Proceedings of ICAD2002
Second International Conference on Axiomatic Design
Cambridge, MA – June 10-11, 2002
ICAD 012

SUPPLY CHAIN DESIGN: AN APPLICATION OF AXIOMATIC DESIGN

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ABSTRACT

There are ever increasing pressures on companies to improve the quality of their products whilst reducing both costs and the time it takes to deliver products to customers. Traditional Concurrent Engineering approaches have been widely used by organisations to improve their business processes – resulting in reduced costs and shortened lead times. More recently, the idea of Three Dimensional Concurrent Engineering has been proposed: arguing for the parallel consideration of supply chain issues as well as those related to product and process. Three Dimensional Concurrent Engineering leads to a need for a supply chain design process which, in turn, requires tools to support the process. The research reported here was an early investigation into the feasibility of using axiomatic design theory to support a supply chain design process.

This paper reports an application of axiomatic design theory to the evaluation of a supply chain with respect to the costs and lead times of the parts of a product. A case study considering the materials and parts used in the manufacture of a small single seater sports car is described. Matrices of Functional Requirements and Design Parameters, influenced by Constraints, were captured using the Acclaro software. Design matrices were then created to relate the functional and physical supply chain domains.

The research has demonstrated that supply chain design processes can benefit from an axiomatic design approach. In particular, we conclude that it is feasible to consider both functional and physical domains of a supply chain. Further, these domains can be captured in axiomatic design matrices and a design matrix can be realised. The paper concludes with a discussion of some axiomatic supply chain design issues that arose during the research.

Keywords: supply chain design, axiomatic desgin

1 INTRODUCTION

There are ever increasing pressures on companies to improve the quality of their products whilst reducing both costs and the time it takes to deliver products to customers. Studies by Pittiglio et al [1999] have shown that supply chain best-in-class companies have an advantage in supply chain management cost of 3-6% of sales over average companies. These best-in-class companies also have cash available 2-3 months faster than average and have happier customers. Table 1 shows data from the benchmark studies of supply chains.

Table 1. Data from the benchmark studies of supply chains by [Pittiglio et al 1999].

Factor	Best-in-class companies	Median companies
Supply chain management costs as a percentage of sales	5%	10-12%
Cash to cash cycle time	30 days	100 days
Frequency with which customer delivery targets are matched	94%	69-81%

Traditional Concurrent Engineering approaches have been widely used by organisations to improve their business processes – resulting in reduced costs and shortened lead times. More recently, the idea of Three Dimensional Concurrent Engineering (3DCE) has been proposed [Fine et al 1995]: arguing for the parallel consideration of supply chain issues as well as those related to product and process. Krishnan and Ulrich [1998] identify four kinds of product development decisions that are alluded to in the literature: namely, concept development, supply chain design, product design and production ramp-up and launch. Like any design decisions, support for decision-making processes related to the configuration of supply chains require both representations of alternative supply chain structures and tools that allow the alternatives to be evaluated. A logical conclusion from Fine's work is that people carrying out 3DCE will need such tools when they are synthesising and analysing supply chains in addition to product and process design tools [Malone 1999]. The research reported in this paper asked the question, "Can the use of axiomatic design [Suh 1990] in product design decision-making processes be transferred to the domain of supply chain design?"

Three factors influencing the performance of the product development process, and thus supply chain design are *time*, *cost* and *quality* [Krause et al 1977]. Two additional factors are *risk* and *responsiveness* [Winand et al 2000]. With respect to a supply chain, time can be considered as a function of the summation of lead-times along chains and critical paths. Quality can be regarded as the extent to which the delivered product satisfies the technical requirements (functional requirements and contraints) that where specified by the customer. Risk is the likelihood and consequence of a product of the appropriate quality being delivered on time and to cost. Responsiveness depends upon industry sector; for example, it might be a measure of how quickly an organisation can react to different orders for products or of how quickly they can address changes in requirements. This paper reports an application of axiomatic design theory to the evaluation of a supply chain with respect to the costs and lead times of the parts of a product.

