

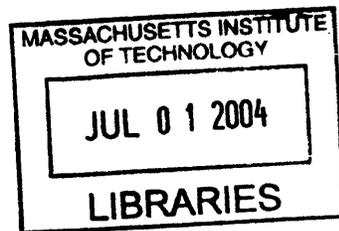
Enterprise Design for Dynamic Complexity:
Architecting & Engineering Organizations using System & Structural Dynamics

by
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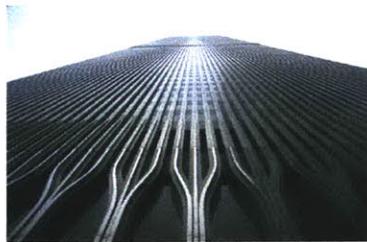
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Abstract

As the business world is neither linear nor static, the mastery of its “chaotic” nonlinear dynamics lies at the heart of finding high-leverage policies that return uncommon benefits for marginal costs. Today’s global enterprises are **dynamically complex** socio-technical systems where cause and effect of management’s strategies and policies are distant in space and time. *Spatial* complexity recognizes that correctly defining the limits of the extended enterprise is essential in maximizing shareholder value via stakeholder management. *Temporal* complexity recognizes that policies, decisions, structure and delays are interrelated to influence growth and stability. An enterprise’s long-term success therefore is a function of management’s ability to control this “dynamic complexity”.

The goal of this thesis is to develop management insights into “**enterprise design**”, i.e. to create more successful management policies and organizational structures. Enterprise design can be decomposed into the science and art, or **engineering** and **architecting**. Using the heretofore-separate academic fields of **system dynamics** and **structural dynamics**, an attempt is made to define the scientific “laws” of enterprise physics that will then be used to construct non-obvious, often counter-intuitive enterprise architectures. The goal is to combine the methodologies from the “business of building” with the “building of business”, in an attempt to draw lessons from the design of high-rise buildings for the design of high-rising enterprises.



Throughout this thesis, examples of a variety of socio-technical enterprises are discussed in order to explore and test the principles and insights developed herein. There is however a unifying case study used throughout of one of the world’s most dynamically complex socio-political-technical enterprises: the Commercial Airplanes enterprise of *The Boeing Company*. This thesis uses the approaches of system and structural dynamics to explore *Boeing’s* stability, growth, market share and profitability.

Thesis Supervisors:

Professors Charles Fine, *Sloan School of Management* and Deborah Nightingale, *School of Engineering*

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While this work has been supported and funded by the aforementioned parties, the contents of this thesis do not necessarily reflect their views, and any errors or omissions are the responsibility of the author. I also add the disclaimer that while part of this thesis was undertaken under the supervision of *The Boeing Company*, this work in no way intends to pass judgments regarding the effectiveness its management, nor to offer normative or prescriptive recommendations for its future vision and operations. Rather, the intent was merely to pose questions and suggest hypotheses and frameworks for dealing with enterprises facing dynamic complexity.

Finally, at one of the first public presentations of this research in 2003, I received a public critique from Dr. Michael Hammer, international author and management consultant of the Business Process Reengineering movement. He colorfully exclaimed, "This is either the work of a madman or a genius, and at this moment I am inclined to think that it is the latter." I would like to acknowledge at this point that if the ideas presented herein appear strange, unconvincing, illogical, or simply wrong, then I take full blame as the "madman" responsible for this work. However, if these insights while unconventional do seem to uncover some truths, then I must quickly acknowledge the true source of any "genius" that may exist.

As my advisor, Prof. Fine acknowledges in his book, *Clockspeed*, "if I have seen farther, it is by standing on the shoulders of giants". My giants are numerous in space and time, ranging from Sir Isaac Newton to my classmates at MIT. I have just served as a humble questioner, listener and integrator of their knowledge, mental models and points of view. I would therefore like to thank those whose inspiration and contributions made this thesis possible, including:

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Dedication

My journey at MIT *Sloan* began on September 11, 2001.¹ As a former designer of high-rise buildings and an aspiring designer of “high-rising” enterprises, I dedicate this work to those who lost their lives on that day.



¹ My very first Sloan MBA class took place from 9:00 to 10:30 am on September 11th, as the flights leaving Boston's Logan Airport arrived at their destinations.

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Part I: Enterprise *Engineering*

“The next two decades may well be a period of transition from the era when society has focused its pioneering attention on science to the era in which we will turn priority attention to understanding the dynamic behavior of our social systems. Wars, revolutions, economic stagnation, inflation, corporate bankruptcies, and the multiple sufferings, insecurities, and frustrations of the individual all proclaim that we fail to understand these systems... we might consider management of the future as ‘enterprise engineering’”²

Jay W. Forrester
Professor, Engineer, Enterprise Designer

² Jay W. Forrester, “Common Foundations Underlying Engineering and Management”, *IEEE Spectrum* 1, No. 9 (September 1964), pp. 66-77.

Chapter 1: Introduction

1.1 Objectives

Can enterprises be predictively architected?³ Can value chains be predictively roadmapped?⁴ How can enterprise design achieve stability and growth?⁵ How does one architect/design future “lean” enterprises?⁶ How does an enterprise’s *clockspeed* define its dynamic performance?⁷ How can “dynamic complexity” be controlled to solve this class of “wicked problems”?⁸

This thesis attempts to answer such questions by bringing new interdisciplinary knowledge to existing disciplines – by building bridges between social and technical sciences. In the process, this thesis aims to present some counter-intuitive insights about world-class enterprises that seem to defy the laws of organizational physics.

1.2 *Principia Dynamica: Isaac Newton’s Guide to Business*

This exploration begins with a simple hypothetical question: “If humanity’s greatest minds were around today, and they applied their intellect to solve some of the most complex business problems of the 21st century, what would they come up with?” For example, if Sir Isaac Newton had not discovered the laws of motion in his *Principia Mathematica* in 1687, but had instead discovered the laws of business over 300 years later, what might he have come up with? As Newton himself bemoaned after losing his savings in the South Sea Bubble of 1720:

“I can predict the movements of the universe, but I will never understand the madness of men.”

³ One of the MIT *Engineering System Division*’s academic research thrust questions.

⁴ From Professor Charles H. Fine’s current research.

⁵ From the preface of Jay W. Forrester’s classic 1961 book, *Industrial Dynamics*, from which much of the methodological inspiration for this work is derived.

⁶ From the MIT *Lean Aerospace Initiative*’s August 2003 research vision statement.

⁷ From Charlie Fine’s 1998 *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*.

⁸ From Peter Senge’s *Systems Thinking* approach.

This thesis attempts to revisit that challenge: as shown in figure 1.1 below, how might the laws governing the dynamics ranging from the orbits of the heavenly bodies to the proverbial falling apple, apply to the dynamics of complex human enterprises?

Figure 1.1: Newton’s Laws of Motion applied to Business?



I will begin by examining the dynamic motion of two “enterprises”. Figure 1.2 below compares the dynamic oscillations of one of the simplest dynamic systems, a pendulum (on the left), with the dynamic oscillations of one of the most complex dynamic macro-economic human enterprise systems, the US automotive industry⁹ (on the right).

Whether a human hand is shaking the physical pendulum on the left, or Adam Smith’s “invisible hand”¹⁰ is shaking the macro-economy on the right, I note that the response in both enterprises has a similar “sinusoidal” oscillation. This oscillation has a notable “clockspeed” – inversely known as a “natural period of vibration” (i.e. mean time between successive peaks), which for the automotive industry on the right is in the region of 6-8 years.

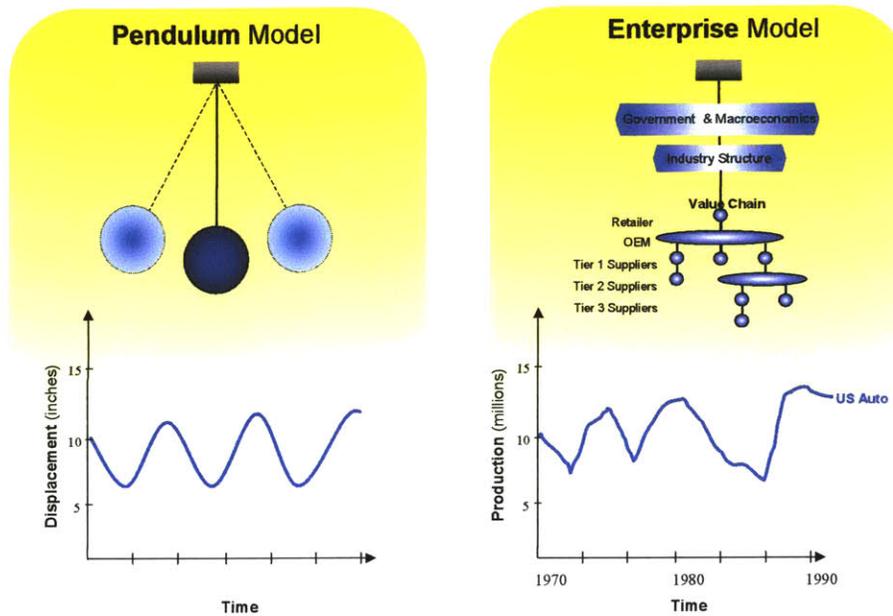
While the automotive “value system” is a complex system of interacting value chains represented as a “Multi-Degree of Freedom” (MDOF) pendulum, the dynamic response can apparently be approximated by a single mass and string pendulum, known as a “Single Degree of Freedom” (SDOF) system¹¹. This greatly simplifies the assessment of the industry, provided that one can estimate the size of the mass and the length of the string, which will be discussed in Chapter 2.

⁹ *The Machine that Changed the World*, Womack, Jones and Roos, Free Press, 1990, pg. 248.

¹⁰ *The Wealth of Nations*, Adam Smith, The University of Chicago Press, 1976.

¹¹ This well-known property of “modal superposition” in engineering dynamics is directly applicable to linear systems, and can be extended without significant loss of accuracy to mildly nonlinear systems which includes a significant class of social dynamic systems.

Figure 1.2: Mapping Physics to Enterprises



Eberhardt Rechtin, an expert on systems architecting notes that “an architect-engineer would describe all of these phenomena as an oscillation of a quasi-stable system – like a pendulum, perhaps – needing a delicate balancing to keep it from destroying itself.”¹²

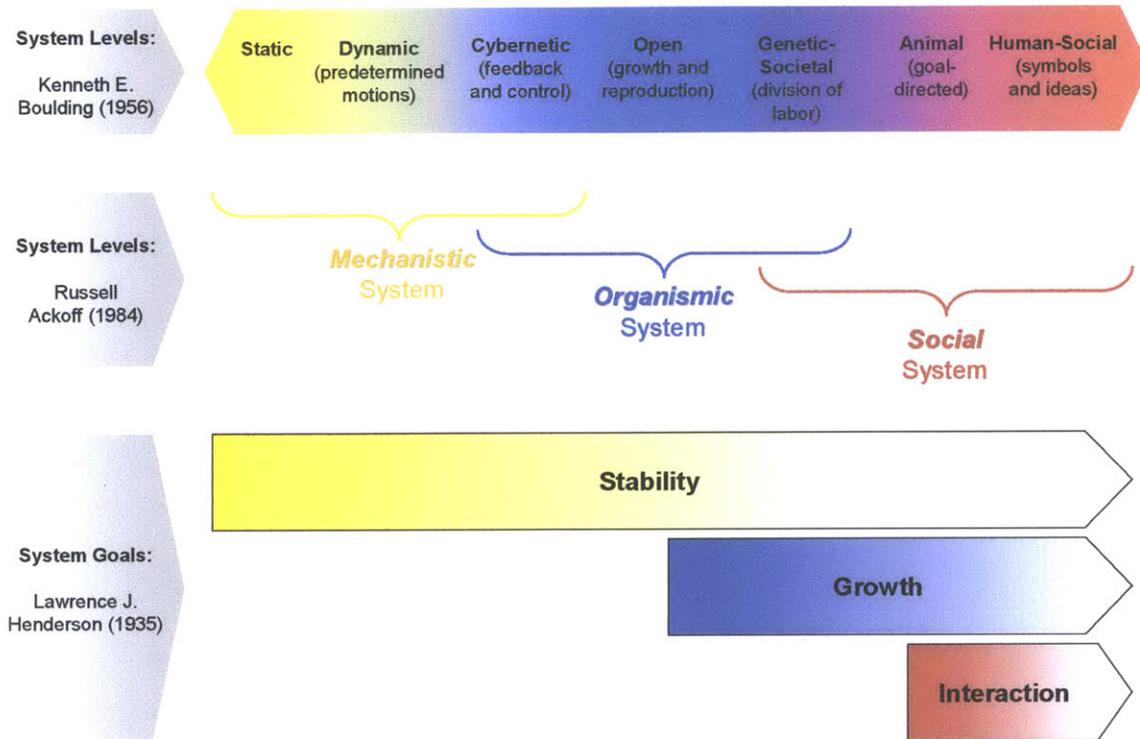
1.3 Enterprises and Systems Theory

Before we proceed, it is important that we understand the potential impact and limitations of attempting to use physical-social analogies. Classical *General Systems Theory*¹³ makes a significant distinction between the two systems in figure 1.2, the physical pendulum and the complex macroeconomic industrial system. As shown in figure 1.3 below, systems can be classified as a spectrum of different levels. At one end of the systems spectrum lie static and simple dynamic systems (like the pendulum and the motion of the solar system), while at the other end of the systems spectrum lies human social systems (like the automotive industry).

¹² *Systems Architecting of Organizations: Why Eagles Can't Swim*, Eberhardt Rechtin, 2000, pg. 71.

¹³ Kenneth E. Boulding, “General Systems Theory – The Skeleton of a Science,” *Management Science*, April 1956, pp. 202-5.

Figure 1.3: Classification of System Levels & Goals



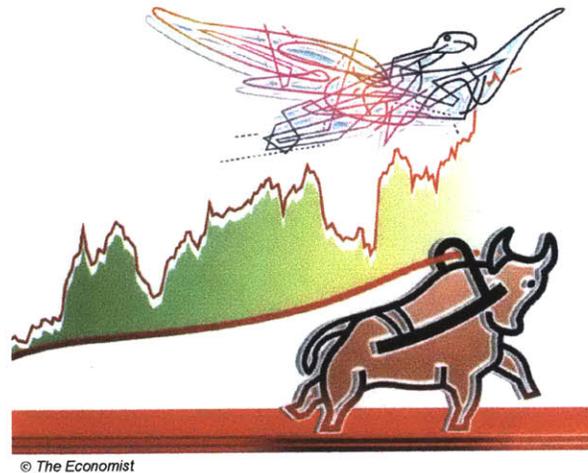
Systems theory also notes that all systems have goals of stability, growth and interaction. The spectrum of system levels can also be characterized by cascading combinations of these goals as shown in figure 1.3. For example, the primary goal of static, dynamic and cybernetic systems is to seek stability. While the primary goal of open, living systems is growth *and* stability.¹⁴ In fact, the more dynamically complex the system, the more sophisticated the goal. Close examination of figure 1.2 reveals that the automotive industry exhibits a subtle long-term trend growth coupled with the oscillatory instability, while the standard physical pendulum exhibits instability without growth.

As shown in figure 1.4 below, much of this thesis is an exploration of the underlying nonlinear dynamic causes and effects of the pursuit of various system goals ranging from stability to growth to interaction. It is search for the strategic architecture which produces long-term competitive advantage.¹⁵

¹⁴ Scott, William G. and Mitchell, Terence R., *Organization Theory: A Structural and Behavioral Analysis*, Irwin-Dorsey Press, 1972, pg. 60.

¹⁵ © *The Economist*, December 17th, 2003, pg. 77.

