Supply-Chain Boundaries in Multi-Firm Product Design:
A Multi-Industry Study

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Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

January 10, 2002

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Executive Summary

This work examines the structure of boundaries between firms who design products together in a supply-chain relationship. These scenarios are termed design-chains, to differentiate the supply of designs from the supply of actual manufactured products. Fundamental system architecture concepts are augmented with a basic argument from economics. The result is a new and formal distinction between two fundamentally different types of design-chain boundary: the integral boundary and the modular boundary.

With a theoretical footing for these boundaries established, they are applied to a multi-industry study of industry practice. Interviews with 43 employees from 17 organizations are used to shed light on specific design-chain practices in industry. Results are presented in a series of short design-chain maps, which show the relationships between firms in actual design processes. Cases from the telecommunications, automotive, and heavy-truck industry are presented.

Tools such as supply-chain mapping, clockspeed analysis, and the so-called industry 'double-helix', are applied to the results of the chain mapping procedure. The concept of design-chain interfaces, and the industry cases as gleaned from interviews, will be the basis for discussion on several crucial strategic issues. Finally, new issues in design are explored, including the problem of integral design-chain "hold-up", and the nature of functional decomposition in modular-design markets.
1. Introduction

1.1 Background

Engineering design has received increased attention in recent years. As engineering methods become more advanced, and information on engineering processes becomes more plentiful, the need to incorporate a good design process is seen as a key asset. Recent authors have converged on the concept of design as a decision-making process. Engineering development processes are designed in support of these decisions. Indeed, much of the literature on engineering design is devoted to various aspects of decisions making processes.

Unfortunately, the existing literature takes little account of shared design processes, wherein design decisions are distributed among two or more firms. Most authors deal with decisions contained within a single firm. And yet no business can ignore the impact of supply chain structures, which distribute processes among firms. Supply-chain effects make themselves known in many scenarios, including manufacturing, logistics, and business strategy. Not surprisingly then, industry supply chains have a major impact on design decisions. Indeed, it is no exaggeration to say that most all products are designed and engineered by several firms in a supply-chain structure.

Designs are collections of decisions. These decisions are distributed along the supply chain. But what roles in the decision-making process are assigned to which players? How do industries manage this shared design process, and how do participants position themselves to gain from their engineering design capabilities? This thesis seeks answers to these questions.

1.2 Objectives

The main objectives of this work can be classified as follows:

1. to develop the concept and/or framework necessary to describe the nature of the boundary between firms in product design processes.
2. to apply this concept, as a part of the larger framework proposed by Fine (1), in order to investigate the distribution of design processes along supply chains. (Inherent in this objective is the goal of learning about current industry practice in this area.)
3. to draw meaningful conclusions about impact of firm boundaries on design processes in general, and on strategy in particular.

1.3 Approach

First, a literature review is conducted, which summarizes the strongest thinking on the topic of supply-chain interfaces, product development, and shared design processes. The concept of a design chain is introduced to distinguish this subject area from the traditional manufacturing-based supply-chain arena. Incorporated in this literature review is a short theoretical discussion of design processes, including the terminology and basic principles of design. These principles are then extended to the two-firm case, where design decisions are shared by the two parties. This scenario, which is typical of many supply chains, presents several new problems at the interface between firms.

These problems are solved via one of two interface types, defined here as the modular and integral design-chain interface types. These types are analogous to previously defined concepts in product architecture, but are applied specifically at the interface between firms. The design-chain boundary types are defined in some detail in the context of design-chains.

With this concept in hand, a group of nine short, industry-based case studies are performed. Following the work of Fine (1), a fast-clockspeed industry (telecommunications) is examined, compared and contrasted to two slower-clockspeed industries (automotive and heavy-truck). The cases are based on interviews with 43 people in 17 different organizations, incorporating input from all levels of the supply chain.

Having proposed design-chain boundary types, and illustrated their application in industry-based case studies, generalized lessons are discussed. The telecommunications industry, with its rapid change and technological advancement, is used to forecast events in the slow-clockspeed automotive and heavy-truck industries. Several overarching themes are extracted from the analysis, and new concepts are introduced with mathematical models as appropriate.
2.0 Literature Review

2.1 Engineering Design

This review of engineering design is provided for two reasons: 1) to introduce basic concepts of form, function, system decomposition, and design process; 2) to set the stage for theoretical work presented in later chapters. This is not meant as an exhaustive review of engineering design, but rather, as an introduction to several key engineering and design concepts, as they apply to the subject at hand.

2.1.1 Form and Function

Two high-level concepts drive engineering design and guide the processes by which design is accomplished. These are the concepts of form and function. Briefly: form describes what the object is; function describes what the object does. In the well-known words of Louis Sullivan "Form follows function."

Function is the starting point for the design process. User or customer needs are defined in functional terms; that is, in terms of what the product does. From there, a set of high-level functional requirements are derived. These functional requirements are the essential goals of the design process. The design will have value, or not, depending on how well it meets some required function of the end user (2).

Intertwined with functional requirements are constraints, which are also functional statements of what the product must do, or not do. Some authors, notably Suh (3), define a separate classification for functional constraints. In practice however, constraints and requirements are often indistinguishable, and form an inseparable set. The set of requirements and constraints will be referred to, from here forward, as the requirements set.

Form is the space in which the designer operates. In the words of Alexander, "The form is the part of the world over which we have control, and which we decide to shape while leaving the rest of the world as it is" (4). These formal elements, over which designers exert their influence, are called design parameters. The design process is a process of selecting design parameters, which in combination satisfy the requirement set. Formal decisions are the currency of design.

2.1.2 System Decomposition

For very simple systems, the entire requirements set can be met by a limited number of design parameter choices. But in complex systems, the map between form and function is
intractably complex, unless some structure is applied in advance. Imagine the design process of an expensive automobile, where a luxurious ride is a high-level functional requirement. A designer cannot, on the basis of that high-level function, decide the height tolerance for the left-front engine mount. The high-level functional requirement must be decomposed into more manageable functions, which can be met by a limited set of design decisions.

This decomposition process is considered by several authors. Suh (3) proposes a decomposition of function which, at each level of decomposition, is followed by an associated decomposition of form. This method has been accepted and adopted by others (see for example (6)). and will be used here as a 'generic' decomposition method. Although others have developed different methods with some success (see for example (7) and (8)), the objectives of this work can be met with the 'classical' decomposition method of Suh.

Figure 2.1 shows a generic example of a system decomposition. At each level, function is mapped to form, and that form is assigned its own functional requirements at the next level of decomposition. This abstraction is applied to a specific example of an automobile in Figure 2.2. Functional boxes in the decomposition are composed of requirements sets, including constraints. These functional sets are stated explicitly at each of the decomposition, with greater detail applied at lower and lower levels.
Figure 2.1: Three Layers of a Generic System Decomposition
Requirements Set: Apply brake torque of 75NM per 1kPa of line pressure applied, with
  o no resonance under 60Hz;
  o no audible noise;
  o no durability failures in component test spec #XX;
  o cost under $6.00

Requirements Set: Transform user input to vehicle directional control in a safe and comfortable manner, while maximizing performance-vehicle feel and driving dynamics performance of (benchmark vehicle), at a cost of under $25.00.

Figure 2.2: System Decomposition Applied to an Automobile
2.1.3 Level Zero

Note that cost targets are included as part of the requirements sets in Figure 2.2. However, there is no stated financial goal in the level-1 functional requirements. How did financial requirements creep in to the decomposition if the high level requirements had no financial component? The answer lies in an unseen part of the decomposition, at a level higher then was shown in Figures 2.1 and 2.2. This highest level, termed 'level zero' for our purposes here, is the financial requirements set. This level of requirements applies, not to the end user, but to the firm who owns the design. This concept will be critical later, when multiple firms are considered. The level-zero concept is illustrated in Figure 2.3.

Firm-level requirements are typically associated with some financial targets. For our purposes, we make the blanket assumption that firms seek maximum profits. With that in mind, we should reconsider the cascaded cost targets shown in Figure 2. Although target setting is often used as a guidepost in design, many targets are somewhat arbitrary measures of acceptable 'goodness.' For cascaded targets of cost, profit, or other financial concerns, a simple target does not describe the 'profit-maximizing' nature of firms. Put another way: even if the target cost is $1.00, the buying firm still prefers a cost of $.99. This point seems academic here, but will be critical in a later chapter.

The back-and-forth decomposition, between function and form at ever-more specific levels, is at the heart of system engineering and product design. But this decomposition does not describe the actual design process at every step. At each level of each path in the decomposition, a development process must be applied to the problem at hand. This is the topic of the next section.
maximize value for shareholders

supply user function that commands a price of (XX%) over cost

provide wireline voice link to communication network

(marketing and sales)

(finance)

Level 0 (firm level)

Level 1

telephone

Level 2

Accept user I/O

transform, transmit signals with PSTN

handset I/O device

phone body

Level 3

receive user digit input

receive user voice input

provide user audio output

connect electronic I/O

keypad

microphone

speaker

wiring subsystem

Figure 2.3: System Decomposition for a Telephone, including Level-0 Firm Goals
2.1.4 Development Processes

At each level, detailed design must be performed to generate specific, buildable designs. This process is commonly referred to as the product development process. Many authors, and most firms who design products, have their own structures of PD processes. Specifically, Ulrich and Eppinger (8) have documented a PD process which represents a 'typical' product design case. This process is embedded in each linkage between function and form, and must be completed not only for the lowest tiers of each chain, but for the built-up subsystems along the way, and for the final system as well. This concept is illustrated in Figure 2.5.

2.1.5 Thesis Objective Number One

Almost unanimously, design process guidelines treat the design process in a single-firm environment. That is, their methods assume that 'the designers' or 'the design team' is motivated by the same incentives toward a design, which optimizes value. But in fact this is seldom the case. In practice, design decisions are made by multiple firms, typically arranged in a supply-chain network. This network includes armies of designers, employed by various firms, each with varying capabilities, incentives, and ideas about what constitutes 'good design.' There are boundaries then, not only between the location or attitude of supplier and customer, but between their fundamental view of the design process. When a supplier designs a subsystem for their customer, what is the nature of the design-process boundary between them?

The first objective of this thesis is to answer this question.
function A

function $B_1$

function $B_2$

function $B_3$

form $B_1$

form $B_2$

form $B_3$

form $C_1$

subsystem $B_2$ design and development process:

concept  CAD  analysis  prototype  test  mfg

subsystem $C_1$ design and development process:

concept  CAD  analysis  prototype  test  mfg

Figure 2.5: System Decomposition with Embedded PD Processes at Various Levels
2.2 Supply-Chains

It is apparent that, although the existing literature treats engineering design in single-firm environments, a multi-firm environment is more realistic. These multiple firms are typically engaged in a supply relationship of some kind. With this in mind, it is necessary to consider the literature of supply-chains, and the means by which they are studied.

2.2.1 Traditional Views of Supply Chains

The traditional view of supply chains stems from the science of operations and manufacturing. Supply chains have been treated as points of entry for raw materials or components into production processes, and managed accordingly. Some authors have considered various facets of these supply-chain problems, such as models of inventory planning (9), and demand-based supply-chain models (10).

This manufacturing-oriented view of supply-chains is based on an old idea: suppliers were chosen based on their ability to build parts, not to design them. In models of supply-chain operations, even sophisticated modules are just inventory. There was traditionally no consideration of product design. This view necessitates a completely designed (and therefore completely defined) product, which can be considered as a discrete piece of inventory.