2 BACKGROUND

Benefits can be gained, especially in terms of improved quality and reduced costs and lead times, by considering and implementing chains for the flow of information that do not necessarily mirror the [product] supply chain [Christensen 1997]. Supply chain modelling and research has directed much effort towards improving the performance and operation of supply chains [Towill 1992]. Supply chain design, on the other hand, has received far less attention [Anon 2000]. SCOR (The Supply Chain Council's Supply Chain Operation Reference model[1]) identifies four key processes to the operation of a supply chain: source, make, deliver and plan. Sahlin [2000] describes a use of the SCOR reference model as a basis for an application of axiomatic design to the concurrent design of supply chain and product with a view to minimising lifecycle costs and other supply chain performance indicators.

Fisher [1997] argues that, before devising a supply chain, one should consider factors such as the demand for the product and the kind of product that is being produced. These can be seen as requirements in a supply chain design process.

Suh [1990] described an early application of axiomatic design to the design of a university engineering college: a research and education organisation. More recently Lenz and Cochran [2000] have described an application of axiomatic design theory to the design of a product development organisation. In their paper product development is described as an information transformation process and the decomposition of FRs and DPs for a product development system are provided.

This contrasts with supply chain design where the flow of goods must be included. Whilst such [product development] systems may be distributed across a number of organisations the decompositions of FRs and DPs do not explicitly address issues concerned with design of systems composed of multiple organisations. For example, each player in a supply chain is likely to have its own strategic direction and may well have different kinds of relationships with other organisations. Brandenburger et al [1997], for example, identifies co-operation (e.g., along a supply chain) and competition as two types of relationship that occur in supply network. Other relationship types include complementation (doing things that improve the product of another organisation's product for its customer) and collaboration (for example, partnership). Engelhardt and Nordlund [2000] describe a use of axiomatic design theory for strategic planning but the case study that they use is limited to one company.

Supply chain design is fundamental to business strategy [Agouridas et al 2001a]. Hence the need for systematic approaches to supply chain design: starting at the very early stages with problem definition. Fine [1998] argues that supply chains should be designed concurrently with the product and the process: namely, 3DCE. A logical conclusion from Fine's work is that people carrying out 3DCE will need such tools when they are synthesising and analysing supply chains in addition to product and process design tools [Malone et al 1999]. McKay and de Pennington [2000] describe a framework for the representation of product, process and supply chain that can be used to underpin the information that flows during 3DCE activities. In contrast, the work described in this paper explores the applicability of axiomatic design theory and process to the synthesis and analysis of alternative supply chain structures – another key aspect of the computing infrastructure needed to support 3DCE and, particularly, computer aided supply chain design. A specific example is used to illustrate the way in which axiomatic design theory can be used to capture functional requirements and design parameters of a supply chain. The independence and information axioms can then be used to verify the quality of the DPs before more exhaustive and costly techniques such as supplier assessments and supply chain simulations are carried out [Hines et al 2000].

3 CASE STUDY: UNIVERSITY FORMULA STUDENT CAR CHASSIS

Each year students at the University of Leeds design, build and test a single seater formula-style Racing Car. The car is entered into events such as the Formula SAE competition in the USA, The Institution of Mechanical Engineers Formula Student Event in the UK and the Formula SAE Australasia competition. The students responsible for delivering the car start work on it in October each year and the critical deadline is the Formula SAE competition held in May the following year. Thus the students have to design, make and test a car in 8 months. The item most critical to delivering the car is its chassis. Over the last 5 years the chassis of the Leeds car has been made from T45, a steel alloy, and carbon fibre panels. Figure 1 shows the chassis of the 2000/01 car.