Figure 1.4: *Strategic Architecture* underlying Stability, Growth & Interaction



Whether I use the terms, “mechanistic” vs. “organic”¹⁶, “mass” vs. “lean”, “higher-faster-farther” vs. “better-faster-cheaper”, this work contends that there are fundamental architectures that perform better than others given environmental constraints.

Although by definition, the physical pendulum and the social enterprise have radically different levels of dynamic complexity, Scott points out that “a good deal of insight could be thrown on social systems if structurally analogous elements could be found in simpler systems. It is usually easier to study the less complex and generalize to the more complex.”¹⁷ Scott also quickly points out however that, “care should be taken that analogies used to bridge system levels are not mere devices for literary enrichment. For systems to be analogous, they must exhibit inherent structural similarities or implicitly identical operational principles.”¹⁸

This thesis therefore seeks to walk the fine line between capturing the true complexity of human enterprises while conveying meaningful understanding through the use of appropriate simple analogies and metaphors.

¹⁶ From the General Systems Theorists.

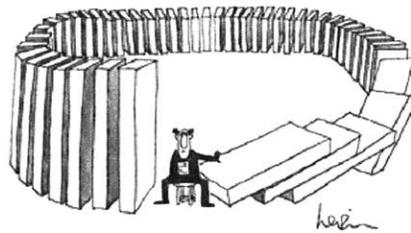
¹⁷ Ibid. pg. 54.

¹⁸ Ibid. pg. 54.

1.4 Dynamic Complexity and “Wicked Problems”

This project attempts to wrestle with complex socio-political-technical systems or enterprises. As shown in figure 1.5 below, a distinguishing characteristic of these systems is the presence of a high degree of *dynamic* complexity (i.e. cause and effect are distant in space and time).¹⁹ The solution to a current problem (the creation of more space, by pushing aside an obstruction) may seem helpful in the short-term, however or “side-effects” may lead to “unintended consequences”²⁰ or undesirable results in the long-term.

Figure 1.5: Dynamic Complexity in Action



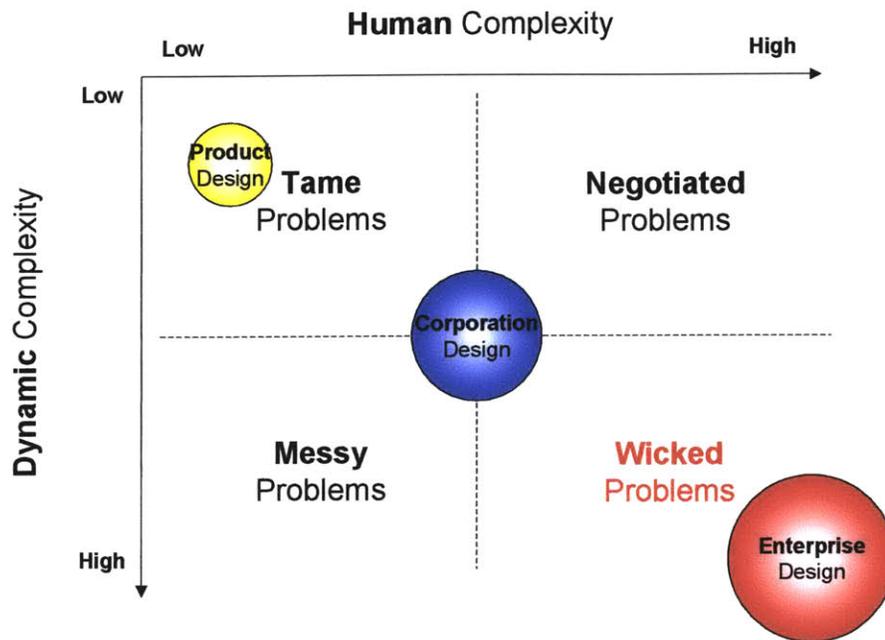
As shown in figure 1.6 below, Senge defines the space of socio-technical problems by considering another dimension of *human* complexity.²¹ Conventional engineering systems, even those having a high degree of *detail* complexity like a commercial airplane, fall into the category of “tame” problems. Traditional corporations however have much more human and dynamic complexity, making them political or “negotiated” problems or “messy” structural dynamics-type of problem. Enterprises, with their focus on longer time scales and a broader set of stakeholders, by definition has the highest degree of both human and dynamic complexity, making them “wicked”. I will discuss the dynamic complexity of enterprises in Part I, and the human complexity of enterprises in Part II of this report.

¹⁹ © Cartoonbank.com (by Arnie Levin, *The New Yorker*, December 27, 1976). Idea borrowed from John Sterman’s lectures in 15.874.

²⁰ From John D. Sterman’s, *Business Dynamics*.

²¹ Peter Senge, lecture in “Organizations as Enacted Systems”, MIT course, Fall 2002. See also *PA Consulting Group* paper, “Putting Complexity Thinking into Practice”, 2003.

Figure 1.6: Classification of Complexity



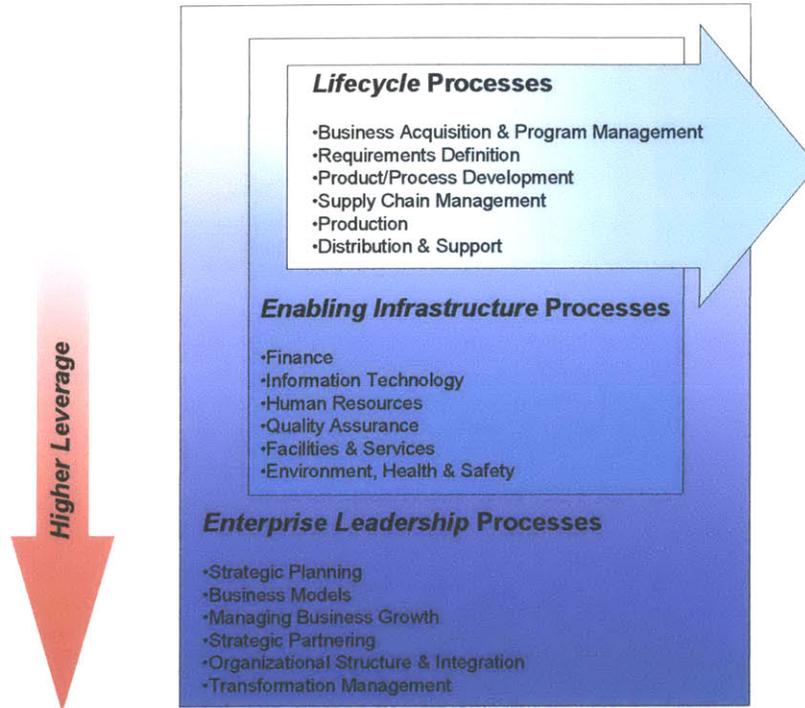
“Enterprise design” therefore in this context means a rethinking of the logic of cause and effect. The problem with such complex socio-political-technical enterprises, however is that most managers embedded in them tend to operate in the world of linear, direct cause-and-effect and conventional curricula at most business schools does not cover this class of business problem.

The good news is that there are methodologies to deal with this class of problem. The bad news is that most methodologies deal with dynamic complexity in a complex way – a way that most managers don’t have the time and/or interest to master. As the old saying goes, “the hard part is making it look easy.” One of my objectives therefore is to identify the methodologies appropriate to solving this class of problem and to transform them into more simple or usable terms. This work then is an attempt to act as a “management filter”, which I will argue in later chapters of the design of enterprises with appropriate “organizational filters” to successfully deal with this dynamic complexity.

This thesis builds off of the research of a number of MIT faculty in different sub-fields ranging from engineering systems to management science to organizational behavior. In particular, it furthers their general hypotheses which posits that the enterprise solutions with the *highest* leverage often lie at the

greatest *depths* of enterprise structures and architectures. As a case in point, Nightingale et al.²² put forth a model which show that greatest architectural leverage lies in the underlying leadership processes which then support the enabling and life-cycle processes (see figure 1.7 below).

Figure 1.7: Enterprise Process Architecture



Building on this theme, I synthesize three other MIT models (shown in figure 1.8 below) which support this view: Ancona et al’s “three lenses” of organizational analysis²³, Schein’s “three levels” of organizational culture²⁴, and Senge/Sterman’s “three levels” of systemic change. We will return to Senge/Sterman’s three notions of “reactive”, “responsive” and “generative” in chapter 2 when we derive the physics of organizational dynamics.²⁵ While this thesis begins with the surface phenomena of business, it attempts to uncover the architectures of deeper causality associated with Systemic Structure, Leadership, Culture, and the Invisible Assumptions or enterprise DNA.

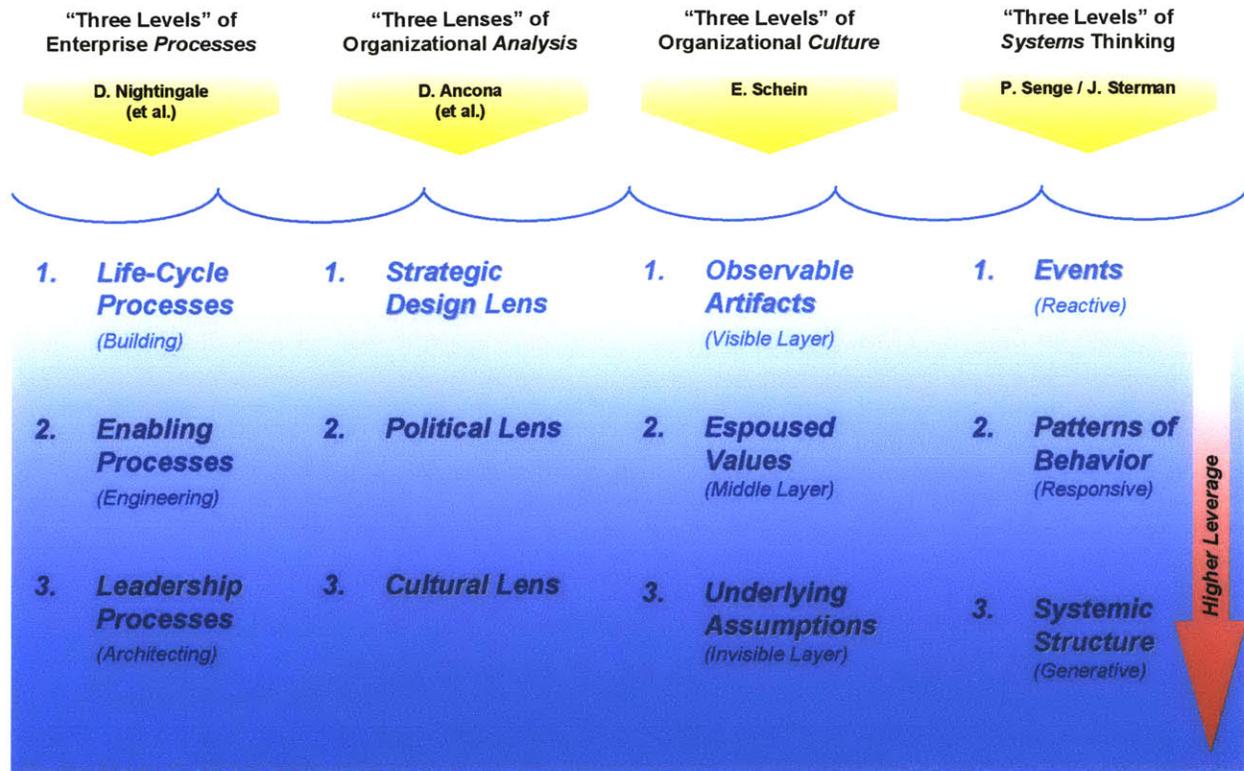
²² E. Murman et al., *Lean Enterprise Value*, 2002.

²³ D. Ancona et al., *Managing for the Future: Organizational Behavior & Processes*, 1999.

²⁴ E. Schein, *Organizational Culture and Leadership*, 2nd ed., San Francisco, Jossey-Bass, 1992.

²⁵ P. Senge, “The Leader’s New Work: Building Learning Organizations”, *MIT Sloan Management Review*, 7 Fall 1990. J. Sterman, Executive Education System Dynamics course – the Beer Game.

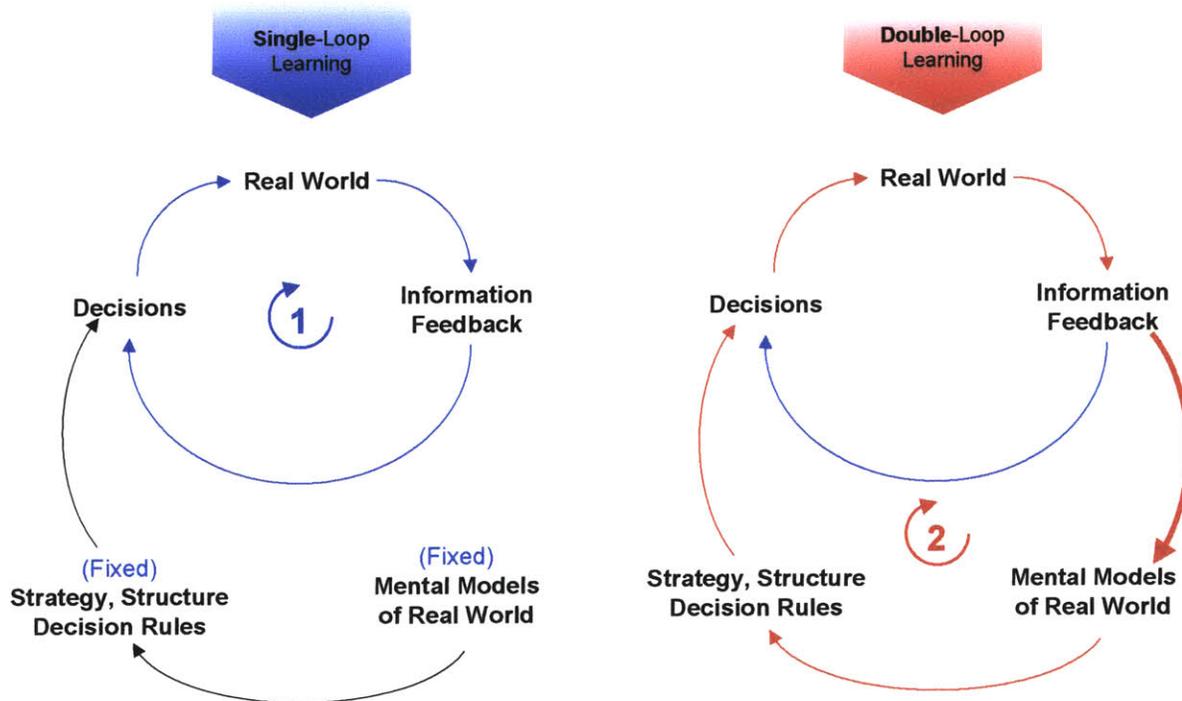
Figure 1.8: *Highest Leverage increases with Enterprise Depth*



In order to arrive at these deeper systemic architectural or structural truths, this thesis will attempt to move beyond *first-order* learning in which data, facts and analyses of the real world are fed-back into the cognitive process to update future managerial decisions. Instead, (as shown in figure 1.9 below) we hope to secure a deeper *second-order* learning in which knowledge about the real world is fed-back to challenge the mental models of our understanding about the underlying dynamic structure of the enterprises that we are responsible for designing and delivering.²⁶

²⁶ From Chris Argyris’ “double-loop learning”, in *Strategy, Change and Defensive Routines*, 1985.