This view began to change, with the widespread success of Japanese companies in a range of US markets in the 1970s. As US industries struggled to keep up, they focused on Japanese success stories, such as Sony and Toyota. What US companies found was a close link between engineering design and manufacturing. US companies began to realize the importance of design for manufacturing, and concurrent engineering of product and their manufacturing processes. (See especially (11) and (12)).

As manufacturing and design formed closer links, the manufacturing view of supply chains struggled to keep up. Was a supplied part just a piece of inventory? What about the design of supplied components, or subsystems? What were the strategic implications of outsourced production, or outsourced design?
2.2.2 The Ultimate Core Competency

Recently, an expanded view of supply chains has taken hold in the literature. This view, championed by Fine (1), is described as follows:

"The battlefront in today's competitive wars is the design of the supply chain. No longer can it be relegated to the company's tacticians; rather, it must be part and parcel of the organization's key strategic thinking."

In this view, the selection of suppliers and customers are strategic concerns. The core competencies of a company include, not only specific knowledge about their products, but about how source subsystems of those products. In the words of Fine and Whitney (13),

"the main skills companies should retain transcend those directly involved with product or process, and are in fact the skills that support the very process of choosing which skills to retain."

These authors propose a wide array of concepts to aid in strategic supply-chain thinking. Three of these concepts will be used extensively here; the concept of integral versus modular architectures, the concept of clockspeed analysis, and supply-chain mapping.

2.2.3 Integrality versus Modularity

Though related concepts have been around for some time, it was Ulrich (14) who first formally proposed the distinction between two types of product architectures: the integral architecture and the modular architecture. Modular products are composed of modules with simple and standardized interfaces, such that various module designs can be interchanged. Integral designs are composed of parts with intractable and non-standard interfaces between subsystems, such that alternate subsystem designs cannot be interchanged.

Fine noted that this distinction between architecture types is closely associated with the vertical/horizontal dichotomy of industries as a whole. Further, he proposed that industries are not static, but oscillate between the integral/vertical state and a modular/horizontal state. Figure 2.7 illustrates this process. The rate of oscillation was termed by Fine as the industry "clockspeed," and was shown to relate fundamentally to the rate of change in technology (that is, the technology clockspeed).
2.2.4 Clockspeed Analysis

The concept of industry clockspeeds is vitally important to study the supply-chains of slow-moving industries. In many industries trends are slow to develop, and history repeats itself on a very long time scale. Fine proposes a sort of 'business genetics,' wherein a fast-clockspeed industry may be studied in the place of a slow clockspeed industry, and the results projected to the slower industry. This method is a structured way to investigate the topics of product architecture and industry structure, and is well-suited for the subjects investigated here. Specifically, the strategic implications of multi-firm product design (or design-by-supply-chain) can be explored within this framework. In upcoming chapters we will compare and contrast three industries of various clockspeed; namely the telecommunications, automotive, and heavy-truck industries.

2.2.5 Supply-Chain Mapping

Supply-chain mapping is a straightforward technique, by which the supplied components and subsystems of a product are identified and documented. The entire chain, including lower tier suppliers-to-suppliers, are included as an integral part of the map. For organizations at the downstream end of the supply-chain, this map can grow quite large.

For organizations, the map is a way of documenting their supply chain, and a starting point for designing that supply chain according to strategic objectives. For our purposes here, the
objective is somewhat different. We are focused on product design, and are interested in the means by which firms design products as a part of the supply chain. For these purposes, we will designate a slightly different concept, termed the design-chain.

2.2.6 Design Chains

The concepts explored in this paper are applicable to supply-chains and product design processes. In order to simplify our terminology, we will define the concept of a design-chain as the chain of organizations which is responsible for designing and developing a product. This distinction from the term 'supply-chain' allows us to apply Fine's methodologies to specific cases of product design, without unnecessarily delving into manufacturing or actual product realization. (For the record however, it will often be necessary to look at exactly these 'traditional' supply-chain concepts.) With the established concept of design-chains, we can consider firms on the basis of their input to product design, as opposed to their input to actual product generation/manufacture. The distinction varied from case to case: sometimes the design and manufacture is co-located within a firm; other times the design and manufacture are entirely separate.

Design-chain maps will follow the same guidelines as supply-chain maps, and other clockspeed-based analysis tools can be used interchangeably within the domains of manufacturing and design.

2.2.7 Thesis Objectives, Numbers Two and Three

Design-chain maps can tell us how firms combine to generate complete designs. But this information is just the beginning of a larger and less obvious issue. In the words of Baldwin and Clark (2), "Designers see and seek value." In a single-firm case, this point is straightforward. But in a design-chain, value suddenly has a different meaning to each participant. If and when designers find value, to whom does it accrue?

The answer depends on the design-chain structure of the specific case. This structure forms based on the combined strategies of participants, and the ever present hands of fate, markets, and technology. Design processes go on continually, and connect firms who share a supply chain structure. How do specific industries distribute design processes along their design-chains? And what is the impact of these firm boundaries, on design processes and product strategy? The second and third objectives of this thesis are to answer these two questions.
3.0 Objectives

The literature review points to several remaining questions in the field of shared design processes. The nature of design decisions, and their means of crossing inter-firm boundaries, remain unspecified in most cases and unclear in general. One objective then is to develop the concept and/or framework necessary to describe the nature of the boundary between firms in product design processes.

These boundaries are meant as a tool, for use in the study of supply-chains in which product design is a major concern. The concept of a *design-chain* was created for exactly this purpose. The second objective is to apply this concept, as a part of the larger framework proposed by Fine (1), to learn how firms distribute design processes along their design chains. Inherent in this objective is the goal of learning about current industry practice in this area.

The final objective is to draw meaningful conclusions about impact of firm boundaries on design processes in general, and on product strategy in particular. This will be done using lessons learned in the industry study. This objective is met largely in the discussion section, where the results of the study can be formed into overarching observations and conclusions about industry practice in design-chain strategy.
4.0 Method

A framework will be presented in this chapter, for the purpose of meeting the objectives of Chapter 3. First, some system-architecture and economics concepts are used to develop the ideas of design-chain boundary types. With these boundary types established, parameters of the industry studies are described.

4.1 Theory

4.1.1 Breaking the System Decomposition

Recall from Chapter 2 that a full-system decomposition, including a map of form to function at each level, is the start of a full-system engineering design process. And at each level of this decomposition, a design process is applied, which results in a completed design at that point in the overall decomposition. Recall also that the entire process is typically divided among a supply network, by means as yet unspecified. It is now time to clarify the methods by which portions of the design process are distributed among a supply network.

Consider two firms, arranged in the simplest supply-chain, as shown in Figure 4.1. The firm who plans to sell the final completed product is denoted the downstream firm (Firm A). The supplier of a particular subsystem or component is denoted as the upstream firm (Firm B).

In a traditional manufacturing-related supply chain, product design is the job of Firm A. With the design completed, Firm A sends completed prints to Firm B, who bids on the production of the part. But in a design-chain, the design work may be spread between the two firms. This distribution typically begins at the downstream firm, who generates the system decomposition of their end product. At some point in the decomposition, a functional requirement set is transferred to firm B as a subsystem specification. These requirements are controlled by firm A, but they will be satisfied via firm B's design parameter choices.

![Figure 4.1: A Simple Design Chain](image)

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4.1.2 Functional Set Mismatch at the Firm Boundary

Recall that, due to monetary 'level-zero' requirement sets, financial requirements are present at every level of the decomposition. But unlike physical functional requirements, financial requirements are firm-specific. These financial requirements cannot cross firm boundaries without being transformed. The reason is clear: both firms are profit-maximizing, but their requirements for profit maximization are in conflict at the boundary. This conflict is shown in the expended requirements set, viewed from both sides of the supply-chain boundary, in Figure 4.2. This disagreement in requirements sets creates a fundamental tension between firms.

This tension is fundamental when firms are profit maximizing. Yet many authors in the field of design see cost as a simple constraint. Under this incorrect assumption, firms have no interest in maximizing profit, as long as they meet some specific price- or cost-targets. This naive view may simplify the single-firm design process, but it leads to gross oversimplification of the multi-firm case.

4.1.3 Boundary Pollution via Cost Variables

In pure commodities, the design parameters (i.e., the form) is fixed. The tension between firms is confined to the financial variable; i.e., the price. In theory, the same is true for highly engineered products. But in practice, this price-tension will spill-over to the rest of the functional specification, as soon as the supplying firm begins a formal design process. The 'small difference' in functional sets becomes a difference in the entire set of design parameters. That is, the supplying firm will maximize its value, not just by negotiating price, but by negotiating the entire functional specification.

This sounds abstract, but can easily be clarified with examples. It is easy to imagine, that a supplier of steel beams will design them as thick as possible, in order to sell more steel, while the customer will prefer the thinnest acceptable beam, in order to save money. Note that "thinnest acceptable" has now acquired two different interpretations.

Similarly, if a microchip manufacturer has invested in equipment to make X μm line-width chips, they will propose such chips to their potential customers. The customer will accept the X μm design or not, based on their own profit-maximizing functional requirements for the end product. In either case, in-sourcing would allow engineering designers to design for optimum function (including optimal internal cost). Outsourcing will lead to some negotiation, which may or may not lead to the optimum formal solution.
Function 2.2 to Firm A:
Perform function 2.2 under constraints x, y, and z, and at the lowest possible price to Firm A.

Function 2.2 to Firm B:
Perform function 2.2 under constraints x, y, and z, at the highest possible profit for Firm B.

Figure 4.2: Generic System Decomposition with Supply-Chain Break
4.1.4 Example: Air Induction System

These examples cannot convey the intractable nature of more complex designs. Consider the example of an air induction system in an automobile. Imagine an original equipment manufacturer (OEM) releases a request for quote with the following information:

Requirements:

- Pressure drop under 100Pa at 0.15kg/s airflow
- Filter 99% of particles over 3microns at .15kg/s airflow
- Durable to 30,000 mile via durability test spec XX
- Radiated noise < 79dBA, at 2500rpm, using 1m std mic location
- Packages within allotted space (given CAD model)
- Cost less than $20.

The supplier does some preliminary work and predicts that, although $20 is unattainable, he could profit at a $22 price, if he were allowed to use:

- The injection-molding process in which he has recently invested, which will lead to 81dBA noise levels
- An existing filter design, which would drive pressure drop to 180Pa.

If he cannot use these formal design elements, he will not bid. Now the two firms must come to some agreement, not only about the price, but about the requirements.

Note also the trend of the above example. There is no reason, initially, for the supplier to disagree with any of the specification, except the price target. But as soon as the supplier searches for design parameters to solve the functional requirements, he finds the price tension has spilled over into the entire functional specification. In practice, this is what the boundaries of design-chains look like. They are a disagreement between functional requirements sets.

Of course, sometimes a supplier has a design that meets all the original requirements (including price). But after this happens once, the OEM will reduce its price target, and the supplier will increase their price requirement, in future programs.