[1] Supply Chain Council - http://www.supply-chain.org

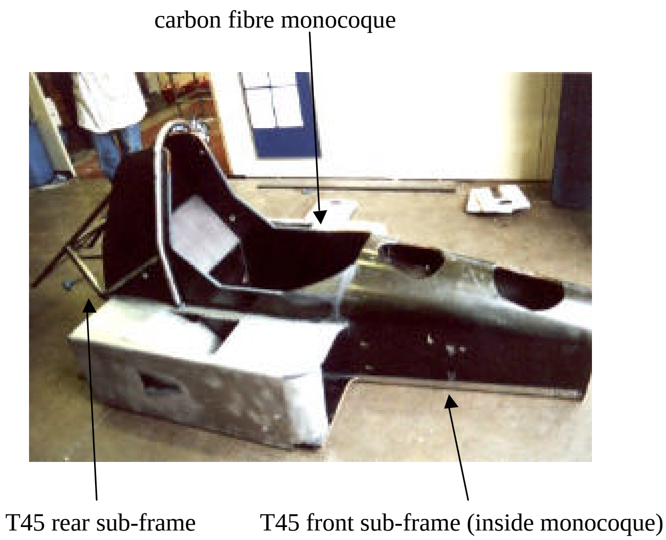

Figure 1. 2000/01 car chassis.

The chassis is the critical element as the majority of other parts are attached to it and it has a long lead-time relative to the car's other parts. Thus, in turn, the supply of the chassis raw materials is critical. The chassis of the car can be split up into three different parts: the composite carbon fibre monocoque, the front sub-frame (internal to the monocoque) and the rear sub-frame. These parts are made separately and then assembled together to form the chassis of the car. These parts themselves consist of a number of sub-assemblies. The carbon fibre panels are cut, folded and formed to the required shape. The parts of the sub-frames are cut and bent to the required shape and welded together. The sub-frames are glued to the monocoque using structural adhesive.

The car is designed to be produced in a volume of 1000 per year. The parts and the raw materials for the car come from a range of suppliers. Table 2 shows the main raw materials used in the manufacture of the chassis

Table 2. Chassis Materials.

Description	Form
Carbon fibre panels with NOMEX® honeycomb core	1130mm x 2400mm
T45 steel alloy	25.4mm diameter tube in lengths 4.6m±0.1m
Welding consumables	box
DP490 Structural Adhesive	37ml tube

There are 2 cases to be considered.

1. The design of a supply chain for the design manufacture and racing of a car over an 8 month period where time is the main driver.
2. The design of a supply chain for the manufacture of 1000 vehicles per year where the main driver is cost.

An alternative to supplying the T45 steel alloy in standard lengths is to order it cut to length. This is advantageous if the supplier of the T45 steel alloy can cut the material to length more cheaply than its customer.

4 CASE STUDY: APPLICATION OF AXIOMATIC DESIGN

4.1 CHASSIS SUPPLY CHAIN REPRESENTATION

In this section an axiomatic design view of the supply chain for the raw materials of the car chassis is developed. Elements of the customer, functional and physical domains are considered for the supply chain.

The notion of customer in a supply chain is a role played by the majority if not all companies in it. The customer for the purposes of defining an axiomatic design customer domain with in the case study is the car manufacturer. In the case of the chassis supply chain the customer need is to obtain the materials necessary to manufacture the chassis efficiently. Furthermore, the customer needs to receive materials of an acceptable quality, at the appropriate time and at an acceptable cost. These needs map onto the following top level functional requirement (FR) and design principle (DP).

FR1 Obtain material for chassis
DP1 Chassis material supply chain

The chassis material supply chain can be viewed as providing carbon fibre panels with a NOMEX® honeycomb core, T45 steal alloy and DP490 structural adhesive. Hence the FRs that result are to obtain carbon fibre panels, T45 and structural adhesive. It is anticipated that the carbon fibre panel supplier has knowledge of the structural adhesive used in carbon fibre production it is proposed to use the same supplier for the carbon fibre panels and structural adhesive. This results in the following FRs and DPs.