Figure 1.9: “Double-Loop Learning” Required to Master Dynamic Complexity



Regarding appropriate methodologies to deal with dynamic complexity, researchers at MIT and elsewhere have been developing frameworks and/or “lenses” to begin to tackle this problem. For example, Professor Ancona has recently developed the notion of the “temporal lens” through which to study the evolution of organizations²⁷, and Professor Fine²⁸ is developing a lens through which to capture this dynamic complexity. He has identified a series of interacting dynamic forces which he represents as interlocking cogs in a mechanical metaphor as shown in figure 1.10 below. In a way, “Fine’s Five Cogs” aims to supplement other static models like “Porter’s Five Forces”²⁹ to gain a deeper understanding of the dynamic equilibrium of technologies, firms and value chains.

²⁷ Ancona et al., “Time: A New Research Lens”, *Academy of Management Review*, 2001.

²⁸ Professor Charles Fine, MIT Sloan School of Management course 15.795 “Technology and Industry Roadmapping”, Fall 2002. See also *PA Consulting Group’s* ‘planes analysis’, from “Towards Better Government”.

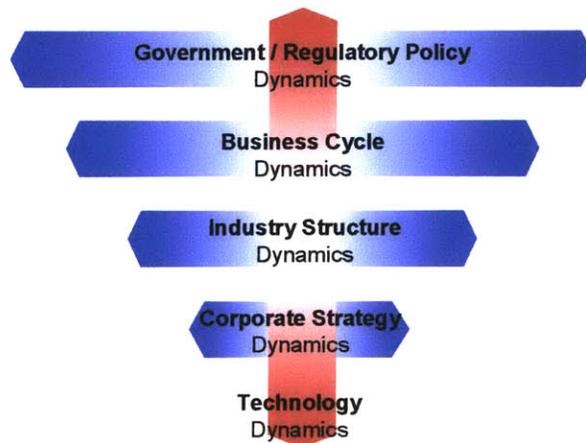
²⁹ From Michael E. Porter’s *Competitive Strategy*, 1980.

Figure 1.10: “Fine’s Five *dynamic* Forces”



One of the things that this thesis aims to accomplish is to recommend one (of many possible) underlying frameworks for the articulation of the interaction of the multiple dynamic forces acting on an enterprise. As shown in figure 1.11 below, one such representation of “Fine’s Five Forces” is to arrange them as a multi-tiered pendulum, with each mass corresponding to a different cog. This concept will be developed over the first half of the thesis.

Figure 1.11: Pendulum Representation of “Fine’s Five Forces”



Therefore, returning to Rehtin’s previous observation about the architect-engineer observing a stability-seeking pendulum embedded in various systems, I might add that the *enterprise* architect-engineers seeks stability, growth and interaction in his/her pendulum designs.

1.5 Architecting & Engineering

As Jay Forrester, the father of system dynamics pointed out in the preface to his seminal 1961 work, *Industrial Dynamics*: “The goal is ‘enterprise design’ to create more successful management policies and organizational structures.”³⁰ To that end, I will approach design from its two constituent parts: the art and science, or in applied terms, architecting and engineering. I begin with a discussion of architecting. As Rechtin noted: “Architecting, the planning and building of structures, is as old as human societies – and as modern as the exploration of the solar system.”³¹

In this work, I hope to bring this entire range of “architectural metaphors” (from buildings to the solar system) to bear on the design of the most complex enterprises – human organizations³². As metaphors are a technique to educate through similarity, I will also invoke other more generalizable heuristics or insights from system architecting.

As every system and organization has an architecture, or “structure” which largely defines what the system can and can’t do³³, I propose to develop a physics-based model that is rooted in the disciplines of structural dynamics and system dynamics. While this approach is based in the realm of “enterprise engineering”, (i.e. meeting requirements to ensure performance) its focus is on “enterprise architecture” (i.e. designing forms to follow function). From this methodology, I will attempt to derive a physics-based expression for an organization’s clockspeed and use it to predict the response of organizations to competition, etc. In addition, I will attempt to derive a physics-based definition of a “lean” enterprise and use it to develop a new organizing principle – “Organic Architecture”, giving examples of architect/engineers of physical enterprises like Frank Lloyd Wright as well as architects of human enterprises like Taiichi Ohno (see figure 1.12 below).

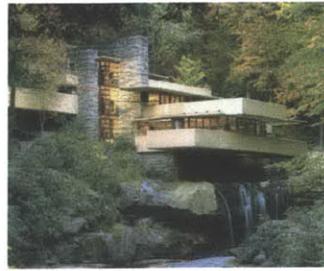
³⁰ *Industrial Dynamics*, Jay W. Forrester, Pegasus Press, 1961, pg. vii.

³¹ *Systems Architecting, Creating & Building Complex Systems*, Eberhardt Rechtin, 1991, preface.

³² In the use of metaphor, I take my cue from the Italian economist, Vilfredo Pareto, who was described by Mirowski (1989) pg. 221 as “the most ruthless proponent of the physical metaphor.”

³³ Rechtin, 2000, pg. v.

Figure 1.12: Artifacts of “Organic” Enterprise Architecture



Wright's *Falling Water*



Toyota's *Prius*

The approach will try to embrace both worlds: the incremental, analytical, optimization-based world of engineering, as well as the breakthrough, intuitive, systems thinking based world of architecting. As Rechtin notes: *“The world of an engineer is one of facts and figures, science and mathematics, and the world of an architect is one of ideas, insights, and inspiration.”*³⁴

Therefore, while this work will present a number of conventional engineering-based analyses, I hope that its value will lie equally in the architecting insights. As Rechtin notes: *“An insight is worth a thousand analyses,”*³⁵ or more directly: *“Architectural insights are worth far more than ill-structured engineering analyses.”*³⁶

With respect to what emphasis of problem solving (analysis or design) I will use in this thesis, I rely on Albert Einstein’s belief that “the best analysis is the simplest that will do the job”. The job in this case is to deliver compelling and powerful enterprise designs. A deep understanding of the underlying enterprise structure and its environment is obviously necessary – and acquiring such knowledge will undoubtedly require some sophisticated analysis techniques, both quantitative computational and qualitative heuristic. I will however try to maintain balance by having analysis as the complementary servant of design – in other words, one can always design oneself out of a difficult analysis problem.

Figure 1.13 below summarizes the differences between architecting and engineering in the overall process of enterprise design. In distinguishing between architecting and engineering, it is helpful to note

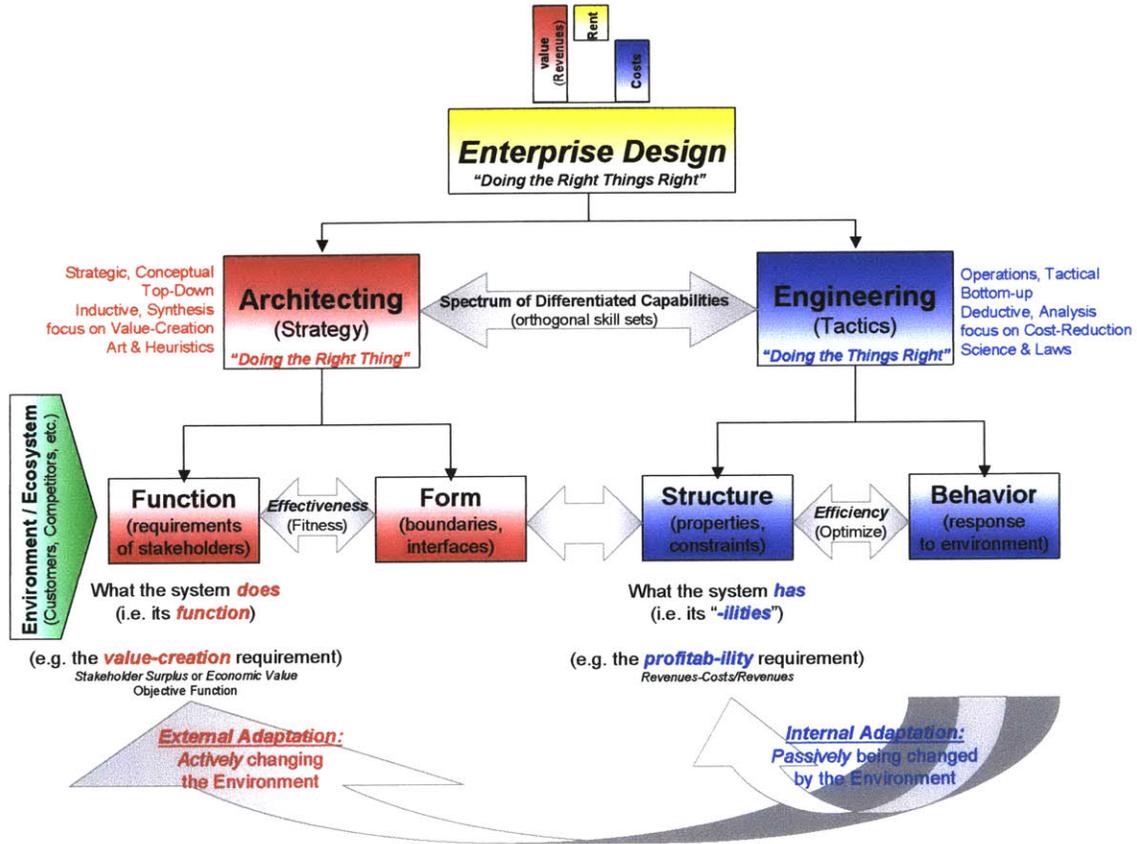
³⁴ Rechtin, 2000, pg. 139.

³⁵ Rechtin, 2000, pg. ix.

³⁶ Rechtin, 2000, pg. x.

that the architect is more than a generalist – she is a specialist in *simplifying* complexity³⁷, while the engineer is a specialist in *managing* complexity.

Figure 1.13: Enterprise Architecting & Engineering



1.6 Architectonics: The Science of Architecture

In order to achieve excellent enterprise designs, I draw inspiration from the surprisingly similar fields of economics and seismology. Thurow points out that economists like seismologists have a deep and reasonably reliable understanding of the mechanics of markets and plate tectonics respectively.³⁸ Both can predict with reasonable accuracy *what* will happen as well as *how*, *where* and *why* it will happen. Market bubbles and crashes, like earthquake faults and epicenters are understandable. The trouble for both professions is answering the crucial *when* – the problem of dynamics of timing. In the

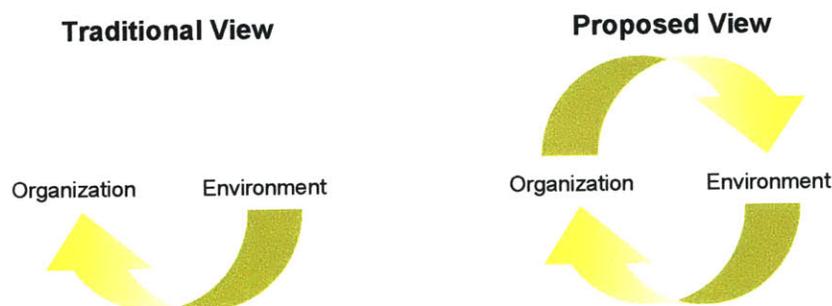
³⁷ Professor Ed Crawley, *Systems Architecting* class.

³⁸ Thurow, Lester, *Fortune Favors the Bold*, The MIT Press, 2003.

face of such uncertainty, enterprise designers who (knowingly or otherwise) build on top of active fault lines will either suffer economic collapse or serious damage to their enterprise if precautions are not taken. But the conventional enterprise design options are often not economically viable. Those few who do take precautions often employ the expensive yet ineffective strategy of “fail-safe” designs. That is, “I don’t know when or how big the (economic) earthquake will be, so I will make sure that my enterprise won’t fail no matter what.”

Skillful enterprise design for dynamic complexity is not interested in answering the questions of “when” or “how big” will the next economic earthquake be? Instead, the objective is inverted – that is, it takes as a given that my enterprise is in a volatile environment and that it will “fail”. However, I want it to “safe-fail”,³⁹ that is in the way that I the designer intend it to. I will define how the environment defines my enterprise. This safe-fail design (a.k.a. “damage-tolerant design”) can be highly robust and economical, and it takes significant enterprise leadership to pull it off. By the end of this thesis, I will demonstrate however that this is precisely what world-class enterprises do. In the process, this thesis aims to present some counter-intuitive insights that demonstrate that traditionally accepted organizational theories⁴⁰ do not capture exceptionally high-performing enterprises. In these enterprises, organizational form does not necessarily follow the environment, but rather *enterprise leadership* defines how it allows the environment to shape the organization (see figure 1.14 below).

Figure 1.14: Enterprise Leadership

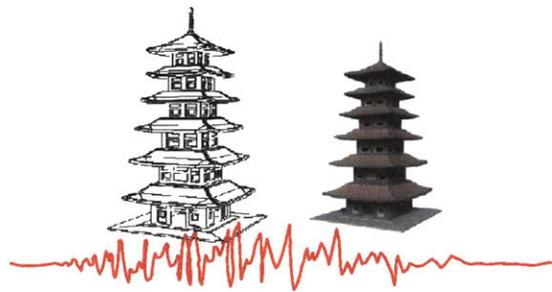


³⁹ Linstone, H.A., *Decision Making for Technology Executives: Using Multiple Perspectives to Improve Performance*, Artech House Boston, 1999.

⁴⁰ From “contingency theory”. Examples include: Child, J. (1973), Galbraith, J. (1973), Lawrence, P., and Lorsch, J. (1967) and Thompson, J. (1967), and Steiner G. (1979).

As an international structural designer of high-rise buildings and an earthquake engineering specialist, I was interested to note first-hand in the 1995 Great Hanshin (Kobe, Japan) earthquake that although 15 seconds of strong ground motion caused direct and indirect economic losses exceeding \$200 billion, some of the only buildings standing amidst stretches of destruction were the ancient Japanese pagodas (see figure 1.15 below).

Figure 1.15: “Safe-Fail” “Damage-Tolerant” Enterprises

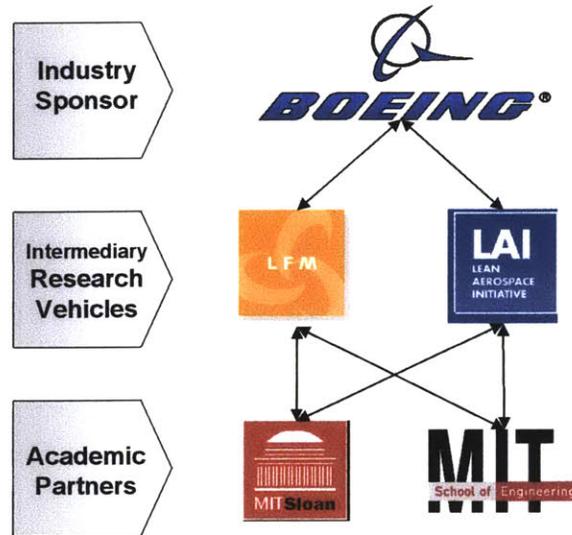


In fact these structures or “physical enterprises” have endured the relentless attack of these devastating earthquakes for over 2,000 years, while “modern” buildings suffer excessive damage or collapse. I pose the question, “what did the ancient architects and engineers know that we have somehow forgotten today?” I believe that the answer lies in understanding the physics of the physical enterprise and its environment. In fact, in chapter 9, I shall attempt to uncover the mystery behind the Japanese pagodas and offer suggestions as to how lessons can be extended to the design of human enterprises.

1.7 Research Methodologies

But what methodologies can be applied to solve such a complex problem? For this I turned to the vast array of knowledge that permeates an institute like MIT, academic-industry partnership programs like the *Leaders for Manufacturing* program and the industry-consortium, *Lean Aerospace Initiative*, where bi-lingual management and engineering principles are cross-fertilized. The structure of this academic collaboration is shown in figure 1.16 below.