4.1.5 'The Battle of the Sexes' meets Product Design

To better illustrate the dynamics of this design-chain boundary, we can use concepts of game-theoretic analysis. The relation between firms can be described in a two-by-two game
between our two firms A and B. Consider a design parameter x, which defines some aspect of the module supplied by B to A. Design parameter x may be set to x=a or x=b. If the design is such that x=b, firm B's profit is maximized, at some expense to Firm A. Alternately, if x=a, firm A's profit is maximized at some cost to Firm B. Assume also that both firms are profitable if they work together, and that the costs of non-cooperation are such that neither earns a profit unless they do business. (For the supplier B, this is straightforward, as not selling to B indicates no sale and a profit of 0. For the buyer A, we must assume that their cost of eliminating B, finding and certifying a new supplier, and re-designing their product, will eliminate their end profit.)

If, for simplicity, we assign the maximum profit of 2 to either firm, and the non-optimal profit of 1 to either firm, we can create the following matrix of payoffs:

```
<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
```

Figure 4.3: Classic 'Battle of the Sexes' Game

Each square shows the end payoffs from the combination of players’ actions. For example, if both firms agree to use design parameter ‘a’ then Firm A receives a payoff of 2 and Firm B receives a payoff of 1. If the firms do not cooperate (i.e., if they demand different design parameters,) then they do not profit, and both payoffs are zero.

In this basic game scenario, B chooses which design to offer, and A chooses which design to ask for. If they agree to either A or B, both will profit, but each to a different degree. If they cannot agree, they walk away and do not profit. This scenario is known to game theorists as the 'battle of the sexes'. Both players want to cooperate, but each prefers a specific form of cooperation. Games of this type are well known to require coordination, in order to reach some mutually profitable solution. But they also involve some tension and risk, as each seeks to drive the solution toward their own optimal scenario.
This tension would threaten to sink the design process, as the two sides (both of who must participate in order to profit) disagree about the 'best' design. How can they agree on an optimal solution, when 'optimal' is dictated by their own economic concerns? This design-process tension is the defining characteristic of design chains. We will now propose two ways of dealing with this tension, and classify two design-chain boundary types accordingly.

4.1.5 Supply Chain Boundary Classifications

There are two ways of resolving the natural conflict in dual-firm PD processes. These two methods will become the basis for a new distinction between types of design-chain links in product-design cases. This distinction will be applied in the industry study, and used to differentiate between fundamentally different practices for multi-firm product design.

The first way to resolve this tension is via an active partnership. The supplier agrees to work specifically toward the non-financial design specifications of the buyer, without a specific regard to profit. In return, the buyer agrees to compensate the supplier fairly, even though 'fair' compensation often cannot be determined in advance. This requires a trusting relationship between the two. In this scenario, the downstream firm still controls the specifications. It is up to the downstream supplier to enforce or modify the specifications during the design process. This type of boundary is defined as the integral design-chain boundary.

The second way to resolve the tension is to create a market for module designs, where suppliers design and develop modules according to their own goals and perceptions of the market. The designs of various suppliers then compete in an open marketplace, with the best designs (e.g. those that give the most value) rising to the top. The resulting design-chain boundary is conducted via arms-length transactions, with interchangeable modules competing on function and price. This type of boundary is defined as the modular design-chain boundary.

In a general sense, these concepts are not new. Economists refer to 'spot outsourcing' versus 'relational outsourcing' as different phenomena requiring different contract structures (15). Strategists consider the alignment of product architectures and supply-chain architectures, incorporating the 'integral' and 'modular' terminology (1). Design engineers are familiar with the same terminology for product architecture types, as first coined by Ulrich (14).

The distinction in this case is small but crucial: the integral/modular dichotomy applies specifically to the boundary between firms in design processes. Application of these concepts at the boundary will be shown as a critical augment to design-chain mapping techniques, which can be used to describe and interpret supply-chain networks.
As with product architectures, there is a spectrum of possibilities between the 'totally modular' and 'totally integral' design chain boundary types. For example, configurable products, which are designed in advance but customized later to specific customer requirements, are considered to be partly modular, partly integral.

4.2 Industry Study

So far, we have waded into an academic discussion of supply-chains, product design, and the link between the two. This was done, not for academic purposes, but to fully define the integral/modular distinction at design-chain boundaries, before applying the distinction to an industry study. Recall objective #2, which is

- to apply the design-chain boundary concept, as a part of the larger framework proposed by Fine, to learn how firms distribute design processes along their design chains.

With the interface types now in place, it is possible to outline the specific industry study used to meet objective #2.

4.2.1 Structure of the Study

The concepts of business genetics are used to structure the current study. The original concept was to study the top tiers of the automotive and heavy truck industries. But in order to forecast the trends of these slow-clockspeed industries, it is necessary to consider a faster-clockspeed industry. For that purpose, the telecommunications industry was chosen. Telecom and automotive are related in some important ways, including the following characteristics:

- both are broadly-defined, and include aspects of each others technologies
- both are in the midst of change, toward increasingly modular/horizontal structure
- both begin their design space with a single high-level function (to transport people or things; to transport information), which can be interpreted in various ways.

Both industries are spread over a broad range of technologies, including some overlap between them. By studying both, a wide range of design and supply-chain scenarios could be observed.
The heavy-truck industry was also considered. The addition of heavy-truck content, originally planned as an 'add-on' to augment automotive results, also overlaps with the other industries, though not in the ways previously thought. With heavy-truck data, the study is expanded to a very-slow clockspeed industry, which is already highly modular, and perhaps moving slowly toward integration.

Figure 4.4: Design Space of the Three Industries
4.2.2 Industry Interviews

To understand these topics, specific industry cases were studied. The main source of data came from interviews with industry representatives. 43 interviews were conducted, with employees from 17 different industry companies and organizations. Participants were chosen from the ranks of engineering, design and development, purchasing, sales, and high-level executives.

The primary goal of the interviews was to determine the nature of the supply-chain boundaries in specific industry design processes. To determine this information, it is necessary to define the characteristics of the integral and modular boundary types. These are derived informally from the theory presented in section 4.1.

What observable factors indicate the presence of the integral versus the modular boundary? The primary factor considered was the control of engineering specifications. In the integral case, specifications are controlled by the downstream firm (the buyer) and transferred to the supplier via an integral relationship. The supplier's product is designed specifically to meet these specs. In the modular case, specifications are controlled within the supplier, in anticipation of market demand. In the modular case, the buyer still has subsystem specifications, but must choose a pre-existing design to meet them. In the modular case, each supplier designs to his own specifications.

Several specific questions were asked in each interview, after which some wide latitude was used in determining interview direction. The standard questions were:

- What are the engineering requirements of your product, and what parameters do you work with to meet those requirements?
- Who has the authority over the engineering specifications and design parameters of the subsystem(s) in question?
- How, if at all, has this outsourced design process changed over time?

After these common questions were asked, the interview typically delved into the individual's expertise. Hence the later part of the interviews were more loosely structured, and were used to flush out details of the shared design process.

4.2.3 Presentation of Results

The results of these studies are presented as miniature case summaries. Each is divided into three sections:
4.2.4 Design-Chain Boundary Redux

The integral and modular design-chain boundaries were developed in section 4.1. These ideas are applied, in the next chapter, to specific industry scenarios. At each design-chain boundary, the type (integral or modular) is discerned from interview questions. As outlined in section 4.2.2, there are specific characteristics of different boundary types, which came to light via the interviews. These boundary types will be denoted in the supply-chain maps as shown in Figure 4.5.

A determination of boundary-type is made for every inter-firm boundary considered in Chapter 5. With this determination made, the design chain is mapped, and some initial strategic concerns are considered for each case. In Chapter 6, general lessons and issues are considered, in light of the industry study results.
The Integral Boundary

primary characteristic: \( B \) designs to the engineering specifications of \( A \)
secondary characteristics:
- \( A \) and \( B \) design concurrently;
- \( B \)'s product is specifically designed as a subsystem of \( A \)'s

The Modular Boundary

primary characteristic: \( B \) designs to their own internal specifications
secondary characteristics:
- \( A \) and \( B \) design separately
- \( B \)'s product is designed to be used by various customers

The Mixed Integral/Modular Boundary

primary characteristic: \( B \) designs to their own specs and to \( A \)'s specs
secondary characteristics:
- \( B \)'s product is configured to \( A \)'s needs
- \( B \)'s product is modified to meet \( A \)'s needs

Figure 4.5 Boundary Type Indicators for Design-Chain Mapping
5.0 Results

This chapter is devoted to eleven specific industry cases, developed from industry interviews. The interview results are consolidated into maps of the design chain for each of the cases considered. Names of firms are changed throughout, in order to shield proprietary data and strategies from publication. For each case, a product overview is given, followed by a review of the design-chain structure and a summary of strategic concerns. The design chains will be displayed according to the following format:

![flow of design content](image)

**Figure 5.1: Design-Chain Mapping Notation**
5.1 Case 1: Wireless Telephones

5.1.1 Product Overview

Wireless telephones are the portable communication devices at the consumer end of the wireless telecommunications value chain. These devices are composed of electronic components, a battery, electromechanical conversion devices such as LCD screens, speakers, etc., and a housing structure into which the parts are mechanically integrated.

The basic function of the phone is to transmit and receive data to a fixed wireless base station (which in turn interfaces to the wire-line publicly switched telephone network or PSTN). It must process, transmit, and receive data with minimal time lag, and must do so within several physical constraints. These include

- small size and weight
- low power consumption
- durable during shock events such as drops onto a hard surface

Although there are many components that make up a wireless telephone, we will focus on two: the exterior housing and one of the electronic components known as a DSP (digital signal processor).

5.1.2 Design-Chain Structure

PhoneCo sells its wireless telephones to retailers, who do not customize or dictate design parameters to PhoneCo. Therefore this is a modular supply-chain boundary. (This is a simplification, as the phone is sometimes bundled with a service plan. For this analysis however, we can consider this a modular boundary, because the design of the phone is not changed according to the demands of a specific retailer.)

Although wireless telephones are composed of many components, two are chosen for analysis here. One is the plastic housing, which holds the phone together and protects the electronics. The housing in this particular scenario was part of a drastic new design, which aimed to far surpass the size and weight performance of competitors. This system-level goal was decomposed into targets for the case, which were impossible with the current technology in place. PhoneCo created a special program, with their chosen housing supplier, to implement a new thin-wall molding technology. The new molding process required new plastic resins, which had to be
custom-designed by the plastic resin supplier. As such, the design chain for the housing was integral, and intertwined, as shown in Figure 5.2.

By contrast, the DSP is an off-the-shelf item, designed to the specifications of its supplying firm. The DSPs were sourced as a commodity item, making the design chain boundary highly modular.

![Diagram of Design Chain for a Wireless Telephone](image)

**Figure 5.2: Design Chain for a Wireless Telephone**

5.1.3 Strategic Concerns

The resulting wireless telephone set a new standard in weight, size, and market acceptance. Certainly the overall design was a success; however, it necessitates close coordination and cooperation between players in the design. There were questions of how to compensate the specific design efforts of the case and plastics supplier, who reported to whom in the development, and how to remain on the same time frame for the development.

These issues were largely non-existent in the supply of chips for DSPs. These chips are available on an open market, with standard interfaces and varying grades of performance at market-determined price points. There was no coordination between PhoneCo and ChipCo in the design of the specific DSP used. ChipCo retained authority over their DSP design, and PhoneCo designed their overall system knowing the specifications of the available DSPs on the market. True, the DSP supplier will worry about becoming a zero-profit commodity supplier. But their design processes, and their investments in technology, are explicitly under their own control.