FR11 Obtain material for monocoque assembly
DP11 Identified supplier of carbon fibre panels

FR12 Obtain material for sub-frames
DP12 Identified supplier of T45 steel alloy

FR13 Obtain joining material
DP13 Identified supplier of carbon fibre panels

FR14 Welding
DP14 Identified supplier of welding rods

The design equation relating these FRs and DPs is:

$$\begin{pmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \end{pmatrix} = \begin{bmatrix} X & 0 & X & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{pmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{14} \end{pmatrix} \qquad (1)$$

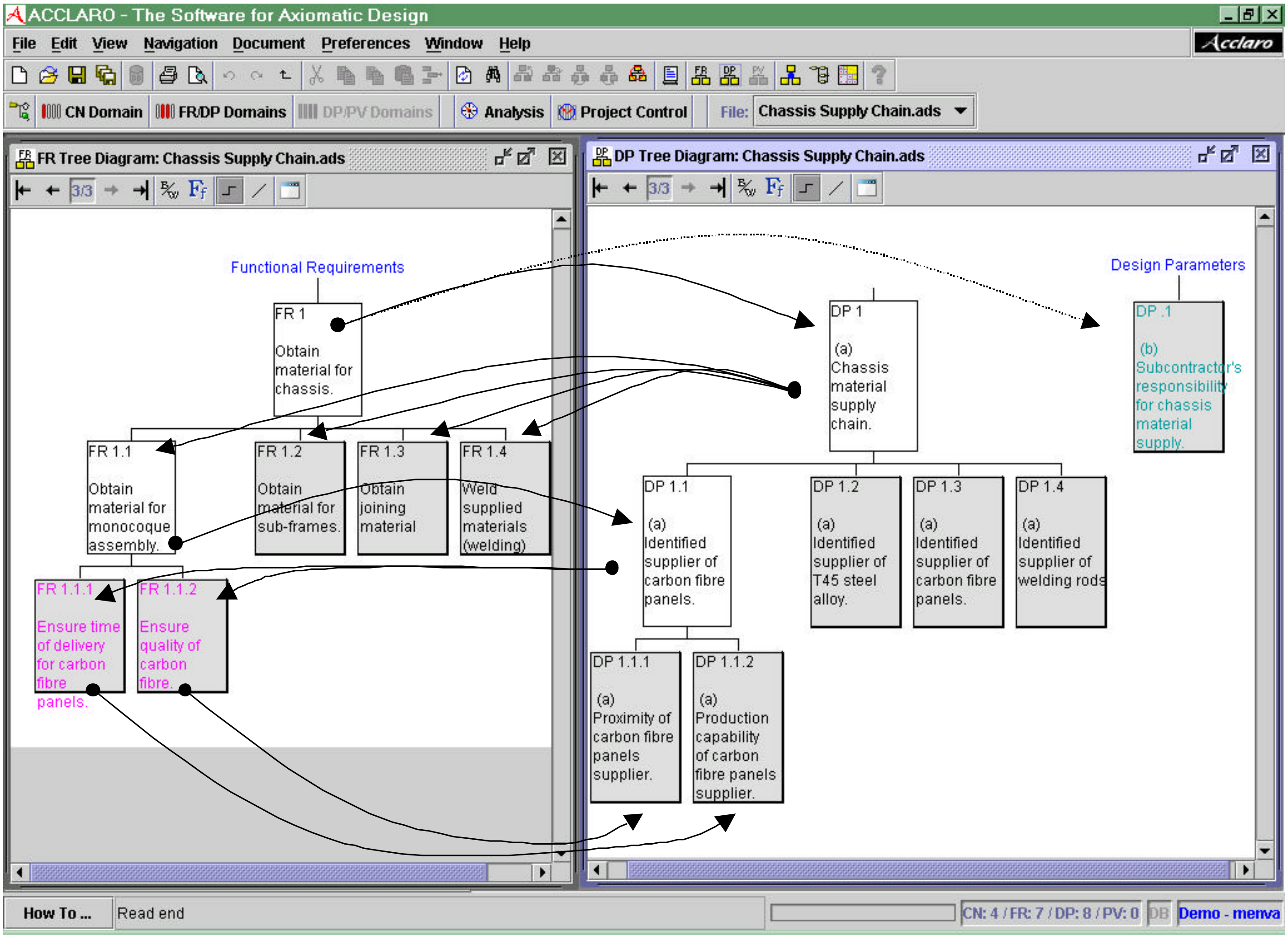

Figure 2. Car chassis supply chain FR and DP hierarchies defined in Acclaro software

FR1 and FR3 are both dependent on DP1 and DP3 as the same supplier is used for both the carbon fibre panels and the structural adhesive.

