$), “Document

Formats & International Standards" (α = 0.912) and "Web-based PDM & Consideration given to UEEs prior to the project" (α = 0.916). These high Cronbach's alpha values for each factor show that each is a reliable representation of the underlying variables which contribute to each factor, with values of α > 0.7 being widely recognised as "acceptable".

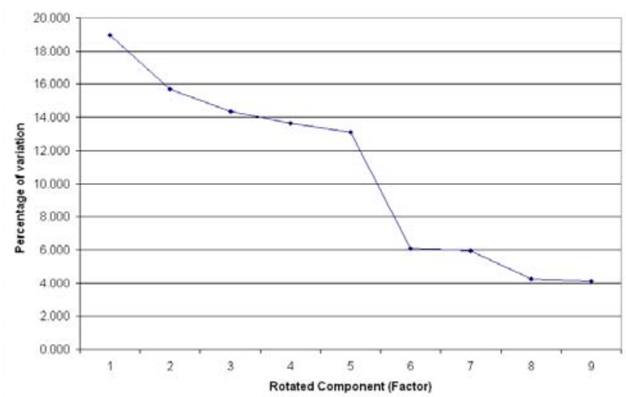

Figure 3 - Scree plot of the 9 principal components of questionnaire data after varimax rotation

In order to show the relationship between the factors and the agility of the projects, the values of each of the two most significant factors were calculated for each dataset. "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 4.

For each company the agility of their most recent project was also calculated as a ratio of the amount of time spent during the projects responding to Unpredictable External Events (the KAI). The hulls marked on the map indicate the groupings of "agile" companies (KAI <= 0.2) and "non-agile" companies (KAI > 0.2).

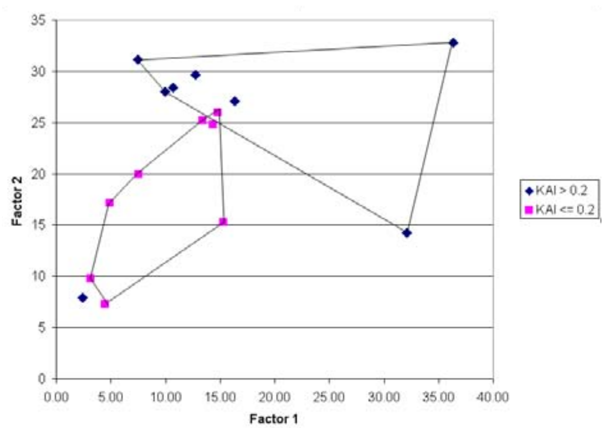

Figure 4 - Chart plotting the questionnaire responses calculated as factor 1 and factor 2

With the exception of a single outlier scoring low on both factors, the groupings clearly indicate that the more agile projects were carried out by companies who scored lower on the two principal factors. More specifically, this means a lower score on the variables concerned with Project Setup, Measurement Units; Reaction Process to UEEs; and Planning for UEEs. A low score indicates a high level of agreement to the questions posed, and therefore a higher level of adoption of the techniques and tools in these areas.

5. Conclusions and future research

From the literature Four Core Areas of collaborative design have been identified as the Agile Design Framework. From the results of the study carried out we can clearly demonstrate a relationship between the level of adoption of the techniques and tools covered by the Agile Design Framework and the level of agility achieved by design projects adopting its principles. Furthermore, the results suggest a strong relationship between the level of agility and the "Project Setup" which included such techniques 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. This conclusion supports the hypothesis of a meta-design stage carried out at the beginning of the project, and at which these issues are addressed, increasing the agility of the collaborative project.

The next stage of this research will be an industrial experiment with some of the companies who have responded positively to this first stage of the research programme in Agile Design. The objective is to clearly demonstrate in practice the benefits to agile collaborative design of a meta-design process and the other collaborative techniques of the Agile Design Framework supported by this study.

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8. Appendix 1

	Component				
	1	2	3	4	5
Measurement Units are agreed on by the whole team	0.954				
Measurement Units are agreed at the beginning of the project	0.929				
All team members use the measurement units agreed 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	-0.695				
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					
Training in responding to unexpected events is undertaken by all team members		0.823			
If assistance is required there is a method of identifying the necessary		0.807			
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					
Reducing the number of parts/components in a design is important		0.602			
Everybody in the project knows who is coordinating the project			0.907		
Making Manufacture/Assembly as easy as possible is important			0.849		
All team members use the terminology agreed on for the project			0.847		
Terminology is agreed on by the whole project team			0.681		
Using standard 'off the shelf' parts is important			0.662		
Terminology is agreed on at the beginning of the project			0.623		
We are always aware of design changes by other members of the project team			0.580		
Team members never use different measurement units to those agreed				0.869	
We have a procedure to follow when a change we make affects others				0.868	
All team members use the file formats specified for the project				0.814	
Document formats are agreed on at the beginning of the project				0.668	
Problems never occur sharing files between project team members				0.633	
Document Formats are agreed on by the whole team				0.564	
We always adhere to International Standards for designs				0.562	
New members to the project could QUICKLY gain access to all the project data				0.455	
Consideration is given to potential unexpected events prior to the project					0.865
There is a standard method for sharing project data within the team					0.809
New members to the project would easily understand how to use the system					0.771
This method is electronic (i.e. not paper based)					0.702
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					