This case illustrates the dramatic differences in design-chain structures, between two components of the same wireless phone. As a final strategic note, consider the long-term impacts
of success. With a hot product, both *ChipCo* and *CaseCo* will need to invest in new production, to meet soaring demand. This investment will provide benefits of scale to *ChipCo*, who can sell the same DSP to many other customers. But for *CaseCo*, the investment is customer specific; an added production line is a customer specific investment for PhoneCo alone.
5.2 Case 2: Optical Network Equipment Installations

5.2.1 Product Overview

Optical network installations are the physical equipment that connects computers together, in order that data can be shared between computers. Network installations are the infrastructure which supports data transfer, both within the boundaries of a firm (such as in corporate intranets) and to more general data systems such as PDM systems or the internet. These networks rely increasingly on optical transmission of data via fiber-optic lines. The network installation consists of optical switching and data processing equipment, and the controlling software which manages the data flows via user inputs.

The core function of a data network installation is to provide data connectivity between computers. These installations must meet several other design constraints, including cost, size, power consumption, etc. Perhaps the biggest constraint is compatibility, in that most network installations are asked to interface with legacy systems. These functional objectives are met with fundamentally electronic and optical data-processing subsystems.

The components of network infrastructure include various items needed to process optical data, including pump lasers, terminations, optical switches, etc. These components typically have a specific dedicated function in the optical network engineering design.

5.2.2 Design-Chain Structure

The end customer of data network installations fall into one of two categories: network operators and other businesses. Network operators are primarily in the business of providing wide-area network coverage, and selling the resulting bandwidth to local customers (such as Worldcom, Verizon, SBC/Ameritech, etc.). Other businesses are the wide range of companies who need network installations to support their own needs (including non-telecom firms, from GM to mom-and-pop operations). Network operators, of which there are only a few, tend to buy vast quantities of infrastructure equipment. Other companies, of which there are thousands, buy much more limited quantities (down to a single switch installation containing just a few channels). The design and development varies highly between the two customer bases. Because a few large players dominate the network operation space, their orders can easily be in the hundreds of millions of dollars. With this kind of sale on the line, the infrastructure provider will incorporate customer-specific design elements into the products. This is classified as an integral design-chain boundary, as the customer's design specifications are met via custom efforts at the top-tier supplier.
Other business customers (i.e., those who do not sell network services) make much smaller buys, and their needs are typically met with slight configuration of off-the-shelf network designs. This has the flavor of modular supply, where design requirements are met with pre-existing designs (although the parts are configurable to some extent).

At the next tier upstream are suppliers of the hardware itself. The network installation hardware is highly modular, composed of pre-designed module supplied by a second supply tier. These module suppliers in turn rely on off-the-shelf components from a third tier. Suppliers may play in several tiers at a time, supplying module groups with their own internal component divisions. In all these design chains, the boundaries are highly modular, with suppliers offering off-the-shelf designs to meet their customers engineering specifications.

![Design Chain for Network Equipment Installations](image)

**Figure 5.3: Design Chain for Network Equipment Installations**

5.2.3 Strategic Concerns

According to several sources in the module supply business, the winners are component suppliers who produce specific in-demand devices. One interviewee noted that "There is little value in integrating components together, because the parts are so standardized. But the components themselves are sometimes in short supply, and can be quite profitable." In this case at least, it is apparent that modular component suppliers are not doomed to the fate of 'commodity supply.' By contrast, providers of "integrated modules" are not providing significant added value.
The downstream end of the supply chain illustrates the lessons of Fine (1); specifically, the impact of firm size on supply-chain control. Only the network operators can dictate their design preferences directly to Equip-Tech; the rest must be content as a small part of a large customer base. This power by network operators will be implemented on the terms of design engineers, who will codify this power shift in stricter, and more Telco-specific, design specification. As will be noted later, the shift of power in integral supply relationships is often coded in engineering requirements, as engineers of the more powerful partner get their preferences implemented.

In this case, Equip-Tech finally ended up splitting itself into two separate companies. Their logic was that, with such vastly different customer bases, they could better serve the market as two separate organizations. Whatever the other advantages, engineers must certainly have appreciated the switch, as they could now design for more specific markets, and thereby attain more optimized designs.
5.3 Wireless Telephone Headsets

5.3.1 Product Overview

Wireless telephone headsets are an emerging technology, which should see commercialization in the next 12 months. They allow a transmission of voice signals via a short-range wireless connection from a wireless phone to a headset worn by the user. This allows a form-decomposition of the wireless phone, with input/output (voice and listening) performed at the headset, and all electronics and transmission function performed by the traditional phone unit.

The wireless headset's primary function is to transform voice signals wirelessly from acoustic signals (at the mouth or ear) to electronic signals in the phone, and vice-versa. Secondary design constraints include the weight-comfort, and aesthetics of the headset, the durability of the unit, and cost.

The current form of the product is divided into two parts: a small 'plug-in' which attaches to the base of the telephone, and the headset itself which the user can wear by attaching to the ear. Each contains a receiver and transmitter, which utilize the small-area wireless link to transmit voice data. The core function of the transmitter/recievers is handled by application-specific integrated circuits (ASICs).

5.3.2 Design-Chain Structure

MiniSet Inc. is the designer of the current generation of headsets, which are sold directly to retailers as aftermarket items. This arrangement is inherently modular, as MiniSet's design is suitable for various wireless telephone designs. In accordance with this modular boundary, Aura controls its own specifications and design requirements, based on their own interpretation of the market need. Notably, this may mean some wireless phones (with, say, a strange shape or unusual connector pattern) will not be compatible with MiniSet's product.

MiniSet is serviced by two primary suppliers. One is a design firm called DesignCo, which was contracted to design and develop the physical implementation of the headset. DesignCo works very closely with MiniSet, developing shapes and sizes for the headset itself. DesignCo does some detailed design work, including CAD, testing, and prototype production. But Aura controls the design process, issuing specifications and approving designs for production. The relationship between DesignCo and MiniSet is a classic integral boundary, as DesignCo works strictly to MiniSet's requirements for this design, and MiniSet will own the final design.
MiniSet's other primary supplier is the manufacturer of the ASIC chips, the giant semiconductor manufacturer TTC. The boundary between Aura and TTC is modular in nature. TTC publishes a specific list of their process capabilities, and their design rules (to which chip designs must rigidly conform, if TTC is to guarantee their function). MiniSet designs their product in accordance with these design rules, independently of TTC in every other way. This well-defined interface establishes a market for TTC's particular capabilities, and codifies the modular boundary between chip designer and chip manufacturer.

![Diagram](image_url)

Figure 5.4: Current Design Chain of Wireless Headset Supply-Chain

5.3.3 Strategic Concerns

MiniSet's product is projected to do well as an aftermarket addition to wireless telephones. However, users would prefer to eliminate the snap-on component at the phone itself. This could be done if a wireless telephone maker, such as the now-familiar PhoneCo Inc., chose to integrate the snap-on transceiver into their phone. With this capability embedded in the phone, the headset could be bundled with the phone at the point of sale. But this would require coordination between MiniSet and PhoneCo, on interfaces, package size, signal strength (versus location in the phone casing), power usage, and price. The integration of the design creates issues for engineers of both firms, and an immediate question about how to cooperate and compete in this newly forming space.
These difficulties may be suppressed in the near future, as PhoneCo recently took an equity stake in MiniSet. With incentives thus aligned, it will be easier for engineering designers to come to decisions on the placement, size, range, and power consumption of the integrated transceiver. A second unresolved issue, which is big enough to remain through the equity transaction, is the application of MiniSet’s technology to the designs of PhoneCo’s competitors.

Figure 5.5. Possible Future Design-Chain of Wireless Headset Design Chain
5.4 Case 4: Wireless Base Stations and Adaptive Processing

5.4.1 Product Overview

Wireless base stations are core components of wireless telephone networks, which allow mobile telephones to function. The base station transmits radio signals to and from wireless telephones within a several mile distance, and connects these wireless devices to the publicly-switched telephone network (or PSTN).

The primary functional requirement of base stations is to transmit these signals in real time, over the widest coverage distance, and to the greatest number of simultaneous users. These requirements are typically met within strict limits on package space, and within pre-imposed constraints of backward compatibility with legacy components. There are also strict limits on the available frequency range, which is a scarce resource auctioned by the FCC. A wireless network must be designed to operate using one of several air-interface standards (GSM, TDMA, CDMA, etc), which are simply protocols for multi-channel data interchange between wireless devices. The chosen air-interface protocol is designed into the hardware of the base station and the associated wireless telephones.

5.4.2 Design-Chain Structure

The wireless base station market has historically been a vertically integrated market, with a handful of dominant network providers and a similar small group of base station providers. These two players hold dominant roles in a wide-ranging web of participants, who all must combine to provide mobile communications functionality to end consumers. The base station supplier PhoneCo and the network operator Telco have a long-standing and intertwined relationship. A key part of this relationship is a wealth of legacy systems, built to a customer-specific set of standards (including air-interface standards).

Currently, there is a close link between a PhoneCo and Telco. 95% of Telco's network is built on PhoneCo-designed base stations. PhoneCo has financed Telco's purchase of the equipment, and will void warranty and service contracts if Telco mixes another supplier into the network of base stations. On paper, PhoneCo's product could be used by anyone. But in practice, the design process is closely integrated between PhoneCo and Telco. The arrow connecting them is double-headed, as shown in Figure 5.6, indicating that neither completely controls the design specifications. PhoneCo is under heavy pressure to design to Telco's specifications, but Telco cannot switch supplier without great difficulty. There is a perception, at Telco and in the industry in general, that PhoneCo extracts large profits from this integral relationship.
Mars Inc. is a potential supplier to PhoneCo, and to PhoneCo's competitors. Mars offers an embedded, high-powered computer, which can be used to optimize the base station performance. For example, the computer can allow for 'high-profit' users, on a more expensive calling plan, to take precedence over economy-plan users in times of high network usage.

PhoneCo's base station architecture is integral, with no interchangeability between the subsystems of PhoneCo's base stations and their competitors. Mars has therefore adopted an integral design strategy, working closely with PhoneCo's engineers to design a PhoneCo-specific system.

5.4.3 Strategic Concerns

It is noted by Mars engineers that, although their design is PhoneCo-specific and their relationship is integral, a much more modular approach is possible. Core elements of the computer can be adopted to the specifications of PhoneCo's competitors. Indeed, a major driver for customization is the packaging difficulty, which stems from the tight enclosures of the base stations. Package concerns force Mars to configure their product creatively, and to verify its reliability under these configurations. It is also notable that Mars markets to Telco directly, and works with them on technical issues.

In the words of a Mars manager, "The network operators say it: 'I want to be able to buy base stations the way I buy PCs...in a modular market, a commodity market, with lots of competition.' They could mix-and match vendors, even mix-and match the guts inside the equipment. That would give them a big advantage. And obviously, that advantage is a disadvantage to the infrastructure manufacturers." This concept is as shown in Figure 5.7.
In this scenario, the base station would be much more like the fiber-optic network installations described in section 5.2. The modular links between supply-chain tiers would mean that designs would be designed to market-driven target requirements, as opposed to customer specifications. Elimination of modular links would produce designs less optimized for specific network operators, but would gain the efficiencies of market economics at links between firms.