Figure 1.16: Structure of Research Partnership



Both the LFM and LAI programs are part of the *Engineering Systems Division (ESD)*, an innovative new research and education vision at MIT that aspires to “be a leader in understanding, modeling, predicting and affecting the structure and behavior of technologically enabled complex systems”.⁴¹ One of the ESD’s seminal questions is, “Can enterprises be predictively architected?”⁴² This challenge lies at the core of my thesis work that I will attempt to resolve by studying the system at the artifact, enterprise and societal levels.

I propose therefore to use the latest thinking from Charlie Fine on Industry Evolution/Dynamics and Deborah Nightingale on Architecting Lean Enterprises. This project takes the work of Fine in *Clockspeed*⁴³ and the work of Nightingale and her colleagues in *Lean Enterprise Value*⁴⁴ as points of departure and inspiration as shown in figure 1.17 below.

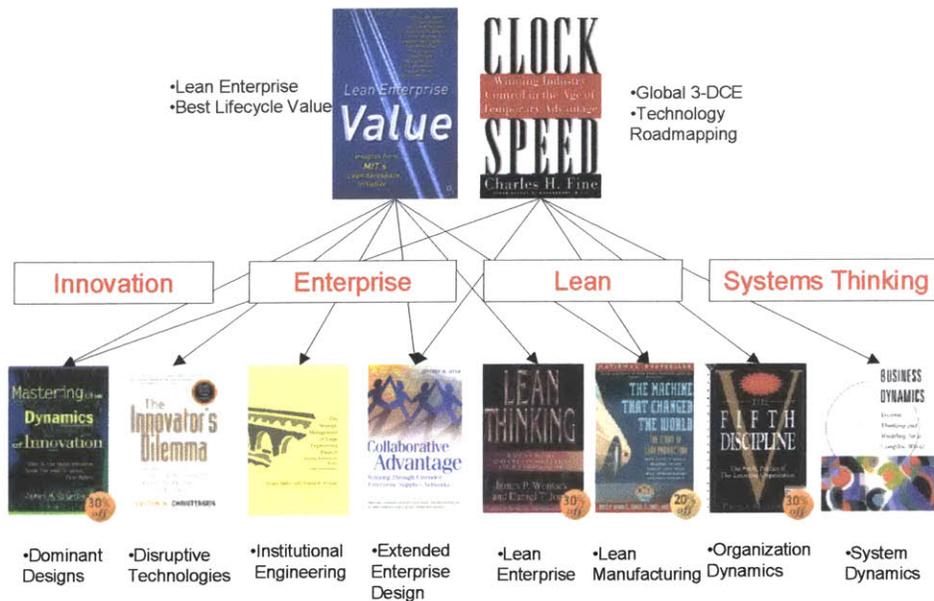
⁴¹ “ESD Message”, Dan Hastings, June 4, 2003.

⁴² Ibid.

⁴³ *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*, Charles H. Fine, 1998.

⁴⁴ *Lean Enterprise Value*, Earl Murman, Deborah Nightingale, et al., Palgrave, 2002.

Figure 1.17: Basis of the Knowledge Pyramid



In short, this work attempts begin where Fine’s challenges left off in the epilogue to *Clockspeed*, namely that “social systems and public institutions have clockspeeds too.”⁴⁵ In addition, I attempt to pick up Fine’s challenge in the appendix to *Clockspeed* – namely, that “the measurement of clockspeed is fraught with complexity at all levels...but (my work) is, I hope, sufficiently suggestive that it will stimulate such research.”⁴⁶

As shown in figure 1.18 below, I use methodologies from a management science perspective in the research and teachings of Professor Charlie Fine and his colleagues at the Sloan School of Management. These include the notions of the “Bullwhip”^{47,48}, “Clockspeed”⁴⁹, and the “Five Cogs”⁵⁰. In addition, I will supplement these with the research and teachings that are borne out of the LFM joint

⁴⁵ *Clockspeed*, pg. 225.

⁴⁶ *Clockspeed*, pgs. 237-238.

⁴⁷ *Clockspeed*, pg. 89.

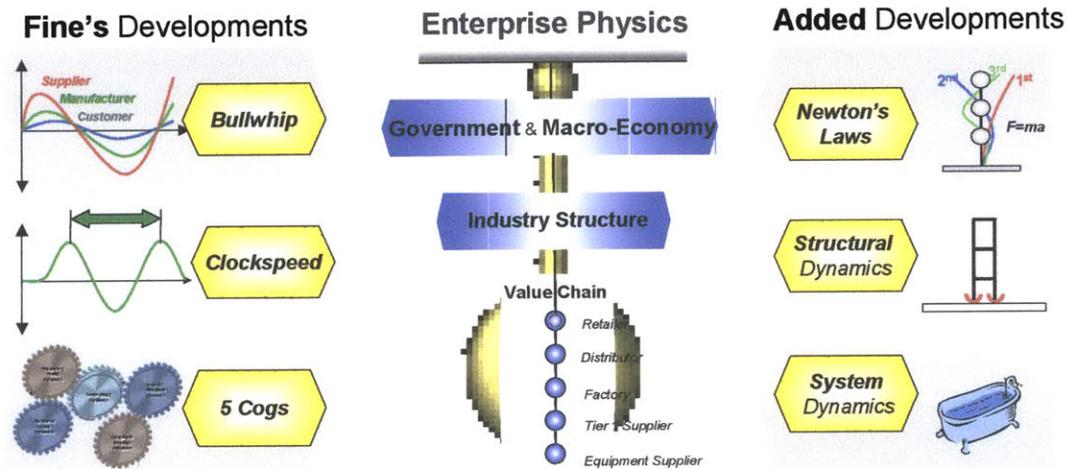
⁴⁸ “Industrial Dynamics: A Major Breakthrough for Decision Makers”, *Harvard Business Review*, 36 No. 4, 1958.

⁴⁹ *Clockspeed*, pg. 6-7.

⁵⁰ Professor Charles Fine, MIT Sloan School of Management course 15.795 “Technology and Industry Roadmapping”, Fall 2002. See also *PA Consulting Group’s* ‘planes analysis’, from “Towards Better Government”.

degree program’s engineering disciplines: Structural Dynamics⁵¹ and Newton’s “Laws of Motion”⁵², and the management discipline of System Dynamics.^{53,54}

Figure 1.18: Enterprises “Re-Fined”



In addition, this work was inspired by Professor Jay Forrester’s call for “enterprise design... to influence growth and stability”⁵⁵ and John Sterman’s challenges to use system dynamics to understand the structure and behavior of dynamic socio-technical systems. As Forrester’s original work could be described as building a “techno-social” *management systems* bridge from the deep academic knowledge of engineering science to management science, this work attempts to close the feedback loop via building another bridge of “socio-technical” *engineering systems* from the mature academic knowledge of management science back toward complex technical domains as shown in figure 1.19 below.

⁵¹ *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, Anil K. Chopra, 1993.

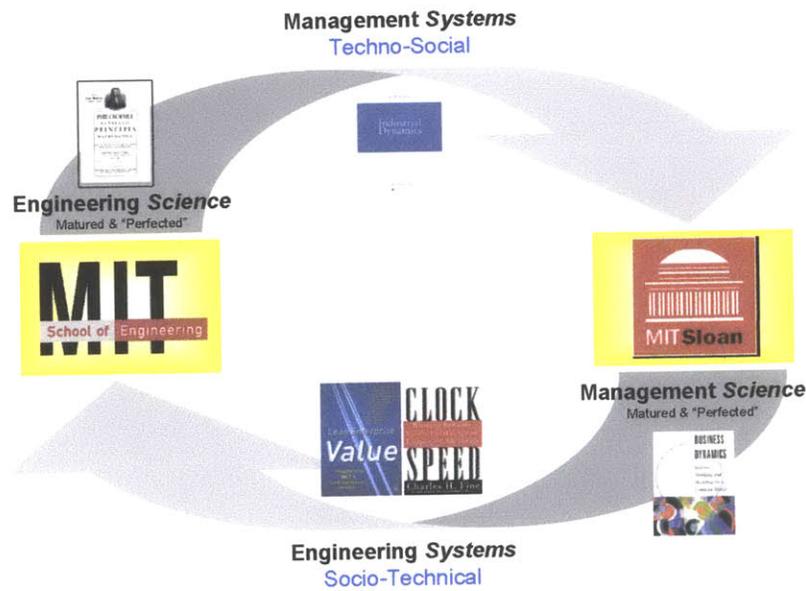
⁵² *Principia Mathematica*, Isaac Newton, 1687.

⁵³ *Industrial Dynamics*, Jay W. Forrester, Pegasus Communications, 1961.

⁵⁴ Sterman, John D.; *Business Dynamics: Systems Thinking and Modeling for a Complex World*, McGraw-Hill, 2001.

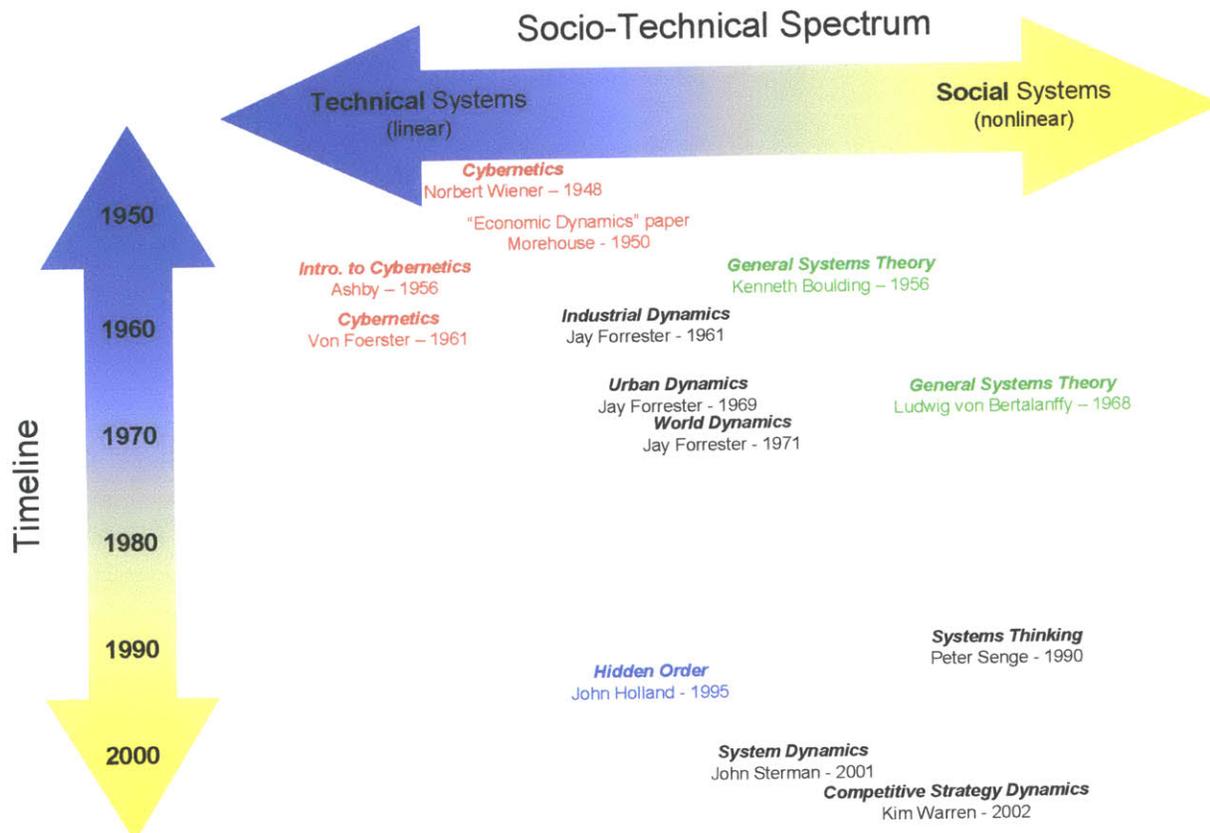
⁵⁵ *Industrial Dynamics*, Jay W. Forrester, Pegasus Communications, 1961, pg. vii.

Figure 1.19: From Techno-Social *Management Systems* to Socio-Technical *Engineering Systems*



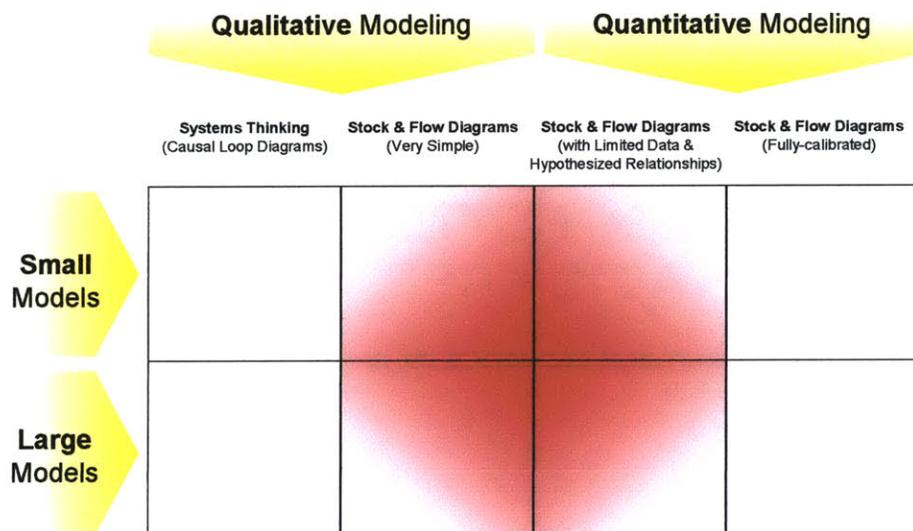
The academic / scientific systems landscape spans more than 50 years and covers the spectrum from Techno-Social systems to Socio-Technical systems as shown in figure 1.20 below.

Figure 1.20: Genealogy of Socio-Technical Systems Theory



Regarding the use of system dynamics, there is a spectrum of complexity that one could introduce as shown in figure 1.21 below. Lyneis notes that system dynamics could range from “systems thinking” on the one hand to small policy-based models, to large detailed calibrated models on the other extreme⁵⁶. In the aforementioned spirit of insight over analysis, I intend this work to focus on the space from the systems thinking to the small policy-based models, with brief mention, summary and extended application of other researcher’s large detailed calibrated models.

Figure 1.21: Range of Dynamic Modeling Approaches for System Dynamics



1.8 The Dynamics of Structure, Conduct and Performance

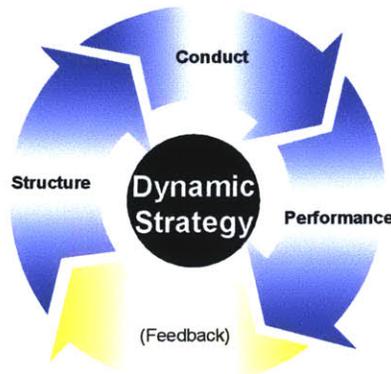
These dynamics-based methodologies allow us to rethink the classical performance paradigm in industrial economics, namely the Structure-Conduct-Performance (SCP) paradigm⁵⁷. Unlike Porter’s Five Forces methodology⁵⁸, which is a static analysis of the structure of an industry, system dynamics explicitly considers feedback richness of the dynamic interactions of all three components (structure, conduct and performance) together as shown in figure 1.22 below.

⁵⁶ “System Dynamics in Consulting: the PA Perspective”, Jim Lyneis presentation to MIT 15.874, May 8, 2003.

⁵⁷ *Competitive Strategy Dynamics*, Kim Warren, John Wiley Press, 2003, pg. 12.