Once potential suppliers of materials have been identified it is necessary to consider the time it will take for the materials to be delivered, the quality of the materials and the cost. For FR_{11} the following sub FRs were defined:

FR111 Ensure time of delivery for carbon fibre panels
DP111 Proximity of carbon fibre panels supplier

FR112 Ensure quality of carbon fibre
DP112 Production capability of carbon fibre panels supplier

The design equation relating these FRs and DPs is:

$$\begin{pmatrix} FR_{111} \\ FR_{112} \end{pmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{pmatrix} DP_{111} \\ DP_{112} \end{pmatrix} \qquad (2)$$

The following system constraints are related to these FRs.

- The supplier of carbon fibre panels will have a maximum capacity they can supply. This capacity should be greater than the capacity needed to meet the requirements of chassis production.
- The customer wishes to minimise the cost of the carbon fibre panels, however this must be balanced against the reliability of both the quality of the material and the delivery time.

Similar FRs, DPs and design equations were defined for FR_{12}, FR_{13} and FR_{14}.

An axiomatic design representation of the supply chain was defined in the Acclaro™[2]. Figure 2 shows the FR and DP hierarchies for the car chassis supply chain and indicates the use of zigzagging in their development. Figure 3 shows the design equation relating the FRs and DPs at the second hierarchical level.