The value of integration, currently preserved by the intractable combination of elements in PhoneCo's design, would be attacked in this scenario. Perhaps for this reason, Mars continues to work without a major customer contract. But there is significant interest from network operators, who are now applying pressure via their integral relationship with PhoneCo and PhoneCo's competitors. Part of this pressure comes from the advent of 'virtual network operators,' who treat bandwidth as a commodity and keep cost pressure on Telco. There are also niche competitors in the base-station space, whose business plans rely on low-cost integration of modular base station components. These niche competitors wait on the fringes of the telecom design space, looking for an inlet to the lucrative telecom industry. Their future hinges on a still-forming market for telecom modules. Modules, such as Mars' engineers envision, can be assembled into full functioning systems, by players unencumbered by the massive overhead of Telco, PhoneCo, and their once-dominant integral competitors.
5.5 Case 5: 'Hot-End' Automotive Exhaust Systems

5.5.1 Product Overview

Automotive exhaust systems carry hot exhaust gas from the engine to the tailpipe, reducing the noise and emissions content of the gas. The so-called ‘hot-end’ of an exhaust system, which conducts all emissions-reducing functions, is composed of the exhaust manifold, the catalytic converter, and the connecting pipe work. The catalytic converter performs the emission-reduction function. Because automotive emissions are strictly regulated in the US and most other industrialized nations, catalytic converters are used on all automobiles sold in the industrialized world.

The catalytic converter consists of a honeycomb-structure substrate, typically made of ceramic material, coated with a layer of material rich in precious metal. The exhaust gas passes through the honeycomb channels, where the precious metal coating catalyzes the reaction that cleans the gas. This substrate is wrapped in insulating mat and ‘canned’ in a metal shell, which is then welded to the exhaust system and manifold.

5.5.2 Design Chain Structure

The end customer in this case is the regulating body, i.e. the Environmental Protection Agency (the EPA). They certify the tailpipe emissions level of all new vehicle models according to test standards developed with industry. In this case, the automaker BigOEM Inc. has formed an integral link with the EPA, and designs their emissions-control systems to meet their specific needs. (These vary from region to region, and necessitate varying designs for various regulating bodies.)

BigOEM has design authority over the entire emissions-control system, including the exhaust system. But they rely heavily on the suppliers of component parts of the system, including:

- substrate – supplied by Ceramix Inc., who invented the ceramic catalyst substrate and are still considered the experts in the field
- catalytic coating – supplied by Engleson, one of a handful of suppliers for the highly engineered catalytic coatings which covers the substrate
- exhaust system – supplied by ExCo, who supply the metal portions of the catalyst assembly, as well as the full exhaust system with embedded coated substrates.
The exhaust system itself is different for every vehicle line, and is highly constrained by package concerns, durability requirements, and heat-transfer limitations imposed by vehicle-level testing. The coatings must be matched to the engine-out gas temperature and emissions content, which is in turn determined by the engine and control-system design. Because both the exhaust system and the catalyst coating are custom-designed to the requirements of each vehicle application, the design-chain boundary is modular between these suppliers and the OEMs.

The substrate design is chosen from a standard list of pre-determined designs. However, *Ceramix* will custom-design new sections if the situation warrants, and cuts substrates to a specific length in specific vehicle applications. The substrate is therefore considered a partially modular system.

![Diagram of the design chain for exhaust hot-end](image)

**Figure 5.8: Design Chain for Exhaust Hot-End**

### 5.5.3 Strategic Concerns

*BigOEM* has been pushing for *ExCo* to become the 'full-system' supplier of exhaust system, and to take on increased design and development tasks. *ExCo* is happy to take on the
'tier-1' status. With ExCo supplying the full system, containing Engleson and Ceramix's components, it would appear that ExCo is in its desired 'top-tier' position.

But BigOEM sources it's substrates and coatings separately, and gives ExCo no authority over the selection of these components. In fact, in the design process, the substrate and coating characteristics are chosen first, in order to begin emissions-system development. ExCo enters the design process later, with the mandate to incorporate the pre-selected components of the second tier. This order is necessitated by the emissions control system development process, which is highly test-dependent. The emissions performance depends more directly on the substrate and coating; hence they are selected before the rest of the exhaust system is considered.

ExCo is caught in the weakest position of this integral web of supply relationships. Their weakness stems from their position: as tier-1, they are responsible for meeting system-level functional requirements. But without control of the highly-engineered components, ExCo must design around their would-be tier-2's. For example, BigOEM has a specification for flow distribution in its catalytic converters, which is highly dependent on substrate shape. But substrate shape is fixed before ExCo performs their design. In one case, ExCo performed over 50 re-designs trying to meet the standard, without once changing the substrate shape. In the end, over $1M was spent in development effort, with no acceptable solution.

A large part of ExCo's problem is of their own making. Without recognizing the integral relationship of the substrate and coating suppliers, they are ill-equipped to understand their own position. When faced with the flow distribution problem, ExCo's engineers contort the design parameters they can control, resulting in designs which might be good for flow distribution, but will certainly be poor in every other sense. Instead, they should realize the limits of their current role, and demand more input to the substrate selection. This would mean more input into the emissions control process, which in turn might require more investment and expertise in emissions control. The other (very real) option is to deny responsibility for system-level design issues, deferring to BigOEM's judgment.

In the end, after their $1M investment, ExCo came up with a design that worked. A few months later, that design was publicly available on an internet sourcing platform, where the manufacturing business offered to the lowest bidder. ExCo charges for design and development as a part of their manufacturing piece-price. This is the supplier's-nightmare of integral supply: all the headaches of full-system support, with none of the benefits.
5.6 Case 6: Window Regulators

5.6.1 Product Overview

Window regulators are the systems which raise and lower automobile windows. There are several types of window regulator, each of which is optimal for different situations depending on the functional requirements. The type considered here is the motorized ‘arm and sector’ type, which consists of the glass-movement mechanisms, the tracks in which the mechanisms and glass are guided, and the motor and the associated wiring.

The two basic requirements of a window regulator system are

- To raise or lower the glass in a specified time limit
- To package within the allotted space

Window regulators are typically judged on their ability to meet these two primary functions, as well as cost, weight, power consumption, and glass stability. Window regulators also impact the side-impact safety performance of the vehicle.

5.6.2 Design-Chain Structure

Window regulator systems are supplied by Meteor Inc. to BigOEM. Meteor designs and develops specific systems for a given vehicle platform. Because the system cannot be used in other platforms or for other OEMs, the supply-chain boundary between BigOEM and Meteor is an integral boundary.

Two of the primary components supplied to Meteor are motors and the arm-and-sector mechanism, both of which are necessary components of the arm-and-sector design. A given motor design may be used in various vehicle platforms, but must be modified for different torque/speed requirements. This is considered a part-modular/part-integral boundary between Meteor and their motor suppliers.

The sector mechanisms are typically custom-designed for specific applications, and are therefore considered as an integral link between the Meteor and the sector supplier. (It should be noted that, in some cases, the motors and sector mechanisms are in-sourced, eliminating the actual inter-firm chain boundary)
5.6.3 Strategic Concerns

Window regulators are not typically seen as product differentiators, and OEMs therefore have a 'commodity mindset' toward them. With this in mind, Meteor finds itself in a precarious position: responsible for engineering a quality system in a 'thankless,' cost-sensitive environment. But Meteor does have control over their own tier-2 position, and can choose to supply themselves or outsource components as they see fit. What then are the issues for Meteor and BigOEM in this case?

Like most integral suppliers, Meteor senses a "hold-up" problem. By designing specific configurations for a specific customers' platform, Meteor runs the risk of handing optimal designs to BigOEM. BigOEM can then outsource the actual subsystem supply to the lowest bidder. To minimize this threat, Meteor has modularized their motor designs. The same basic motor can accommodate different electric-coil windings, different modular gear-sets, and a variety of mount points. In the last 3 years, Meteor has consolidated it’s design space from a wide variety of custom designed motors to a handful of modular, configurable designs. Production facilities accommodate the modular design with flexible manufacturing processes. As a result, the same basic motor design can be used in a much wider variety of systems, and for a wider customer base. On the diagram, the link between the motor and regulator system becomes more and more modular as time passes.

This benefits the OEM as well as the tier-1 supplier. BigOEM only wants the required function at a low price….they don’t care what the details of the regulator are. With the cost of development spread across a wider customer base, BigOEM can demand a lower price from Meteor.
It will be noted later that modularity is not always best. In this case, we can imagine a modular system whose function is not quite as good as a custom-designed integral solution. If the end customer notices, the integral design might have been worth the cost. But with a small 'partially-commoditized' system, the trend toward modularization seems beneficial to all involved.
5.7 Case 7: Automotive Suspensions

5.7.1 Product Overview

Automotive suspensions are dynamic mechanical systems, which control the ride and handling of automobiles. Their design impacts the comfort of automobiles over rough surfaces, the handling of a car in various driving conditions, and the stability of the car during maneuvers. Compared the previous automotive subsystems, suspensions significantly impact a consumer's perceptions of a vehicle.

The functional requirements of an automotive suspension are typically a combination of objective and subjective measures of ride and handling, such as:

- tire grip during cornering
- driver/rider vibration over rough surfaces
- body roll during cornering
- understeer (or oversteer) at the cornering limit

These ride-control requirements must be met under constraints on package, price, and durability. Crash-safety and serviceability are also limiting factors.

Automotive suspensions are composed, physically, of the components that attach the wheel to the car frame. The specific components vary from case to case, but typically include at least a shock absorber, spring, control-arm mechanisms, and anti-roll bars. Although sometimes considered separate from the suspension system, the tire plays a critical role in vehicle ride-control, and is typically selected for use with a specific suspension configuration.

5.7.2 Design-Chain Structure

BigOEM is supplied by a variety of suppliers for the various components of the suspension system. These suppliers typically are sourced early, and support the development process with engineers working directly on-site at the OEM. These links are all integral or partly integral, as the requirements and constraints for a suspension system are highly specific for specific vehicles. Where partial modularity exists, it is usually due to a configurable aspect of the component. For example, a given shock absorber body is 'tuneable' to various damping levels via changes in internal orifices, valves, etc.

Pre-selected suppliers must work closely with each other and with the OEM to arrive at a final system-level solution. Their on-site designation facilitates close communication links.
between the suppliers. However, there is traditionally no formal contract between the suppliers of the components.

As with the previous systems considered, the OEM has final design authority and warranty responsibility for the suspension system design. Traditionally, the OEM conducts significant vehicle-level testing at the end of the development. This critical evaluation of the vehicle level ride-control functions must be done by an experienced group of OEM representatives, typically on the OEM's test track in a prototype vehicle.

![Figure 5.10: Traditional Design Chain for Automotive Suspensions](image)

5.7.3 Strategic Concerns

As is widely recognized, automotive supply bases are consolidating to form integral system suppliers, even as the OEMs shift toward a more horizontal/modular structure. This trend is exemplified in the suspension module business, where suppliers are attempting to engineer
suspension modules or full systems, including all necessary component parts. As the supply base consolidates, more of the components in the suspension are supplied by a single supplier. Indeed, most of the 'bent-metal' products can now be supplied by single full-system suppliers, of which there are only a few. The resulting supply-chain structure is shown in Figure 5.11.

For now, the trend toward 'modularization' has not produced a modular interface between supplier and OEM. Designs are still customized for each vehicle, and development is done jointly by supplier and OEM. However, the idea of modular design is beginning to take hold. In the words of one ride-control manager, 'It's getting to where all they will offer is some standard, off-the-shelf solution. We are stretched so thin, that we have to take it or leave it.' Several interviewees from BigOEM lamented the loss of functional experience in engineering groups, as development engineering is pushed out to the supply base.