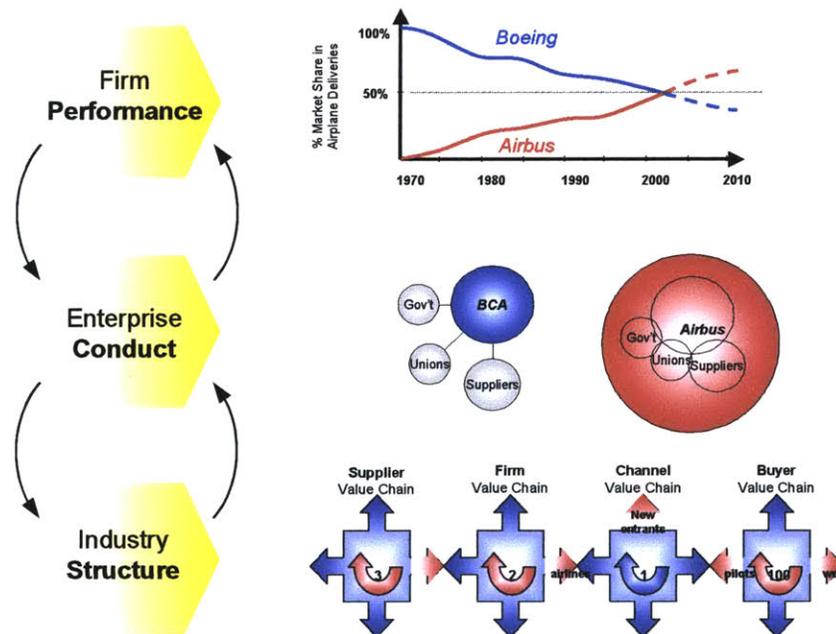
⁵⁸ *Competitive Strategy*, Michael Porter, the Free Press, 1980.

Figure 1.22: “Structure-Conduct-Performance” Feedback Dynamics



Beyond the use of the SCP method, I propose to evaluate the strategic options streaming dynamically from the “structure” of the industry as well as from the “conduct” of the firm that is taking a “resources-based view”. However, I wish to look at resources not statically but dynamically as various researchers have proposed.^{59,60} This attempt in the field of strategic management to tie together structure, conduct and performance, was also tackled by system dynamicists to understand the explicit links between structure and behavior⁶¹ as shown in figure 1.23 below.

Figure 1.23: “Structure-Conduct-Performance” Feedback Dynamics for Airplane Manufacture



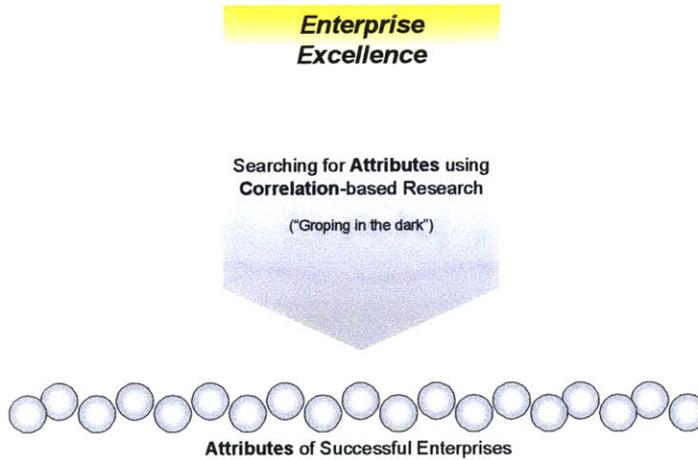
⁵⁹ *Clockspeed*, Charles Fine.

⁶⁰ *Competitive Strategy Dynamics*, Kim Warren, 2002.

⁶¹ “Principles on the Relationship between Structure and Behavior of Dynamic Systems”, Alan K. Graham, MIT PhD Thesis, 1977.

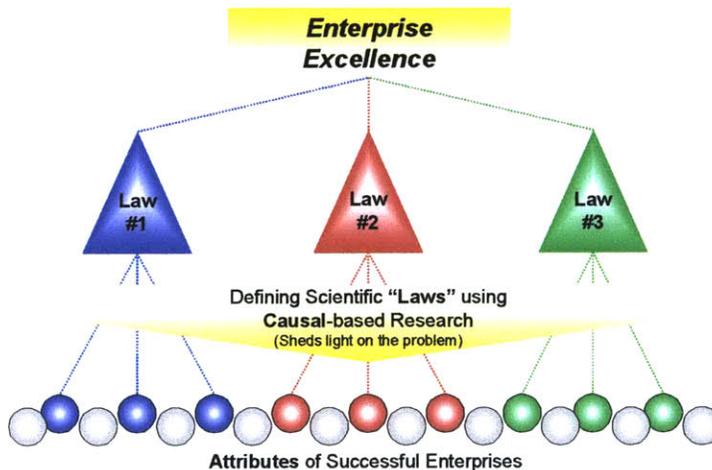
In the search for deeper understanding in the realm of business and management I attempt to look beyond the correlation-based view linking business attributes with business performance. Under this methodology, success is not guaranteed, and searching for truths can sometimes be like groping in the dark (see figure 1.24 below).

Figure 1.24: Current Research Environment



Instead, I propose to establish causality-based research searching for “laws” of business to provide heuristics and insights on what one should look for and what one should expect to find, as shown in figure 1.25 below.)

Figure 1.25: Proposed Research Methodology

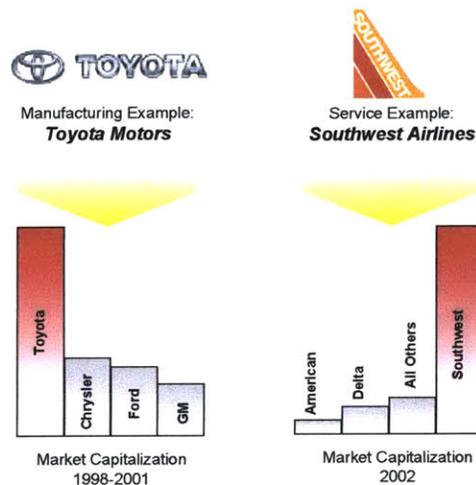


While this approach is not new, it is a path not often traveled. Mirowski quotes economist Paul Samuelson, who noted that Irving Fisher’s 1892 doctoral thesis is “the best of all doctoral dissertations in economics” as it was the first (and last) published work to explore the physical metaphor in great detail⁶². Although this approach is infrequently used, some of the more innovative insights have come from the attempt to view the world through the lenses of existing “scientific” fields^{63,64}.

In fact recently, researchers have begun to use the physical laws of “turbulence” (arising from high velocity fluid flow) to understand turbulence in the business world. Robertson writes, “If we view the business world to be complicated, it is inappropriate to consider models developed under paradigms of equilibrium, stability, and linearity to produce an analysis of a turbulent environment. Just as non-linear mathematics is required when studying turbulence within engineering, we too must adopt models and tools that capture the non-linearity of a firm’s environment.”⁶⁵

With this quest for causality, I will attempt to uncover the often counter-intuitive architectures behind world-class enterprises like *Toyota* (in the manufacturing sector) and *Southwest Airlines* (in the service sector), whose market performance is truly extraordinary (see figure 1.26 below.)

Figure 1.26: Architecture drives Extraordinary Performance



⁶² *More Heat than Light: Economics as Social Physics, Physics as Nature’s Economics*, Philip Mirowski, Cambridge University Press, 1989, pg. 222.

⁶³ *Clockspeed*, Charles Fine, 1998.

⁶⁴ *The Natural Laws of Business*, Richard Koch, Currency and Doubleday, 2000.

⁶⁵ Robertson, Duncan A., “Agent-Based Models of a Banking Network as an Example of a Turbulent Environment: The Deliberate vs. Emergent Strategy Debate”, *Managing the Complex IV*; Naples, Italy; December 2002, pg. 8.

1.9 Case Study: *Boeing* and Commercial Airplanes

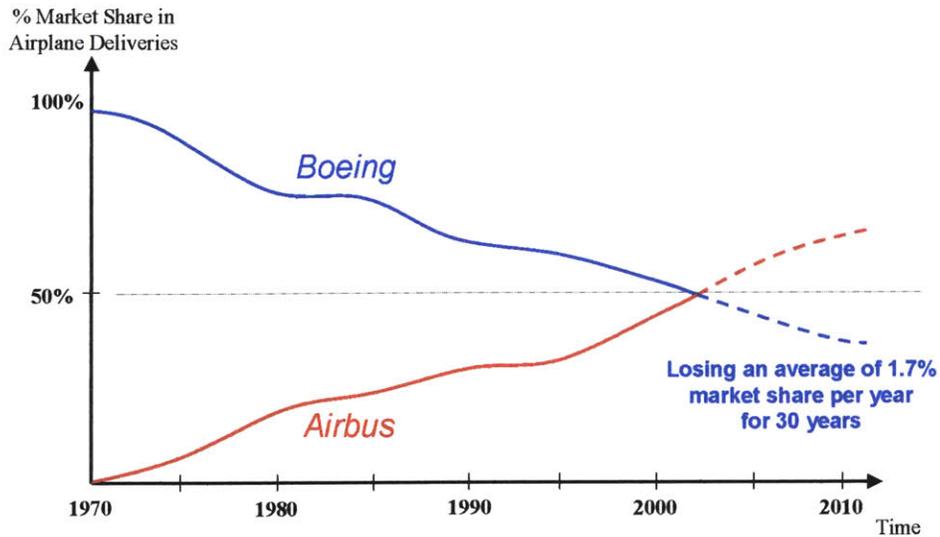
While the primary purpose of this work is to attempt to develop new insights in enterprise architecting via “laws of physics”, a number of varied examples will be used throughout to anchor the development of these insights. However, this thesis will focus on one particularly complex enterprise architecture: the commercial aviation industry.

The commercial aviation industry is currently a duopoly in commercial airplane design and manufacture, with two global competitors: *The Boeing Company* and *Airbus Industrie*. This thesis will therefore compare and contrast the architectures of both enterprises in order to discover and generalize the successful architectures that give competitive advantage in complex enterprises. While approximately equal time will be devoted to the study of each enterprise, the primary client and audience is *The Boeing Company*. One could ask the obvious question, “Why would *Boeing*, the world’s premier aerospace company, at the top of its game and named one of the world’s “visionary companies” in James Collins’ recent multi-year research project⁶⁶ bother to be interested evaluating its current competitive position? The answer appears to lie in the company’s desire to move from good to great or even great to greater. This work therefore is borne out of *Boeing’s* fabled “Working Together” mandate to “celebrate our problems...get them out in the open so that we can work on them”. *Boeing* recognizes that today’s competitor has a different architecture from yesterday’s competitors, and that staying on top requires a continual re-evaluation of the enterprise competencies needed in a new competitive environment. *Boeing* appears to want to move forward with great pride in its past and great aspirations for its future.

This thesis will explore the underlying laws and dynamics that are causing the dynamic behavior (or “reference mode”) shown in figure 1.27 below.

⁶⁶ *Built To Last*, James C. Collins and Jerry I. Porras, Harper Business Essentials, 1994.

Figure 1.27: Boeing – Airbus Competitive Dynamics



In order to frame this question and understand the possible context for its resolution, I take as a point of departure *Boeing's Vision 2016* which defines goals and objectives for its enterprise which encompass all three business processes⁶⁷: Customer Relationship Management, Product Innovation and Infrastructure Management (see figure 1.28 below).

Figure 1.28: Boeing's Vision 2016

V · I · S · I · O · N

People working together as a global enterprise for aerospace leadership
Boeing - Forever New Frontiers

Core Competencies

- Detailed Customer Knowledge and Focus**
We will seek to understand, anticipate, and be responsive to our customers' needs.
- Large-Scale System Integration**
We will continuously develop, advance and protect the technical excellence that allows us to integrate effectively the systems we design and produce.
- Lean Enterprise**
Our entire enterprise will be a Lean operation, characterized by the efficient use of assets, high inventory turns, excellent supplier management, short cycle times, high quality and low transaction costs.

Customer Relationship Management
 Product Innovation
 Infrastructure Management

2016

⁶⁷ From Hagel III, John and Singer Marc, "Unbundling the Corporation", *Harvard Business Review*, August 2000.

In developing the research topic with *Boeing* that led to this work, there was a concerted effort to focus on those “thought leadership” pieces that were both unique to *Boeing’s* partnership with *MIT*, and more importantly would reveal a source of competitive advantage that *Airbus* had leveraged and is using to deliver the market share dominance that is shown above. As shown in figure 1.29 below, the field of System Dynamics, invented at *MIT* and used extensively by *Boeing’s* competitor *Airbus*⁶⁸, airline customers like *Lufthansa*⁶⁹, and regulatory bodies like the *FAA’s National Airspace System* model⁷⁰ forms one of the core methodologies that this research has intended to bring to *Boeing* and demonstrate its potential value.

Figure 1.29: Use of System Dynamics in the Commercial Aerospace Industry



1.10 Scope of Work

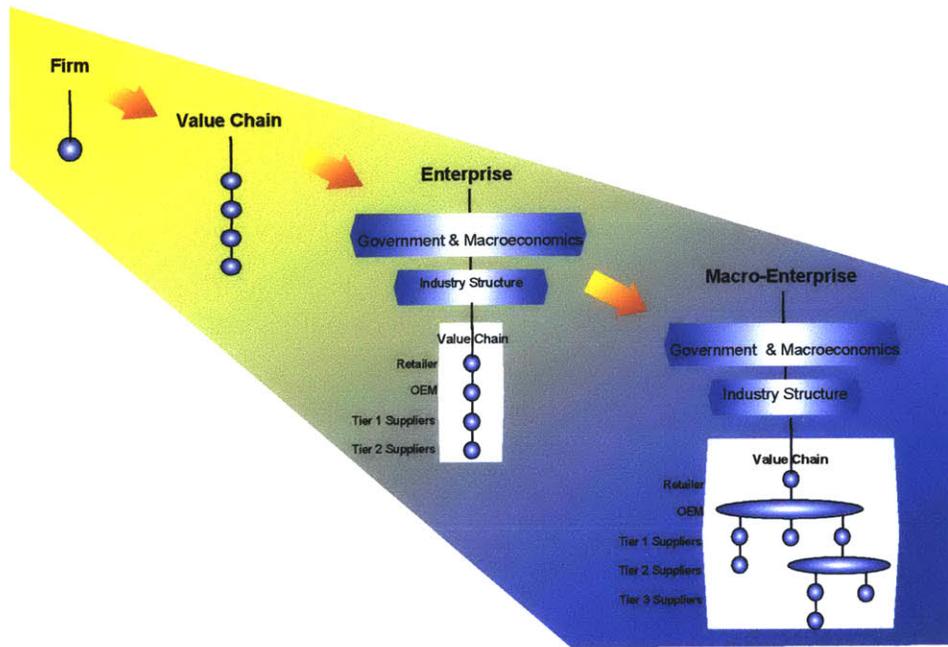
With the methodologies in place, I hope to begin to explore and understand the range of dynamic enterprises ranging from the firm, to a value chain, to an industry, to a macro-economy (as shown in figure 1.30 below). Each enterprise being a simple “superposition” of pendulums allowing us to use simple “laws” for extremely complex “architectural” forms.

⁶⁸ Weil, Henry Birdseye, “Commoditization of Technology-Based Products and Services: A Generic Model of Market Dynamics”, 11 March 1996.

⁶⁹ Liehr, Martin; Grossler, Andreas; Klein, Martin; Milling, Peter M.; “Cycles in the Sky: Understanding and Managing Business Cycles in the Airline Market”, *System Dynamics Review*, Volume 17, Number 4, Winter 2001, pg. 311-332.