[2] Axiomatic Design Software Inc. - http://www.axiomaticdesign.com/

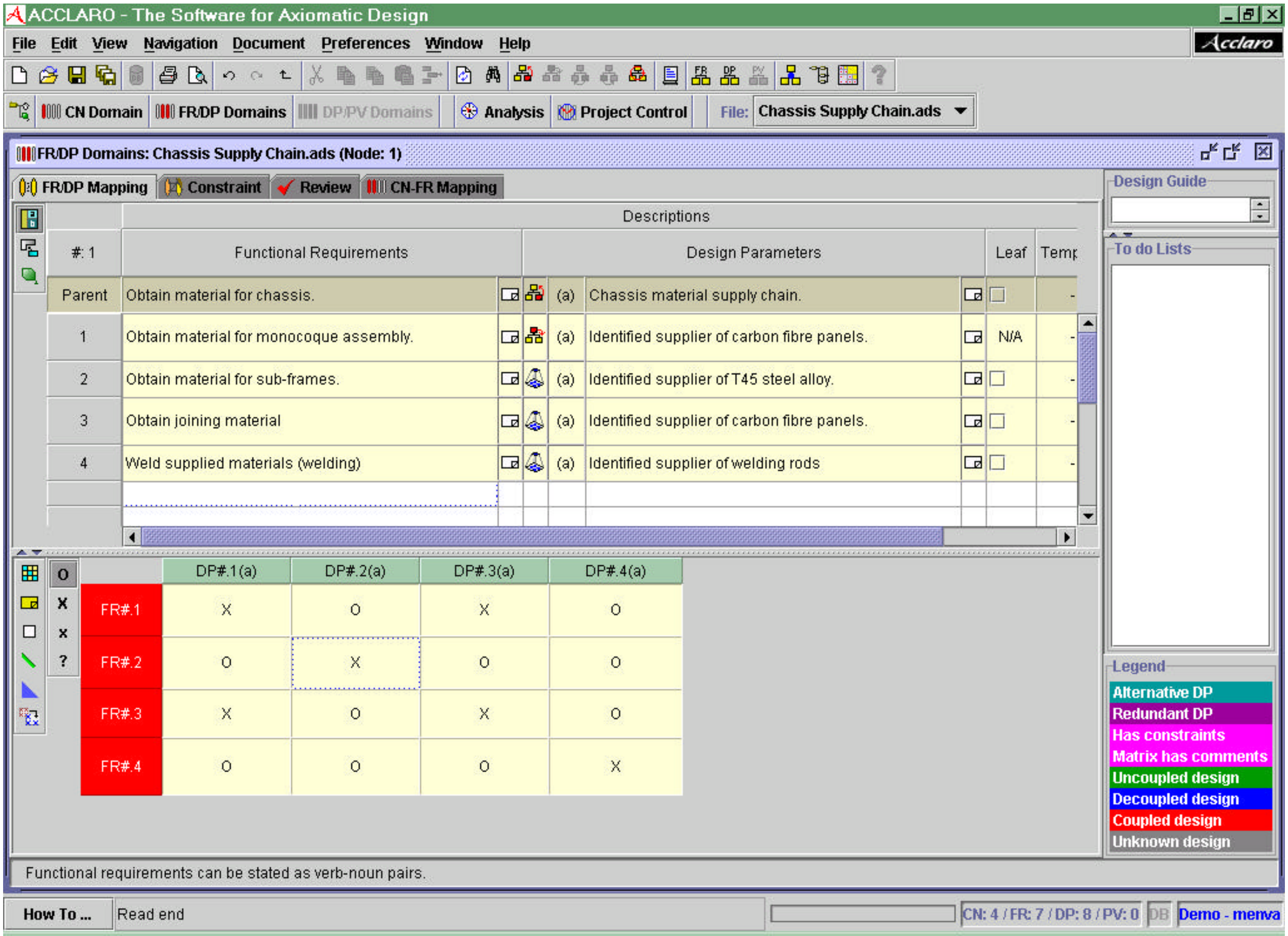

Figure 3. Car chassis supply chain design equation for the second level of FR and DP hierarchy

4.2 CHASSIS SUPPLY CHAIN EVALUATION

The FRs, DPs and design equations defined above represent both the one-off and the 1000-per-year supply chain cases. The solutions to the two cases will be differentiated by the way they address the constraints which are different for each case.

Equation 1 shows that the supply chain design is coupled. This is a consequence of using the same supplier for the structural adhesive and the carbon fibre panels. If separate suppliers were used then the following DP would result.

FR_{13} Obtain joining material
DP_{13a} Identified [separate] supplier of structural adhesive

The new design equation relating these FRs and DPs is:

$$\begin{pmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \\ FR_{14} \end{pmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{pmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \\ DP_{14} \end{pmatrix} \quad (3)$$

Thus the supply chain design, at this level, can be decoupled. The consequences of this decoupling are reducing the consequences of delays in delivery of the carbon fibre panels or the structural adhesive as a result of a delay in the other. Furthermore, if the supplier of the carbon fibre panels ceases to be able to supply them (it may go out of business) the problem of finding a new supplier is limited to finding a new supplier of the carbon fibre panels as opposed to finding a new supplier of both the carbon fibre panels and structural adhesive. However, the consequence of using separate suppliers is that it will not be possible to deliver both the carbon fibre panels and the structural adhesive in the same shipment. This will result in two delivery charges instead of one, which is likely to increase the total cost of the raw materials for the chassis. Thus the decoupling of the design reduces risk in the supply chain but is likely to increase cost.

Equation 2 shows the supply chain design as uncoupled. In this equation FR_{111} *Ensure time of delivery for carbon fibre panels* and DP_{111} *Proximity of carbon fibre panels supplier* relate to the probability that a supplier will be capable of delivering on time. This FR and DP identify an implicit system constraint. One of the measures of the supply chain will be its ability to deliver on time. Not only is this constraint implicit but it also identifies a key element of the design which should be considered using the information axiom. (The information content of a design can be defined as the logarithm of the probability of fulfilling a specified FR [Suh 1990]. If the FR_{111} has associated with it a constraint on the delivery time tolerance then the probability of being within the tolerance defines the information content.)

As identified above, an alternative to supplying the T45 steel alloy in standard lengths is to order it cut to length. This is advantageous if the supplier of the T45 steel alloy can cut the material to length more cheaply than its customer. The FR and DP for the T45 steel alloy being supplied in standard lengths are:

FR_{1221} Ensure sub-frame material is supplied in std lengths
DP_{1221} Supplier capability to provide standard lengths of tube

Requiring the T45 steel alloy to be supplied cut to length gives the following FR and DP:

FR_{1221a} Ensure sub-frame material is cut to length
DP_{1221a} Supplier capability to cut steel tube to length

Again both of these FRs have implicit constraints. The constraint is on the tolerance of the tube lengths supplied. To meet the chassis design tolerance the cut lengths of tube must be supplied to a closer tolerance than the standard lengths. Again, through defining the FRs an issue which should be considered using the information axiom has been identified: namely the standard tube lengths are $4.6m \pm 0.1m$ long, cut lengths need to be supplied within a $\pm 1mm$ tolerance.