What will happen when there is a disagreement between the module supplier and a neighboring component supplier; for example, the tire maker, or some neighboring system that intrudes on package space? Traditionally, all such disputes land on the desks of OEM engineers, who must sort out the problem and dictate design direction to the suppliers. But with fewer qualified engineers, and larger suspension suppliers, the OEM may not have the brains or the brawn for dictating design parameters to suspension suppliers. In this case, the suspension supplier can defend those design parameters that maximize value for themselves.

But full-system suspension suppliers run the risk of full-system responsibility, without controlling the tire sourcing decision. With interfaces to tires, steering, brakes, and a strong vehicle-weight dependency, suspension suppliers are left without control of many interacting subsystems, even as they accept responsibility for meeting full-system requirements. In cases of argument, suspension suppliers leave themselves open to the fate of ExCo in exhaust: full-system responsibility without full-system authority.
Figure 5.11: Emerging Design Chain for Automotive Suspensions
5.8 Case 8: Heavy-Duty Truck Axles

5.8.1 Product Overview

Axles connect the wheels of a truck to each other and, in the case of the driven wheels, to the driveshaft. A truck axle is typically held to three important requirements: cost, weight, and durability. To the end customer, these are all convertible to a bottom-line operating cost, which is the overwhelming decision factor when specifying an axle supplier. The axles must also be packaged in the allotted space, and must interface to the wheels and driveshaft.

Axles are composed of a few basic components:

- the housing, which contains the moving parts
- shafts, which carry torque and shear loads from the wheels and driveshaft
- gears, in the case of the transfer case, which transfer torque from one shaft to another
- bearings, which support shafts while allowing them to turn.
- lubricant, which protects contacting parts from friction and wear.

5.8.2 Design-Chain Structure

Fleet operators, whose business is transporting goods via trucks, buy heavy trucks to conduct business. The trucks are sold by OEMs, who design the overall vehicle structure. The boundary between the OEM and fleet operator is a typical modular interface, such as we expect for market-transactions in general. However, this interface does not fully describe the transaction. The fleet operators can specify the top-tier suppliers of major modules such as axles, as well as engines, transmissions, and brakes.

This structure is made possible by the modular architecture of heavy trucks, which allows fleet operators to 'mix and match' according to their preference for suppliers' designs. Technically, the axle supplier sells to the OEM, but often the sale is based on agreements with the fleet operator.

The supply-chain interface between axle supplier and OEM is highly modular. The axle is designed and developed entirely by the axle supplier, to their own specifications, with only packaging constraints by the OEM. Product improvements in axles, as with other major truck modules, are driven by the suppliers' perceptions of market value, and not directly by OEM requirements.

Bearings are supplied by a tier-two supplier, who offers a range of off-the-shelf designs to the axle designer. However, these designs are sometimes customized, via upgraded materials or manufacturing processes, to meet the needs of a specific axle supplier. The boundary between
axle supplier and bearing supplier is therefore characterized as a mixed boundary, as indicated in 5.12.

![Figure 5.12: Design Chain for Heavy-Truck Axles](image)

5.8.3 Strategic Concerns

In the case considered here, the supply of bearings was a point of concern at the axle supplier. Product designers had worked with a specific bearing supplier, in order to meet the brutal durability demands of the next-generation axle. However, there was no formal contract between the bearing supplier and axle supplier, as the relationship and development had been informal. When purchasing determined a different bearing supplier would be cheaper, disagreement ensued. On the one hand, design wanted to retain their credibility and relationship with the bearing supplier, on whom they counted for specific designs. On the other hand, purchasing noted that they had not been consulted earlier during the design process, and might have warned design about possible price problems.

In short, the classic conflict erupted. Engineering saw the integral boundary; purchasing saw the modular boundary. As with many firms, there was no formal understanding of the difference between the two. As a result, there was no strategy in place to deal with the conflict, other than arguments in program meetings.

On the downstream end of the chain, it is striking to see the modular scenario. This is similar to the electronic hardware of telecom industries, more than to the integral world of automotive industry. In this modular world, the value of system integration is again in question. If suppliers could get together to produce the engine, transmission, axle, brakes, wheels, and frame, they are 90% of the way to producing the entire truck. This would allow them to command the profits associated with integrating the system. Then again, truck assembly is not especially profitable in today's market.
5.9 Case 9: Heavy-Truck Brakes

5.9.1 Product Overview

Heavy-Truck Brakes are similar in function to automotive brakes: their function is to stop the vehicle. This primary function is regulated with a maximum stopping distance for a given truck, as mandated by federal regulation. The brake system must meet this requirement under constraints of

- package size, which is dictated by the wheel, suspension, and axle design
- durability, with requirements of 500,000 miles or more without service
- cost
- serviceability.

In the United States, truck brakes are typically drum-type designs, powered by compressed air. The systems consist of the brake drum, pad, actuator, and 'spider' (onto which the other parts are hung). An air dryer and air lines are also part of the system at the wheels. When the brake is actuated, pressurized air pushes the actuator, and pad, against the drum, which in turn slows the wheel.

5.9.2 Design Chain Structure

The brake market is similar to the heavy-truck axle market, in that the official sales-channel (heavy-truck OEM) is often bypassed by top-tier suppliers. Although there exists a modular link between OEM and the fleet operator, a significant marketing link is in place between tier-1 suppliers and fleet operators, who specify their own subsystem suppliers when making a purchase.

Brakes are designed primarily by the brake supplier, to their own specifications. However, specific configurations are usually designed for specific OEM customers, whose package allowances vary significantly. This package allowance, which drives much of the configurability into the design, is largely dictated by the suspension, wheel, and axle design. With the significant configurability of many brake designs, the design-chain boundary between brake supplier and truck OEM is considered to be partially modular.

Brake designers incorporate friction pads into their designs. These friction pads are typically custom designed, in order to meet the requirements of the brake supplier. As such, they
are classified as traditional integral-boundary components. However, truck OEMs sometimes dictate their preferred supplier, around whom the brake designer must operate.

Figure 5.13: Design Chain of Heavy Truck Brake Systems

5.9.3 Strategic Concerns

At first glance, Meteor's brake business seems ripe for integration. The subsystems limiting brake design, including the suspension and axle, are also supplied by Meteor. And Meteor has significant contact with the final customer, who can specify Meteor over their competitors when buying trucks. These conditions suggest an integration strategy for Meteor, who might be able to bundle their products, design integrally for better function, and capture more share in their markets.

The problem is that Meteor has done too well designing modular brakes. Their configurable designs, produced in highly-flexible manufacturing cells, have captured 75% of the US brake market. According to a Meteor brake-division executive, "That flexibility is our
strength. We can configure our brake to a lot of applications where others can’t." With a strong market position built on configurable product, the shift toward integral designs is a risky step.

The other impediment to integration is user function. Unless the brake can be made more durable or less expensive, there is no end-user functional advantage to be gained through integration. Several Meteor brake engineers feel integration could incrementally improve stopping performance. But such improvements would mean little, since the stopping-distance requirement is a hard limit: once it is met, incremental gains are without value to the operator.

Meteor also faces a possible difficulty with their friction suppliers, who are sometimes dictated by OEMs. This 'pull-through' specification of tier-2 suppliers limits Meteor's ability to control its own destiny. However, with significant market power in brakes, and with OEM's relatively weak by comparison, this issue is not pressing for the time being. And in this slow-clockspeed world, 'the time being' may last for decades.
6.0 Discussion

Based on the cases considered in Chapter 5, some general trends of the three industries are discussed in the following section. Industry locations on the integral/modular double-helix are assessed. Several lessons from the fast-clockspeed telecom industry are applied to the slower-clockspeed automotive and heavy-truck sectors. Several key points are presented in the course of the analysis, including lessons learned and fundamental means of applying the integral and modular boundary types.

Two new concepts are then proposed, in economics and in system engineering. First, the well developed economic "hold-up" scenario is applied to the case of integral-boundary supply chains. A solution from the literature, which aims to solve the hold-up issue, is presented in the context of product design outsourcing. Second, an augmented concept of functional decomposition is proposed for modular design-chain cases. This modified view of decomposition proposes an aggregation component, which applies to outsourced designs. Examples from the case studies are given.

6.1 Industry Analyses: Future Trends of Supply-Chain Structures

In order to understand the supply-chain scenario of the chosen industries, we should look for their current position on the so-called 'double-helix' of industry structure. This is presented by Fine as follows:

![Diagram of the Integral-Modular "Double Helix" of Industry Structure](from Fine (1))
As documented in previous studies (1,2,3,4), industries oscillate from one side of the helix to the other, alternating over time between horizontal/modular and vertical/integral structures. Within this framework, and based on the cases presented in the results section, it is now time to evaluate the position of the telecom, automotive, and heavy-truck industries on the double-helix.

6.1.1 Telecommunications

History

The telecommunications industry was once highly integral, with major monopolies controlling highly-regulated markets for 'one-stop' telecom shopping. Industry clockspeed crept slowly for decades in the mid 1900s, as basic telephone functionality remained constant. Bell and ATT dominated the landscape so entirely, that the idea of a 'telecommunications industry' seemed strange. This was truly a integral/vertical world, if ever one existed.

But with the advance of technology in electronics, computing, information technology, and mobile communications, niches of this vertical model was exposed to aggressive small competitors. With deregulation in the early 1980s, the stage was set for a modular turn in telecommunications.

Current Status

Has this modular turn happened? The answer depends on the specific area of telecommunications. At the interface between end customers and downstream firms, the modular turn has largely taken place. Customers can choose different manufacturers of telephone, different long-distance carriers, ISPs, cell-phone plans and wireless data networks. At the next upstream interface, between top-tier suppliers and downstream firms, the modular turn is in full swing, but has not been completed yet. Cases 2 and 4 show modular product architectures forcing the disintegration of established 'integral' relationships between equipment firms and their service-providing customers. At the next level upstream, the electronic and optical components comprising these systems are highly modular, with modularization taking place wherever it is not fully entrenched. The large majority of electronic components are off-the-shelf designs, or at least fit a modular interface to the overall system. These trends are indicated in Figure 6.2.

Results of cases 1,2, and 3 indicate that electronic components are especially amenable to modular supply-chain interfaces. In the case of routers, DSPs, and ASIC chipsets, supplying firms determined their own product specifications, and met their customers in a market environment. Even the interface between VLSI chip design and manufacture was transacted via a modular design boundary, between MiniSet and TTC in case 3.
And in case 4, the adaptive processor was primed for a modular design boundary. Engineering constraints that limited modular design were only in the packaging, thermal, and electrical design process. The electronic functions of data processing and transfer are highly amenable to modular function, both in case 4 and in general. (See for example (16)).

There are specific cases of product design in telecommunications where design is likely to remain integral. In the cases of the housing in case 1, and the headset design in case 3, both designs were outsourced via an integral boundary. These components share two distinguishing functional properties:

- both encapsulate the user interface
- both are structural parts, encasing and shielding the electronic components.

These 'structural user interfaces' seem resilient to the modular turn, likely because the integrating firm still controls the chain. Competitors may eventually obtain their own case designs or headset designs, but they will always attempt to differentiate it via design differences. That is, although the industry may become modular, the designs of user interfaces will seldom be commonized between two competing firms.