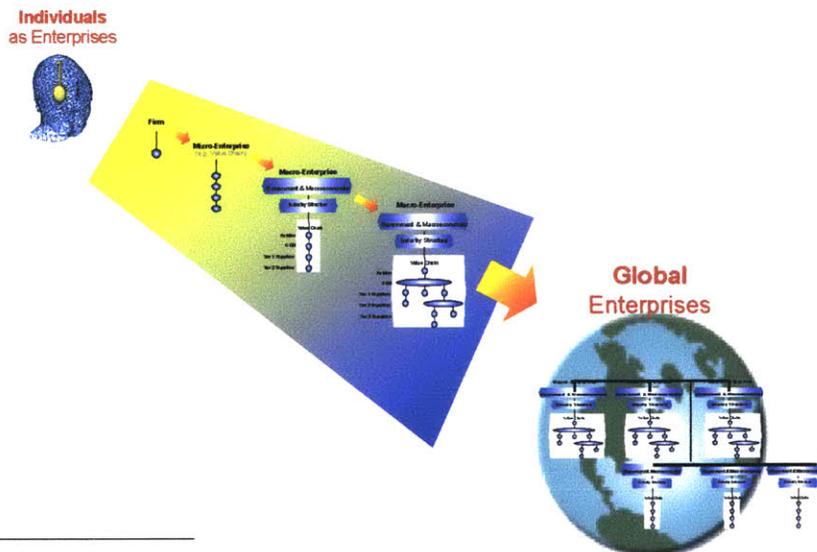
⁷⁰ *Federal Aviation Administration* website and *Ventana Systems* website.

Figure 1.30: Range of Dynamic Enterprises



Finally, (as shown in figure 1.31 below) I will propose that the principles of enterprise physics can be used to provide a “microscope” to view the dynamics of small-scale complex “enterprises” like individual humans as proposed by Fine⁷¹. In addition these same principles can be used as well as to provide a “telescope” to view the dynamics large-scale complex “enterprises” like global trade.

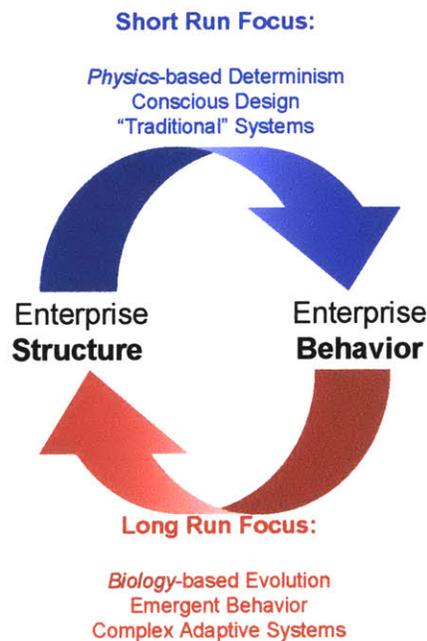
Figure 1.31: Extending the Range of Enterprises



⁷¹ *Clockspeed*, Charles Fine, pg. 225.

Previously, the goals of systems or enterprises were introduced as being stability, growth and interaction. I will focus in the short term on describing how enterprises can secure the first two goals of stability and growth before they can achieve the higher goals of interaction or emergence. As shown in figure 1.32 below, this thesis therefore takes physics as the point of departure, demonstrating the link between enterprise structure and its behavior. I will then move into the realm of biology and theories of evolutionary or emergent behavior of complex adaptive systems, which will demonstrate the way in which enterprise behaviors can adapt and evolve over time to shape new enterprise structures.

Figure 1.32: Enterprise Physics and Biology



1.11 Layout of Report

The structure of this report is laid out in two parts covering essentially the theory and applications, i.e. the science and art, or the engineering and architecting of enterprises.

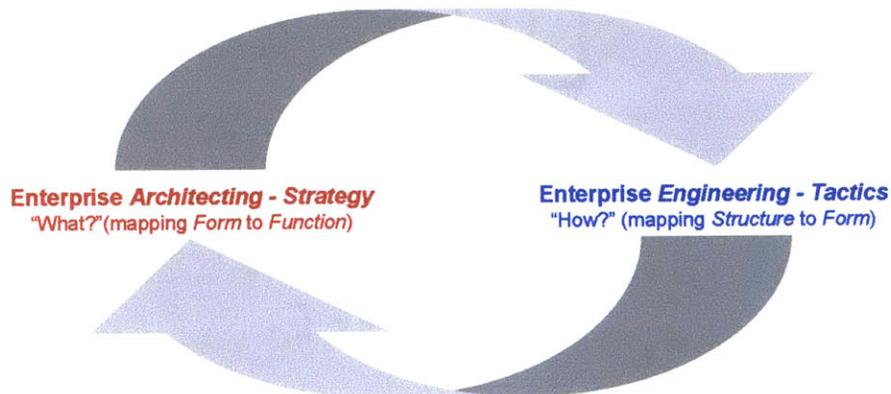
Part I will cover the basic principles of *enterprise engineering* which are based on the “laws of enterprise physics”. This is the first step in mastering “dynamic complexity” – namely the quantification of the *dynamic* behavior of enterprises or the exploration of the *temporal* distance or disconnection of cause and effect. Engineering can be thought of as mapping the enterprise properties and structure to its

form, and in management terms it is similar to defining the enterprise *tactics* – that is, the *how*. Engineering establishes the secondary enterprise requirements, sometimes known as the “ilities” (e.g. stability and flexibility).⁷²

Part II will focus on the principles of *enterprise architecting* which are rooted in the “heuristics of enterprise design”. This is the second part of mastering “dynamic complexity” – namely the quantification of the *complexity* embedded in the enterprise or the exploration of the *spatial* distance or disconnection of cause and effect. Architecting can be thought of as mapping the enterprise form to its function, and in management terms it is similar to defining the enterprise *strategy* – that is, the *what*. Architecting establishes the primary enterprise requirements, like the creation of value or profitability.

Regarding the design of this report, I would like to note that this work takes a “spiral development” approach to defining enterprise design as shown in figure 1.33 below. That is, the *architectural forms* define the *engineering structures* which again feedback to iterate on the *architectural forms*, etc. In this way, one could conceive of a report layout starting either with enterprise architecting or enterprise engineering. I have chosen however to begin with the *how*, (i.e. the enterprise engineering) in order that the reader is exposed to the tactical mechanics of how to achieve an elegant architectural design. In a sense, I have saved the “fun” for the end after the reader has developed a sense of appreciation for the journey towards high-performance, elegant architectural forms.

Figure 1.33: Spiral Development



⁷² ESD Symposium Committee, “ESD Symposium Committee Overview”, *Proceedings of the ESD Internal Symposium*, May 29-30, 2002, Massachusetts Institute of Technology, Engineering Systems Division, pp. 1-30.

Please note therefore that Part I covers some of the more technical aspects of this work. While attempts have been made to make these parts as readable as possible, some general understanding of engineering and systems is assumed. Examples and heuristics then resume in Part II, and it is hoped that the reader will still gain insights from these even with a cursory skimming of Part I.

Finally, although care is taken to use vocabulary common to general managers, there are some technical terms used with definitions (including synonyms and antonyms) given in the glossary in Appendix A.

Chapter 2: “Physics 101”

In this chapter, we will define the three dynamic properties which define the dynamic structure of enterprises, both physical and organizational. We will see that these three properties have both “bad” and “good” qualities, depending on what the enterprise designer wants to do with them. For example, one property, *inertia* can be useful in maturing, capital-intensive environments where “massive” enterprises have competitive advantage. However in new and growing markets with high uncertainty, *inertia* or resistance to change can be a competitive disadvantage.

Also in this chapter, from these dynamic properties we will define an important dynamic quantity of an enterprise called its *clockspeed* or speed of movement. Again, we will see that this derived property can have both “bad” and “good” qualities, depending on what the enterprise designer’s strategy is. For example, *Dell’s* inherently fast clockspeed allows it to attack growth via rapid customer order-to-fulfillment cycle. However, *Airbus’* relatively slow clockspeed may be due to its more *massive* and *damped* enterprise which allows it slow, steady growth in an international socio-political-technical market. Finally, I will argue in chapter 9 that world-class enterprises understand and manipulate their enterprise dynamic properties for competitive advantage. We begin with a brief refresher of high-school “Physics 101”, and the dynamics of a simple pendulum.⁷³

2.1 The Generic Structure of the Pendulum

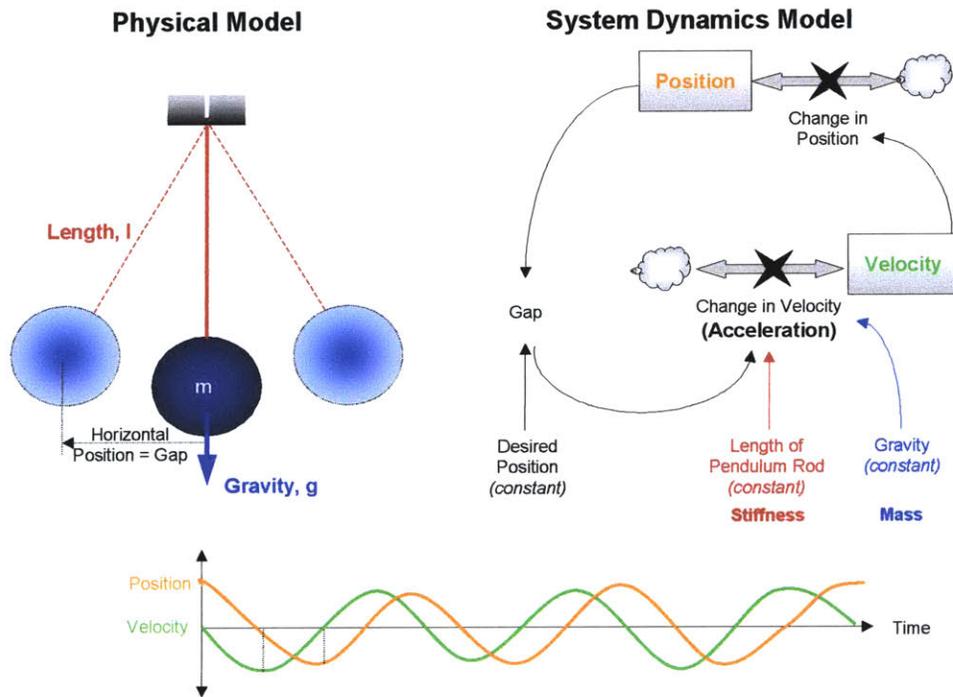
The physics of a pendulum is one of the simplest dynamic systems. As seen in figure 2.1 below, a string⁷⁴ supporting a mass represents the physical model of the pendulum. When the mass is displaced it oscillates back and forth, with the position and velocity of the mass “trading-off”, that is when the position is maximum, the velocity is zero, and when the position is zero, the velocity is at its maximum. In fact, the velocity is simply the first derivative of the displacement with respect to time. This

⁷³ Other equivalent physical metaphors could be used ranging from hydro-electro-mechanical systems. See Appendix B for a brief summary of these equivalent systems.

⁷⁴ Note that the “string” could synonymously be thought of as a rope, chord, cable, chain or even rigid rod without the loss of metaphorical accuracy.

relationship leads to “out-of-phase” response that can be seen at the bottom of figure 2.1, where the position curve leads the velocity curve.

Figure 2.1: Generic Structures: “Oscillating Pendulum”



From a system dynamics formulation⁷⁵, position and velocity are the two “state variables” which describe the system. Each feeds back information to the other in a “balancing loop” with the “goal” being the vertical at-rest position. The pendulum is a 2nd order (two stock) system balancing loop system with delays, which cause the oscillation. The embedded “delays” in the system that cause the oscillation are the length of the string and the magnitude of the gravitational field. Therefore the equation of natural period of vibration is a function of both delays. If you make the string longer, or put the pendulum on the moon (where the gravitational field is smaller), the natural period intuitively should slow down. Sparring the reader the mathematical derivation⁷⁶, the natural period (T_n) of vibration of a pendulum is simply:

$$T_n = 2\pi \sqrt{\text{length of string/gravity}}$$

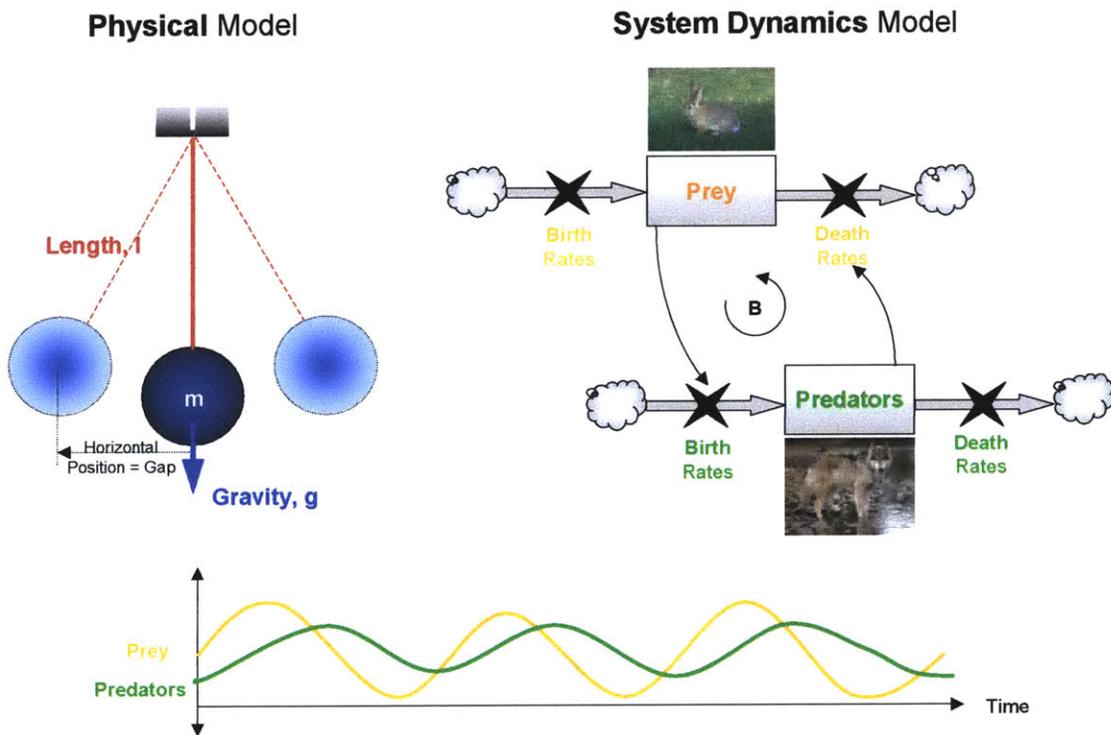
⁷⁵ A brief introduction to System Dynamics is given in Appendix C.

⁷⁶ *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, Anil K. Chopra, 1993.

We could interpret this period of vibration as it applies to organizations as Fine’s “clockspeed”, and the path that the dynamic enterprise charts over time (shown in green and yellow in figure 2.1) as the “double helix”.⁷⁷ In the Fine’s double helix (which will be discussed in more detail later, an enterprise oscillates back and forth between two “architectural” states, namely integral product and supply chain architectures or modular product and supply chain architectures.

Another example of this pendulum structure leading to oscillatory behavior is the classic “Predator-Prey” model. The behavior of this ecosystem can be characterized by its two state variables or populations (e.g. the wolf and rabbit populations). The wolves control the death rate of the rabbits and the rabbits control the net birth rate of the wolves, in a balancing loop with a delay.⁷⁸ The resulting behavior is oscillation as shown below in figure 2.2.