In summary a supply chain representation has been developed and the independence axiom has been applied to it. This application of the independence axiom has led to the establishment of an uncoupled design for the example supply chain. However, the resulting design is likely to increase the cost of the chassis production process. The definition of the FRs and DPs has led to the identification of constraints relating to delivery lead-time tolerance. The consideration of the alternatives of either buying the T45 steel alloy in standard lengths or cut to length has led to the identification of constraints relating to the quality of the product supplied. An application of the information axiom is now required to allow the alternative supply chain structures to be evaluated further.

5 DISCUSSION AND CONCLUSIONS

Cost, quality, time, risk and responsiveness have been identified as major factors to be considered when evaluating the performance of a supply chain.

The case study has focused on applying the independence axiom during a supply chain design process. The representation developed concentrates on designing a supply chain that delivers the right raw materials. This helps to ensure the quality (it supplies the right thing) of provision of the supply chain. Furthermore, the definition of a decoupled design reduces the risk of late or no delivery of materials.

The result of decoupling the design represented by equation 1, where the same supplier is used for both the carbon fibre panel and the structural adhesive is the opposite of that a supplier rationalisation approach would recommend. An open issue for investigation is whether supplier rationalisation creates coupled and so riskier chains that can deliver products more cheaply?

This focus on the purpose of the supply chain indicates why the same representation can be used for both the one-off and the 1000-per-year supply chain cases. In both cases the same raw materials are required. The difference relates to the lead-time driver of the one-off case and the cost driver of the 1000-per-year case. The main drivers of supply chain performance are time/responsiveness and cost for each case respectively. The case study identified the importance of delivery time tolerance. However, the development of FRs and DPs did not naturally lead to targets for, and therefore constraints on, lead-time and cost. The case study did identify a number of implicit constraints, on lead times and quality, and the role of the information axiom in evaluating the design relative to these constraints.

The independence axiom aids in ensuring the supply chain design will provide the right products. The information axiom aids in reaching a trade-off between quality, cost, time, risk and responsiveness of the supply chain. However, for the appropriate trade-offs to be made, the constraints on the design have to be defined. As discussed above, the development of the case study did not naturally result in the definition of cost and time constraints and consequently jeopardised the opportunity to analyse the design using the information axiom.

The identification of cost and time constraints resulted from considering the major performance drivers (cost, quality, time, risk and responsiveness) of the supply chain. This checklist was key in applying axiomatic design to the supply chain.

The use of the Acclaro™ software aided the axiomatic design process by structuring the definition of FRs, DPs and Design Equations. The strong typing of the software requires a systematic approach to be taken in the definition of an axiomatic design representation.

Crucial to the definition of FRs is the context provided by the customer domain. For the purposes of supply chain design, it is not always clear who, if anyone, owns or is responsible for the entire chain. As a consequence, an issue in using axiomatic design, or many other product design methods and theories, is who defines the requirements and, more broadly, is there one set of supply chain requirements or are there many. Other research work at Leeds [Agouridas et al 2001b] is currently investigating tools and techniques for the systematic structuring and definition of the customer domain.

6 ACKNOWLEDGMENTS

Early work on the case study report in this paper was carried out by Soundarrajan Damodharasamy an MSc student in the School of Mechanical Engineering, University of Leeds. The research reported in this paper is related to two UK Engineering and Physical Sciences Research Council research projects: SII Project Number GR/M56715 (MAPPSEE) and, under the auspices of the White Rose Faraday Centre for Enhanced Packaging Technology, Supply Chain Innovation in Packaging Industry, Grant Number GR/M27579(SCIPI). Much of the case study data came from the University of Leeds Formula Student Racing Car Team.

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