<table>
<thead>
<tr>
<th>System</th>
<th>Case #</th>
<th>Boundary Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASIC Chipset</td>
<td>1</td>
<td>Modular</td>
</tr>
<tr>
<td>Plastic Phone Housing</td>
<td>1</td>
<td>Integral</td>
</tr>
<tr>
<td>Wireless Phone</td>
<td>1</td>
<td>Modular</td>
</tr>
<tr>
<td>Optical Network Components</td>
<td>2</td>
<td>Modular</td>
</tr>
<tr>
<td>Optical Network Modules</td>
<td>2</td>
<td>Modular</td>
</tr>
<tr>
<td>Optical Network Installations (telecom customers)</td>
<td>2</td>
<td>Integral</td>
</tr>
<tr>
<td>Optical Network Installations (non-telecom customers)</td>
<td>2</td>
<td>Modular</td>
</tr>
<tr>
<td>Embedded Computer for Wireless Base Stations</td>
<td>3</td>
<td>Integral</td>
</tr>
<tr>
<td>Current Wireless Infrastructure (base stations, etc.)</td>
<td>3</td>
<td>Integral</td>
</tr>
<tr>
<td>Wireless Headset Chip Manufature</td>
<td>4</td>
<td>Modular</td>
</tr>
<tr>
<td>Wireless Headset Overall Design</td>
<td>4</td>
<td>Integral</td>
</tr>
<tr>
<td>Wireless Headset</td>
<td>4</td>
<td>Modular</td>
</tr>
<tr>
<td>Wireless PDA - Video Applications</td>
<td>N/A</td>
<td>Modular</td>
</tr>
</tbody>
</table>

**Figure 6.2: Telecom Design-Chain Boundary Summary**
6.1.2 Automotive

History

The automotive industry began around the turn of the century, with the rise of small, craft-oriented coach-makers entering the new business of 'horseless carriages.' With Henry Ford's advancement of mass-production methods, and specifically with the success of the Model-T, Ford Motor Company became the US's vertical automotive giant. GM would take and hold that title through the middle of the century, but would continue the idea of the vertical corporation as the dominant model.

Although suppliers have always been involved in the manufacture of automotive components and subsystems, their traditional role has been as pure manufacturers, who begin their process with a complete design. The design is provided by the OEM as a complete set of blueprints or CAD models. In recent years, automotive OEMs have pushed for their supply base to take on more design and development tasks. The concept, pioneered by Chrysler in the early 1990s, was to use a small number of top-tier module suppliers, who provide not only the vehicle subsystems, but the design of those systems. As the OEMs try to modularize their design chain, top-tier suppliers are integrating, in order to supply complete module designs.

Current Status

This modular trend is evident in cases 5, 6, and 7, almost without exception. In exhaust, suspensions, exhaust, and door modules, "module" is the keyword. To gather the expertise for designing and producing full systems, top-tier suppliers have been acquiring each other at record rates. In fact, all the top-tier suppliers in cases 5-7 have undergone major mergers or acquisitions in the last two years.

But note that automotive design-chain boundaries are still integral to a large extent. This is indicated in Figure 6.3 The obvious question is: in a world of module suppliers, where are the modular boundaries?

There are two answers to this question. First, the turn toward modularity takes take in this relatively slow clockspeed industry. One supplier interviewed, who had recently developed a new technology, noted that it would be six years before it generated revenue, due to the time-consuming automotive product development cycle. But there is another fundamental reason for the persistence of integral design boundaries in a so-called modular world. Even if suppliers provide full modules, they are still part of a fundamentally integral architecture. The module suppliers at the top tier of cases 5, 6, and 7 all designed to customer specifications, had
representatives on-site at their customer, and deferred to the design judgments (and the warranty protection) of the OEM.

These modules are manufactured, and delivered as modules, but their design must retain at least some aspect of integrality. Until this architecture changes, the design-chain interfaces cannot take the 'modular turn,' no matter how this turn is force-fed into the design process. In fact, some express doubts about how far modularity can be pushed in vehicle architectures (17).

<table>
<thead>
<tr>
<th>System</th>
<th>Case #</th>
<th>Boundary Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalytic Converter Substrate</td>
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<td>Mixed</td>
</tr>
<tr>
<td>Catalyst Coating</td>
<td>5</td>
<td>Integral</td>
</tr>
<tr>
<td>Exhaust Hot-End</td>
<td>5</td>
<td>Integral</td>
</tr>
<tr>
<td>Emissions Certification</td>
<td>5</td>
<td>Integral</td>
</tr>
<tr>
<td>Window Regulator Motors</td>
<td>6</td>
<td>Mixed</td>
</tr>
<tr>
<td>Window Regulator Hardware</td>
<td>6</td>
<td>Integral</td>
</tr>
<tr>
<td>Window Regulator Systems</td>
<td>6</td>
<td>Mixed</td>
</tr>
<tr>
<td>Suspension Components</td>
<td>7</td>
<td>Integral</td>
</tr>
<tr>
<td>Tires</td>
<td>7</td>
<td>Mixed</td>
</tr>
<tr>
<td>Suspension Systems</td>
<td>7</td>
<td>Mixed</td>
</tr>
<tr>
<td>Future Suspension Systems</td>
<td>7</td>
<td>Modular</td>
</tr>
<tr>
<td>Truck Axle Components</td>
<td>8</td>
<td>Mixed</td>
</tr>
<tr>
<td>Truck Axles</td>
<td>8</td>
<td>Modular</td>
</tr>
<tr>
<td>Truck Brake Pads</td>
<td>9</td>
<td>Integral</td>
</tr>
<tr>
<td>Truck Brake Hardware</td>
<td>9</td>
<td>Modular</td>
</tr>
<tr>
<td>Truck Brake Systems</td>
<td>9</td>
<td>Mixed</td>
</tr>
<tr>
<td>Integrated Truck Suspensions</td>
<td>9</td>
<td>(Modular)</td>
</tr>
</tbody>
</table>

**Figure 6.3: Automotive and Heavy-Truck Design Chain Boundary Summary**

*Automotive: Lessons from Telecom*

If there is one lesson for automakers to take away from the telecommunications space, it is the modular potential of electronics. Electronics compose ever-increasing percentages of a vehicle's content. In electronics, component and module designs are already in place. The challenge, for automotive design and development engineers, is to integrate these pre-existing designs into their vehicle in ways that create value to the end customer.

At one OEM, forays into electronically-controlled suspensions were much different than anticipated. OEM suspension engineers were used to outsourcing mechanical parts, the design of which can be 'stolen' just by looking at them. But with the arrival of active-control suspensions,
the parts could not be understood, nor copied entirely, without access to the computer algorithm that controls the electronics. This module was in the supplier's hands, thanks to the 'modular' design paradigm. As a result, the supplier named their price when negotiations got tough. Without that algorithm, or the manpower to develop it, the OEM was stuck in a powerless situation. They were outsourcing for knowledge rather than for capacity, in a new technology they deemed highly important. Similar lessons apply in the realm of engine management electronics, which suppliers control tightly in some cases.

A follow-on lesson for OEMs is that not all items can be designed via suppliers at arms-length. The headset and phone-casing in the telecom cases have their companions in the automotive space as well. The vehicles exterior shape, and the vehicle interior, will likely to be designed in-house or via a permanently integral boundary. Suppliers of body panels or interiors should be aware that they will not be dealing through arms-length contracts any time soon. But what else is considered 'customer interface?' Some customers are very picky about suspensions, engines, gearshift knobs or cup holders. Automotive OEMs must place their bets, letting modular boundaries, and the resultant commonized parts, apply only where the customer does not notice.

6.1.3 Heavy-Trucks

Current Status

Originally, the heavy truck industry was chosen as a compliment to the automotive industry, under the naive assumption that their industry structures would be roughly similar. In fact, nothing could be further from the truth. The heavy truck industry is unlike the other two industries in a crucial sense. At the interface between top-tier suppliers and OEMs, the heavy truck industry is already highly modular. As the cases illustrate, major chunks of a heavy truck (such as the engine, transmission, axles, and brakes) are sourced from separate suppliers, often by the end customer. Truck buyers regularly specify component manufacturers, and task the OEMs with integrating these pre-existing subsystems into an attractive overall package. Like PCs, heavy trucks are configurable at the point of purchase by the end customer. And as in PC markets, this modularity is enabled by standardized interfaces between components. In the case of heavy trucks, these are often specified by industry standards. For example, standard housing connections between engine and transmission are defined by the Society of Automotive Engineers (SAE).

We saw this in cases 8 and 9, both of which dealt with subsystems which could be specified by the end customer. In all three cases the end customer associated product performance, and specifically durability performance, with the sub-system supplier. In keeping
with this trend, the sub-system suppliers are largely responsible for warranty claims. These characteristics are exhibited in the modular interface between firms in cases 11-13. As emphasized in previous chapters, the design-chain interface at the top tier can be identified by the question "is this subsystem designed to supplier specifications for market sale, or to OEM specifications for specific customer sale?" In the heavy truck realm, the answer is clearly the former, suggesting the expected modular interfaces in the supply chain.

At the lower tiers, some anecdotal evidence suggests that supply-chain interfaces are still being worked out. Friction between purchasing and engineering (as in Case 8) and over-specification of the tier-2 domain (as in Case 9) indicate that supply-chain interfaces are still not well understood. In general however, the lower tier components vary significantly, and occupy widely varying locations on the double-helix.

At the top tier of the heavy truck supply chain, the double-helix position is firmly within the modular segment. Having identified this position, the next question concerns future changes in the truck market. Specifically, are there forces at work which threaten to move the industry to a more vertical/integral structure?

Future Trends

The answer is yes, but at a slow pace. There are several emerging technologies that demand a more integral approach. The most prominent of these are electronically controlled braking, steering, and suspension systems. Such systems would eliminate the mechanical link between drivers' input and the truck subsystems, in favor of an electronically actuated system. With the addition of some computing power, such systems can reduce or eliminate vehicle control problems caused by inappropriate driver input. For example, skidding or jack-knife events, which are often begun by severe road input and exacerbated by driver response, can be controlled out through selective application of brakes, steering systems, and engine inputs. Such systems are already being implemented, with impressive success, on high-end automobiles. These systems run counter to the modular-world of heavy-truck supply, as various systems must be integrated to create significant performance benefits. If and when these capabilities are needed, the supplier who can integrate will have a true advantage.

A move toward integrated systems will come, when it does, via regulatory pressure. The current buyers of heavy trucks are fleet operators, who care about hauling more and paying less to do it. Improvements in durability, cost, fuel economy, and weight will continue to command dollars, but enhanced vehicle stability may not appeal to the current customer base. As with
emissions and anti-lock brake systems, government regulation will drive all function that does not directly impact the fleet bottom line.

A less dramatic, but still important factor in integration is package space. Design managers report ever increasing conflicts in package space, which must be negotiated between suppliers and OEMs in the design cycle. Already in the case of heavy-truck brakes, packageability is a key component of design success for suppliers. As space becomes more precious, suppliers may be forced to choose between modular/configurable designs and integral/specific designs. If and when integral designs are chosen, a newly integrated interface will form between customer and supplier. Managing this interface is a key challenge in surviving double helix shifts.