Figure 2.2: Generic Structures: Predator- Prey

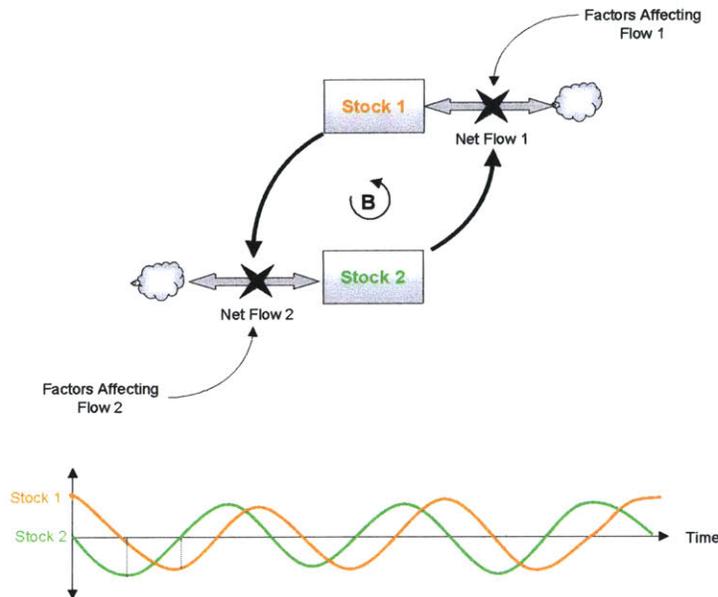


⁷⁷ *Clockspeed*, Charles Fine, 1998.

⁷⁸ Note: the classic predator-prey dynamic which has an oscillatory dynamic with a phase shift of one-quarter cycle, assumes that evolutionary change is slow relative to ecological dynamics. Recent research in evolutionary biology however indicates that in some populations, rapid evolution can impact the dynamics of the system by elongating the period of oscillation and shifting the phase between the predator and prey to one-half cycle. See Turchin 2003 for example. Sterman notes that this may have interesting implications for organizational dynamics.

In fact, the underlying structure of a pendulum is so basic and fundamental that one can find it in a variety of social and technical systems. It is therefore known alternatively as a “System Archetype”⁷⁹ or “Generic Structure”⁸⁰ or “Strategic Architecture”⁸¹ and in fact the general form of this structure is shown in figure 2.3 below.

Figure 2.3: Generic Structures: 2nd Order Balancing Loop with Delays



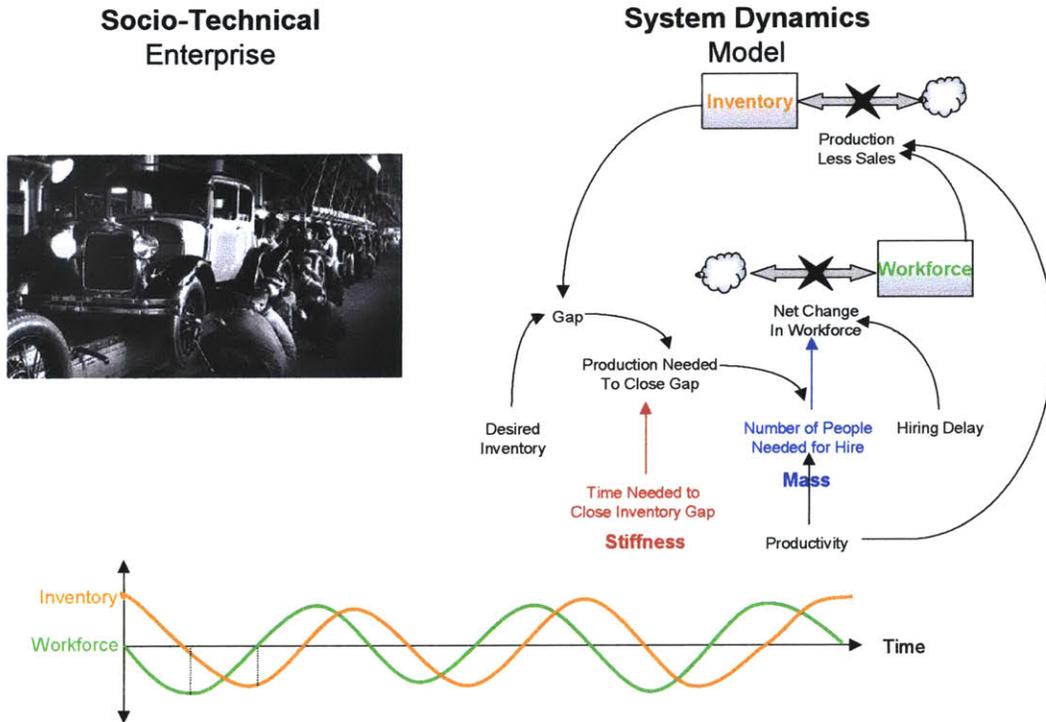
From this observation, one can now look for more examples of this “Generic Structure”. One of the simplest business production models is of the classic, “Input-Output” or “Workforce-Inventory” relationship. It is interesting to note in figure 2.4 below, that the structure and dynamics of this system is identical to the simple pendulum with Input equating to Workforce (or Velocity) and Output equating to Inventory (or Position). In this case, the delays that cause oscillation are actually the hiring delay (like the pendulum length) and the time needed to close the inventory gap between desired and real.

⁷⁹ *The Fifth Discipline: The Art & Practice of the Learning Organization*, Peter M. Senge, 1990, pg. 94.

⁸⁰ “Generic Structures in Oscillating Systems I, Celeste Chung, MIT Education in System Dynamics Project, 1994.

⁸¹ *Competitive Strategy Dynamics*, Kim Warren, John Wiley & Sons, 2002, pg. 57-58 and 89-90.

Figure 2.4: Generic Structures: “Workforce-Inventory Oscillation”



In fact, from this simple model of production system as pendulum analogy, one can draw some interesting counter-intuitive conclusions. As shown in figure 2.5 below, if a company produces a steady-state output of 100 widgets/week, it will have stable growing cumulative profits (red line). However, once there is an order rate change, the system starts to oscillate as is shown in the blue line for a 50% increase in sales. However, when one includes the costs of hiring & firing in the system equation (green line), it is noted that selling 50% more product, can result in making less money!⁸²

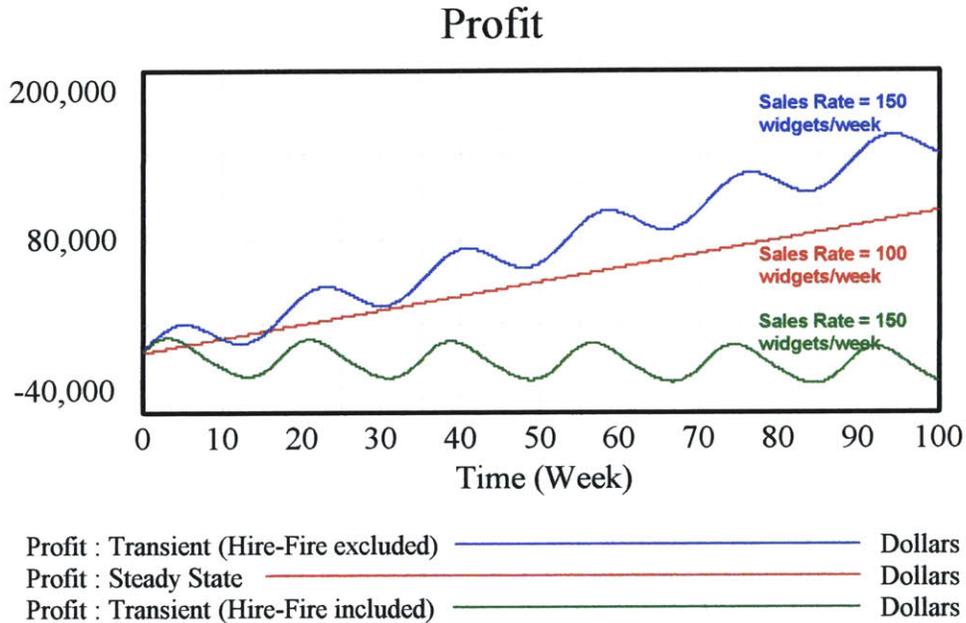
It is important to note that this simple two-stock model is intended to generate insights, not predict or forecast actual behavior. A more detailed treatment of the finances of enterprises under dynamic demand is given by Lyneis⁸³, in which he demonstrates that profitability can diminish *in the short run* due to a step increase in demand. It is interesting to note that the financial measures of cash

⁸² It is interesting to note that this result is made worse if the demand is not an increasing step function, but a sinusoidal function as is the case in the cyclic nature of capital-intensive durable goods like aircraft.

⁸³ *Corporate Planning and Policy Design*, James Lyneis, pg. 298, 1980.

flow and profitability do not exhibit the same dynamic response due the delays embedded in the ways they are accounted for⁸⁴.

Figure 2.5: Counter-Intuitive Insights



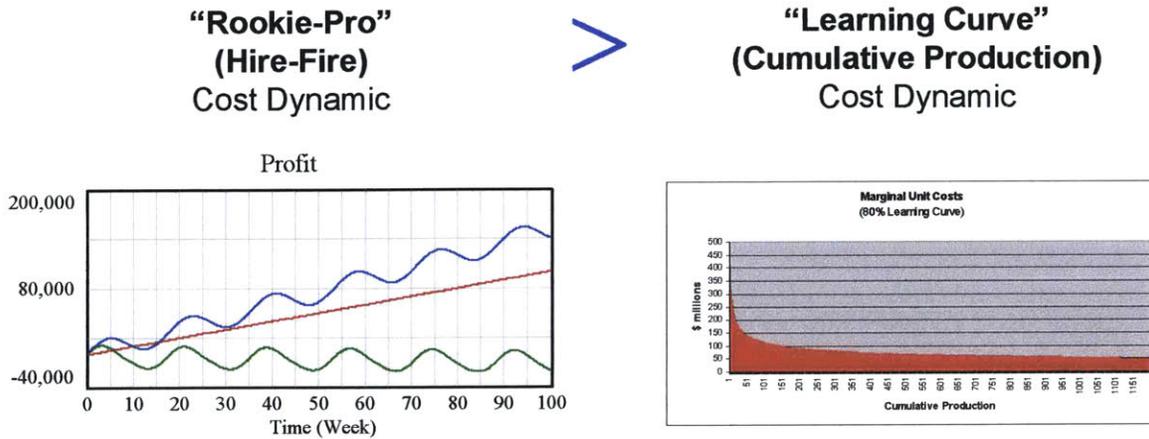
Not only can the locally (or “boundedly”) rational policy of reducing short-term labor costs when market demand drops result in lower profitability when the hidden costs of hiring & firing are included, but there are also “hidden” costs associated with losing and acquiring worker experience known as the “rookie-pro” problem. As shown in figure 2.6 below, this effect may be more dominant than the beneficial effects of the reduction in costs due to the learning curve (shown on the right of figure 2.6) which I will discuss later.⁸⁵

Comparing the relative importance of the hire-fire cycle on the stock of experience is clearly an area for further research that I recommend, especially in industries with high dynamic complexity

⁸⁴ *Analysis for Financial Management*, Robert C. Higgins, 7th edition, McGraw-Hill, 2004, pg. 5.

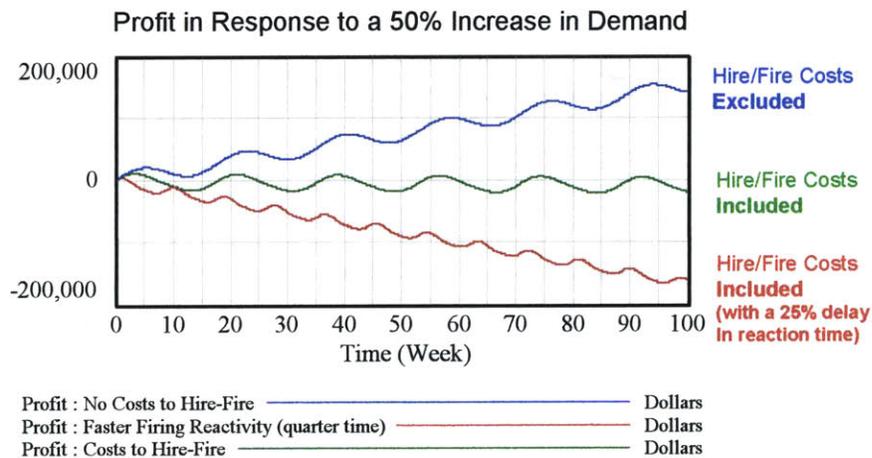
⁸⁵ This type of system dynamics analysis has been done before in the commercial airplane industry. (From a personal communication with Tom Fiddaman, July 2003.)

Figure 2.6: Dominant Cost Dynamics



Finally, it might be tempting to think that it is more efficient (in fact it could be seen as a “core competency”) to react more quickly to the changing conditions of the market, and therefore it might be a virtue to have the ability to hire and/or fire more rapidly. Figure 2.7 below demonstrates for the fictitious widget manufacturer that this may not be a correct assumption in all situations. When we include the costs of hiring and firing into the model, and in fact speed up the hiring/firing time by say a factor of four, we can see that the company can lose even more money by being even more reactive! Therefore considering rapid reactivity to be a core competency, may in fact be a core “in-competency” in which case, doing the wrong things “righter” is worse. This ability to grow and shrink rapidly, which I term, “corporate bulimia” after its binge and purge characteristics, will be revisited in more detail in chapter 9.

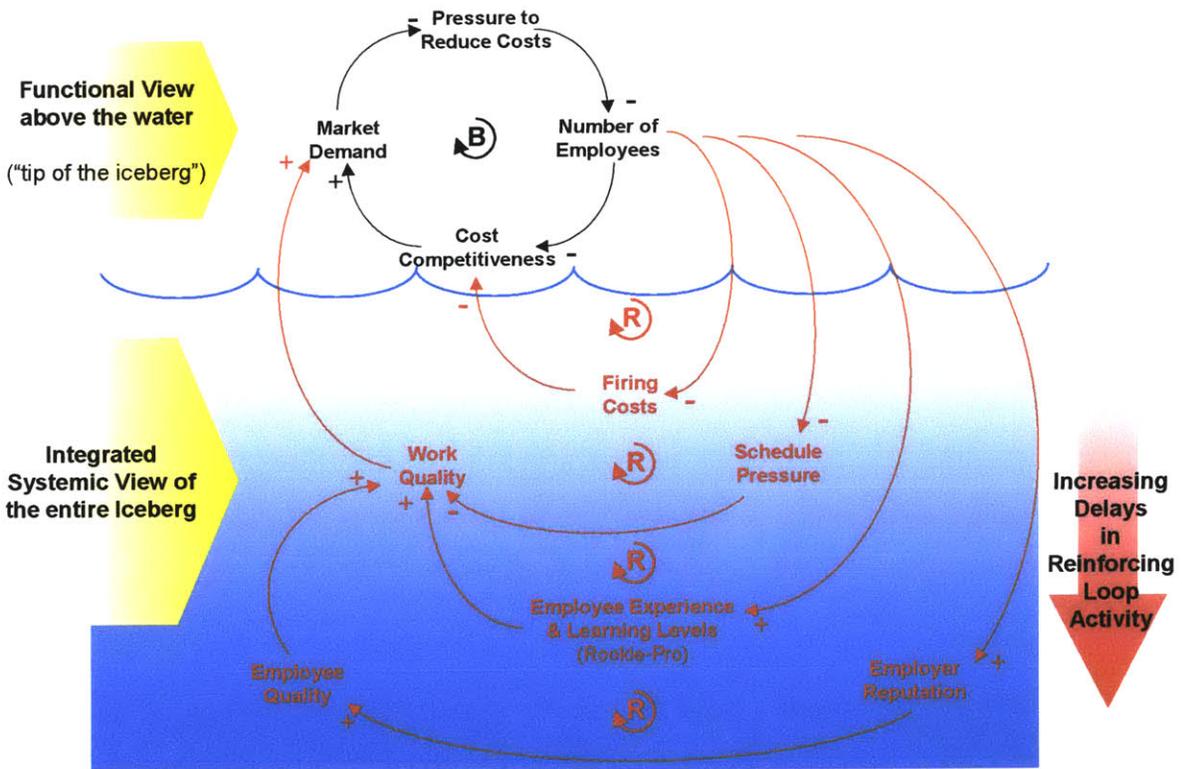
Figure 2.7: Doing the Wrong things “Righter”



It is important to note that the above discussion is based on a generic model with non-specific values for costs, revenues etc. The amount of profits and losses is dependent on a number of variables including the costs of hiring and firing, the ratio of between labor costs and material costs, etc.