Because technology changes slowly in the heavy-truck business, and because end users' demands are relatively unchanged over time, the clockspeed of the heavy-truck industry is extremely slow. As one purchasing agent put it, "we're building basically the same axle we've been building for years." Until regulation mandates something new, or until designers find new designs to reduce operating cost, heavy-truck design is likely to creep forward at a slow pace.

6.2 Observed Phenomena in Outsourced Design

6.2.1 Hold-Up at Integral Boundaries

A commonly held view is that commodities are a terrible thing to supply. Automotive suppliers find themselves rushing to accept full-system design responsibility, in order to distance themselves from the 'C' word. But in integral-boundary design outsourcing, customized designs pose a different threat to the supplier: the threat of design-process 'hold-up.'

Consider the simple economic case of a supplier (Firm B) and two buyers (who we will call Firm A₁ and Firm A₂). The supplier is considering a transaction with firm A₁, whose value of the module is denoted V₁. Suppose that A₁ asks B to make an investment of $I$, which is specifically targeted at A₁'s needs. (For example, the supplier might be asked to invest in specific process machinery, or specific test equipment, which is only useful to buyer A₁.) In this case B is told that, if B invests in the specific equipment, A₁ will be willing to pay some price $P_{A₁}$ for the finished good. In the wings is buyer A₂, who would be willing to pay $P_{A₂}$ for the same product, and is indifferent to the specific gains of investment $I$. (That is, given $I$, the product is specifically designed for A₁. Therefore A₂ has a lower willingness to pay, and $P_{B} < P_{A₁}$. ) Assume for simplicity that production costs are marginal, one unit is transacted, and $(P_{A₁}-I) > P_{A₂}$. If the
supplier believes that $P_{A1}$ will be the final price, the supplier will elect to make the investment and sell to $A_1$.

The problem comes when payment time comes. At that time, the supplier has already invested in the specific capability, and is now ready to produce the good and ask for payment. But $A$ is now in a very strong position, knowing that $B$'s alternative use of the goods is to sell them to $A_2$ at price $P_{A2}$. At this point in time, a rational firm $A_1$ will offer to pay only $P_B$. $B$ is left in a no-win situation. In layman's terms, $B$ is held up by $A_1$. A simple decision tree for this case is shown in Figure 6.4. Backward-induction logic would suggest that the supplier not invest $I$ in the first place.

Obviously, $B$ should demand payment in a formal court-enforceable contract. But a formal contract is rarely worthwhile in a design setting, precisely because the design process has an uncertain outcome. And suing a customer is often not an option for a supplier.

![Diagram of Simple Supply-Chain Game Tree Showing Hold-Up Logic](image)

**Figure 6.4: Simple Supply-Chain Game Tree Showing Hold-Up Logic**
Hold-Up in Engineering Design and Development

In the terms of product design and development, the specific investment \( I \) is any design and development work done on behalf of a specific customer. That is, the specific investment \( I \) is associated with integral supply boundaries. In a sense, integral supply-chain boundaries are defined by this specific investment. In the realm of product design, specific investments are everywhere. A short list includes

- costs for customer-specified testing
- resources used to meet customer-specific package requirements
- costs of incorporating customer-defined technology solutions
- costs of aligning design capabilities with a specific customer (such as CAD/CAE software commonization, tolerancing protocols, etc.)
- customer-specific prototypes

Indeed, similar apply to integral investments of downstream firms (i.e., buyers). Their specific investments can be harder to find, but include tooling, engineering support, etc. More obviously, suppliers hold up their customers by simply refusing to continue a partnership at a critical time. If the window regulators in section 5.6 are custom designs, the supplier has the power to stop the entire vehicle design process. With supplier non-cooperation at the last minute, a tiny part can stop an entire vehicle design process. So although integral suppliers rightly lament their held-up status, their customers feel the same forces, if applied in a slightly different way.

Solution to the Hold-Up Problem

In defense of firms in integral design-chain relationships, the hold-up problem is not trivial to overcome. It has been shown, by Klein et al.\((1)\) among others, that contractual solutions to one hold-up problem typically create new hold-up problems. A convincing and topical case of Fisher Auto Body is often cited as an example. Fisher, who supplied GM in the 1950's, was presented with the classic hold-up problem with a request to invest in GM-specific processes. A summary of the outcome is given by Gibbons \((18)\):

"Both parties understood that GM could hold-up Fisher after such an investment, such as by offering to pay only marginal rather than average cost. Consequently, the parties signed a contract that gave Fisher certain protections, including a formula specifying the price as a mark-
up of Fisher's variable costs. But this contract created ways for Fisher to hold-up GM, such as by threatening to overstaff its plants so as to pad variable cost.

"Ultimately, GM bought Fisher, but at a high price. The price had to be high because Fisher had to be persuaded to give up its strong bargaining position created by the pricing formula in the formal contract."

Some authors, notably Gibbons (18), propose a solution to these dilemmas based on relational contracts. A relational contract is defined as an agreement based on relationship only, which cannot be enforced in courts of law. These are the contracts based on reputation, honesty, and the promise of future cooperation. Using a straightforward application of repeated-game theory, it can be shown that these informal contracts are self-enforceable and therefore a viable means of cooperation.

To illustrate, we can extend the case presented above, and assume that the game will be played in infinitely repeated stages. After each stage, the game is repeated. The supplier is again asked to make investment I, after which, if it is made, customer A can opt to buy at the original price or at the lowered price $P_A$. Discounting takes place using discount factor $r$ (where $r = 1 + \text{discount rate per stage}$).

Now let's assume B makes clear the following strategy:

- B begins by making investment I.
- If A honors the original deal (to buy at $P_A$), then B will make the investment in the next stage.
- If A reneges on the original deal, B will never make investment I in any future stages.

Now, unlike before, $A_1$ has an incentive to cooperate with B in the current stage, in order to profit via cooperation in future stages. This incentive is the present value to A of future cooperation with B. It can be calculated as

$$\sum_{i=1}^{\infty} \frac{(V_{A1} - P_{A1})}{r^i}$$

(Present value to A of future cooperation with B.)
Then $A_1$ will renege in the first stage only if, from $A_1$'s viewpoint:

$$(\text{Value of Reneging in stage 1}) > (\text{Value of Cooperation in all future stages})$$

or

$$V_{A_1} - P_{A_2} > \sum_{i=1}^{\infty} \frac{(V_{A_1} - P_{A_1})}{r^i} \quad (\text{condition under which } A_1 \text{ reneges})$$

This is a shortened example of a general repeated-game problem, which is presented more thoroughly elsewhere (19). Its power is in quantifying the trust relationship between parties. Relationships between firms, in this model, become an economic entity with a real value, and not merely a tool of the social sciences.

To be fair, reneging opportunities are present to both parties in a real-world relationship, and the hold-up problem works both ways. For example, if $A_1$ makes the investment for $B$, then $B$ can still choose to sell to an alternate customer. Again, a formal court-enforceable contract might avoid these problems. But design and development contracts often cannot be codified, because their outcome is uncertain.

For integral suppliers, the implications are quite clear. Invest only in customers who can commit to long term relationships. Pay attention to the alternate use value of custom-designed products. And most of all, pay attention to the timing of contracts as the design progresses. Because designs often begin as non-specific creations, and are then customized for specific customers, there is a time-matching problem with contracts. Suppliers need contracts, enforceable in law or via 'future-relationship' effects, whenever a design becomes customer-specific.

**Risk Classification**

The hold-up problem presented above applies to integral-supply situations. As mentioned previously, there is a well-known risk of commoditization in modular product supply. In general, there are fundamentally different risks associated with modular versus integral supply. These risks are described in Figure 6.5.

The hold-up problem was discussed in detail, and the commoditization problem relatively ignored, because of the attitudes of many interviewees in the automotive and telecom space.
Their opinion, in a wide range of cases, was that commoditization of supplied parts was the major risk to suppliers. The idea of integral hold-up was less clearly defined, and less understood as a major risk. If designers are to understand the value-maximizing strategy for their own firm, they must understand the differences between risks in sub-system product design.

Figure 6.5: Spectrum of Contracts and Product Architectures, Including the Associated Risks

6.2.2 Modular Design: Reversing the System Decomposition

If we return to the conceptual systems engineering process, an interesting trend can be identified. Apparently, system engineering processes are fundamentally different in modular-boundary scenarios, compared to the integral-boundary cases for which these processes were developed.

Recall the system decomposition at the heart of the systems engineering process. This top-down decomposition was used to decompose high-level functional goals into more manageable goals at the lowest level, by 'zig-zagging' between function and form in the decomposition. Recall also that, although some portions of the decomposed system might be
designed by a supplying firm, the decomposition is initially performed by the downstream/integrating firm.

In integral industries this model is fine. But in modular industries, a new and different phenomenon has been observed. Although the system decomposition still takes place, it is performed with knowledge of specific available subsystems. This information changes the strategy of the decomposition. Instead of decomposing according to customer needs and system-architecture principles, systems are decomposed based on the current market for existing modules.

This was seen time and time again in both the telecom and heavy-truck markets, wherever modular boundaries are found. Truck OEMs design their frames and cabs around existing modular axles and transmissions. And those axles are planned around pre-existing gear designs. Wireless telephone concepts are designed with separable headsets, because a supplier has developed such a headset. Network installations are designed to utilize pre-existing optical modules. Sometimes, entire business plans are based on the availability of modular supplied components. As two separate CEOs noted in interviews, their companies began with a realization that supporting modular components were already in place.

![Diagram of portable data manipulation](image)

**Figure 6.6: 'Off the Shelf' Component Changes Decomposition to Aggregation**
Circuit boards in network installations are designed and redesigned around the physical structure of off-the-shelf components. This 'circuit-board' model is a good analogy for the concept of bottom-up functional planning. Although the function of the assembled board is greater than the function of the chips on it, the board is planned around these functional modules. Board-level designers are in the business of: 1) seeing what chips/components are out there; 2) finding ways to assemble them for higher-level function. The process on paper may look like a decomposition, but in practice it is an aggregation of modular components.
7.0 Conclusions

The study presented here is an in-depth investigation of shared design processes, including the nature of design decision-making processes between multiple firms. Conclusions of the study include the following:

1. As economists know, a fundamental tension exists between firms in a supply relationship. This tension impacts the shared design process in a design chain. Economic tension is embedded in the product requirements, which are transformed when transferred between firms.

2. This tension is resolved in one of two different ways. In cases where firms align incentives, form close relationships, and otherwise break-down the tension, the interface between them is termed an integral design boundary. Alternately, if interfaces between product systems are standardized, function is allocated to clearly-defined modules, and a market for product modules is created, the interface between them is termed a modular design boundary.

3. These boundary classifications are applied to design-chain mapping exercises in the telecom, automotive, and heavy-truck industries. Interviews with a wide variety of design engineers, managers, sales and purchasing agents are used to inform the design-chain maps presented. The results are used to assess the location of industries on the "double-helix." Specific recommendations are made for the automotive and heavy-truck industries, based on an extension of observations in the faster-clockspeed telecom industry.

4. The risks of integral and modular supply are presented, including a review of the so-called "hold-up" problem in integral supply. A simplified repeated-game exercise is applied to the integral-boundary case, to demonstrate the power of relationships in integral supply.
5. An observation is made on the effect of modularization on the traditional 'system decomposition' stage of product design. The design process, in modular industries from heavy-trucks to wireless phones, is in fact an aggregation of existing functional modules.
References