Such “core incompetencies” are not uncommon in the business world and are often the result of a functionally oriented organization in which visibility of the overall enterprise is limited. As noted by Sterman⁸⁶, decision-making in these circumstances is equivalent to seeing the tip of the causality iceberg. As figure 2.8 below illustrates, the local decision policy to layoff workers is often in response to the direct causal relationship resulting in control of variable costs in the short term. This results in a balancing loop. This is the part of the decision dynamic that the decision-maker sees and is rewarded for. However there are “unintended side-effects” which are the result of decision-makers treating other enterprise metrics and variables as exogenous or outside their control or interest.⁸⁷

Figure 2.8: Tip of the Iceberg of “Unintended Side-Effects”



⁸⁶ Prof. John Sterman’s 15.874 class lecture, Fall 2003.

⁸⁷ Ibid.

There is a whole host of reinforcing loops that are “hidden” beneath the water level which act as “policy resistance” to thwart the primary decision above the water.⁸⁸ These range from ignoring the costs of layoffs to making the remaining staff work harder to draining the enterprise of its embedded learning network to developing a reputation as a poor place for a career. All these act to reduce market demand, resulting in more layoffs.

2.2 From *System Dynamics* to *Structural Dynamics*

Having presented the case for simple pendulum-based generic structures using *system dynamics*, I will now search for the lessons learned in the sister discipline of *structural dynamics*. Structural dynamics developed from the field of vibrations in mechanical engineering and is largely restricted to vibrations in the linear regime (e.g. high-rise building vibrations due to wind loading and automobile vibrations). However, nonlinear structural dynamics grew out of the field of earthquake engineering and blast-loading on civil engineering structures like buildings and bridges.

In structural dynamics, the pendulum is known as an approximate “single-degree-of-freedom” (SDOF) system, with the dynamic degree of freedom being the horizontal displacement of the swinging mass. A SDOF system has one mode of vibration; a two-degree-of-freedom system has two modes of vibration etc. The mode with the largest modal participation factor (typically with the longest period of vibration) is called the “fundamental” mode of vibration and the associated period is called the “fundamental” period of vibration.⁸⁹

Likewise, in system dynamics the pendulum is a 2nd order, two-stock system having one major feedback loop (a balancing loop). I observe therefore that the number of major feedback loops in a system dynamics model is equal to the number of dynamic D.O.F., or the number of modes of vibration. See figure 2.9 below.⁹⁰

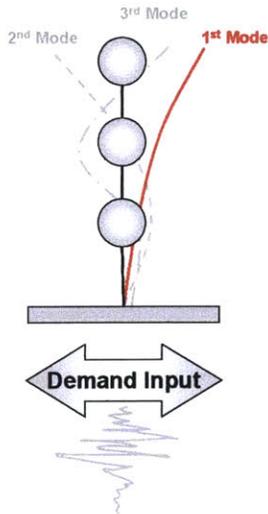
⁸⁸ Ibid.

⁸⁹ “Modal analysis” arises from the solution of the “eigenproblem” in linear algebra, which determines the eigenvalues (i.e. frequencies) and eigenvectors (i.e. modeshapes).

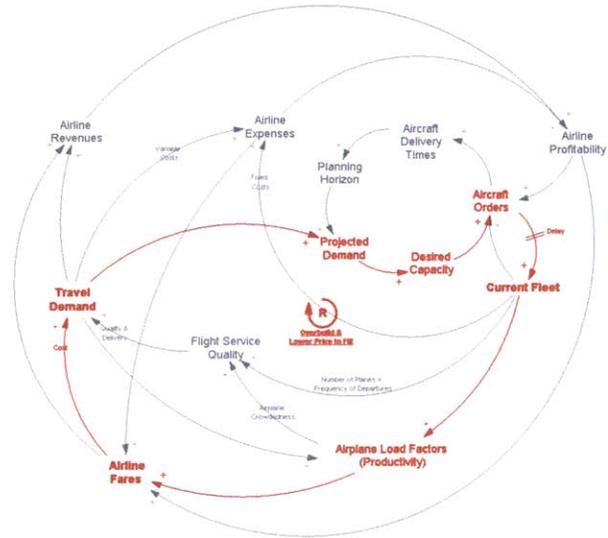
⁹⁰ Nathan Forrester’s 1982 PhD dissertation was one of the first to discuss eigenvalue analysis in system dynamics.

Figure 2.9: Core Building Block in Structural and System Dynamics

Fundamental Mode of Vibration
(Structural Dynamics)



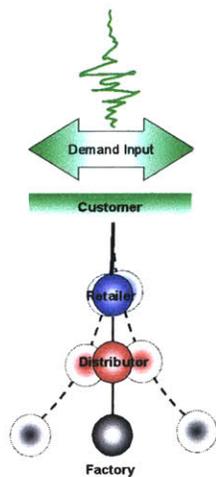
Dominant Feedback Loop
(System Dynamics)



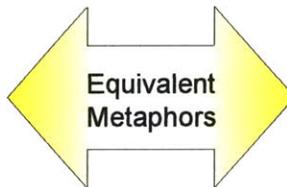
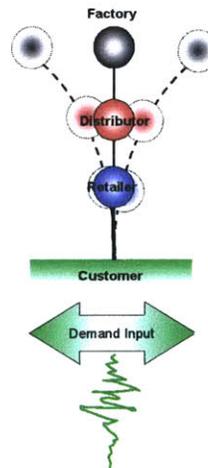
Please note as an aside, that I am using two essentially equivalent physical metaphors throughout this report to represent an enterprise: the pendulum and the inverted pendulum (see figure 2.10 below). The reader should pick whichever metaphor (s)he feels the most comfortable with. The pendulum model should appeal to physicists or clockmakers, while the inverted pendulum model is the tool of trade for structural engineers who are designing high-rise buildings.

Figure 2.10: Alternate Physical Metaphors

Pendulum Model



Inverted Pendulum Model
(a.k.a. Building Model)



Therefore, I can now make the following analogy-based observations:

*1 – Modes of vibration in structural dynamics ≡ Feedback loops in system dynamics*⁹¹

In structural dynamics, the mode of vibration with the longest period of vibration is known as the “fundamental” mode, and its period is known as the “fundamental” period as most of the modal mass or dynamic energy is captured in this mode. Likewise in system dynamics, Graham observes that, “a disturbance will propagate longest around the loop that propagates the disturbance most strongly”.⁹²

2.12 – The mode (i.e. feedback loop) with the longest period of vibration (i.e. propagation time) is called the “fundamental” mode (or loop).

From this, I can make another observation that in many complex structures having hundreds of degrees of freedom and hundreds of modes of vibration one or two modes tend to dominate the dynamic behavior. Likewise, Graham observes that in complex oscillatory systems, “one or two feedback loops often dominate the behavior despite the presence of thousands of others”.⁹³

2.13 – In complex enterprises, one or two modes (or feedback loops) tend to dominate the dynamic behavior of the system.

The dynamic response of a structure is also governed by the dynamic period of the input signal. For example, if the fundamental period of earthquake ground shaking is very close to the fundamental period of the building, then the maximum dynamic response will occur, called “resonance”. Likewise, Graham observes that “when we are looking for the cause of regular fluctuations, a loop with two or more phase-lag subsystems with response times on the same order of magnitude may be the cause of them.”⁹⁴

2.14 – When the fundamental period of the enterprise matches the fundamental period of the forcing signal a condition of resonance will occur.

⁹¹ Jay Forrester noted (at his lecture at the 2003 System Dynamics conference in New York) that the number of eigenvalues in a linearized system dynamics model = the number of stocks in a system dynamics model. Therefore a two-stock pendulum generic structure has two eigenvalues.

⁹² “Principles on the Relationship Between Structure and Behavior of Dynamic Systems”, Alan K. Graham, MIT PhD thesis, 1977, pg. 98.

⁹³ Ibid., pg. 97-98.

⁹⁴ Ibid, pg. 97.

In nonlinear structural dynamics (e.g. earthquake engineering), there is a transfer of dominance from one mode to another. Likewise, in nonlinear system dynamics, there is a transfer of dominance of one feedback loop to another (e.g. in s-shaped growth).

2.15 – *When enterprises enter the nonlinear range, the existence of dominant fundamental modes (or feedback loops) changes over time. This would manifest itself in figure 2.5 above, in which different modes and loops would turn red during the dynamic oscillation. In fact, the notion of a fundamental mode or loop becomes largely irrelevant in highly nonlinear problems.*

When designing the structure of a building to remain stable under a dynamically demanding environment like an earthquake, it is often advantageous to significantly modify the mode shapes and frequencies of the building – to push them away from the damaging energy of the earthquake. We will discuss exactly how to do this for buildings and enterprises in chapter 9. Likewise, Graham notes that “a very efficient way to stabilize a system’s oscillations is to identify the dominant loops and reduce their ability to propagate disturbances through either parametric or structural changes”.⁹⁵

6 – *Excellence in structural (or system) design often entails significant modification to the fundamental modes (or dominant loops) of the enterprise.*

Multiple-degree-of-freedom (MDOF) systems are complicated and their dynamic behavior is difficult to quantify. Fortunately, some simple techniques for linear systems have been developed in structural dynamics. The concepts of “modal superposition” and “response spectrum analysis” (discussed later) allow for the reduction of complex MDOF systems into a sum of simpler SDOF systems.

7 – *Complex structures (or systems) can be decomposed into an algebraic series of simpler modes (or feedback loops).*

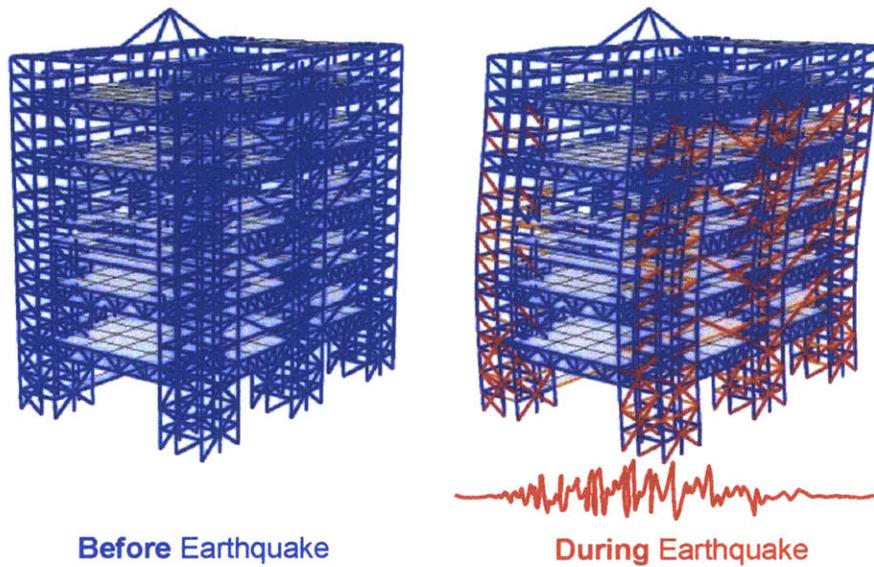
For example, figure 2.11 below shows the dynamic response of a 20-story building undergoing an earthquake. In order to analyze and design such a structure (or “physical enterprise”), it is necessary to model the building with millions of degrees of freedom and analyze the results on a supercomputer⁹⁶.

⁹⁵ Ibid, pg. 99.

⁹⁶ “Seismic Survival”, *Engineering News Record Magazine*, July 1997.

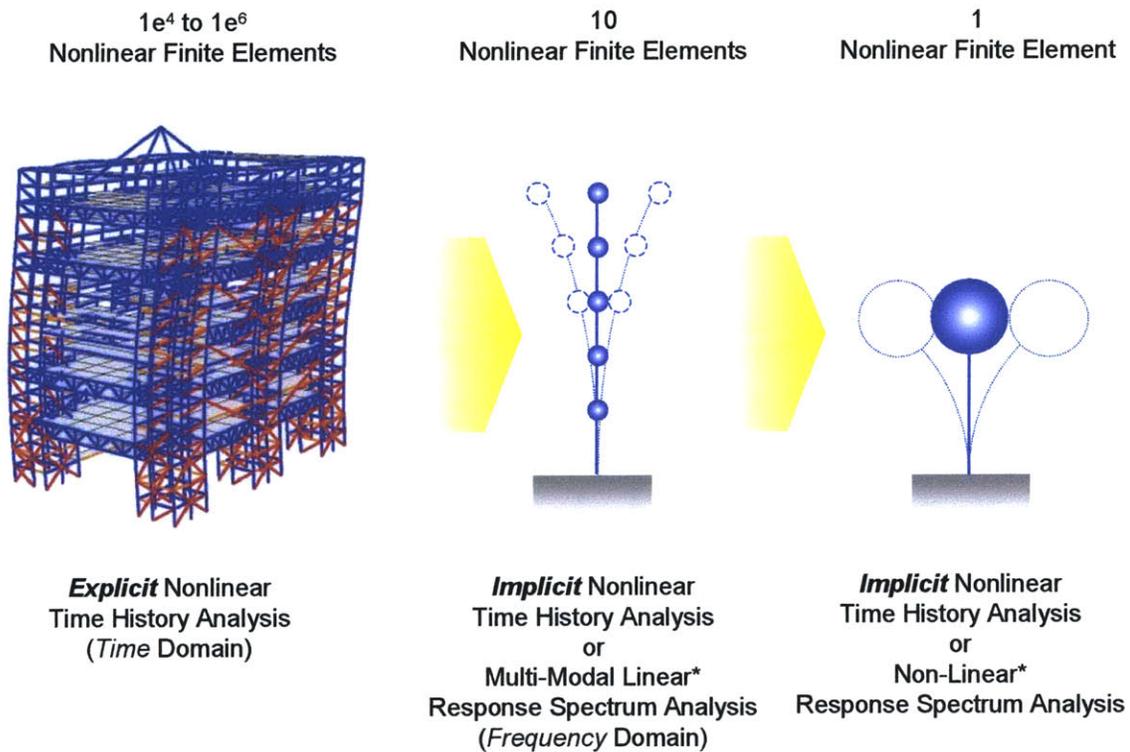
However, structural engineers have developed simple rules of thumb that allow them to greatly reduce the complexity and rapidly estimate the response.

Figure 2.11: Structural Dynamics of Buildings (source: *Arup*)



Instead of working with a detailed 20 story, one million-element model of the structure, designers can simplify it to an equivalent lumped mass “mega-story” model with only five dynamic degrees of freedom. Finally, the structure can be approximated even further as a single degree of freedom model with an equivalent mass and height as shown in figure 2.12 below. The smaller, simpler models are attractive particularly for concept designs as they allow the use of simple design techniques like a “Response Spectrum” which will be discussed in more detail later in subsequent sections. Note that the model looks like an inverted pendulum. This time the stiffness is not the length of the strings, but a function of the properties of the structure. Nonetheless, the same simple laws of physics apply.

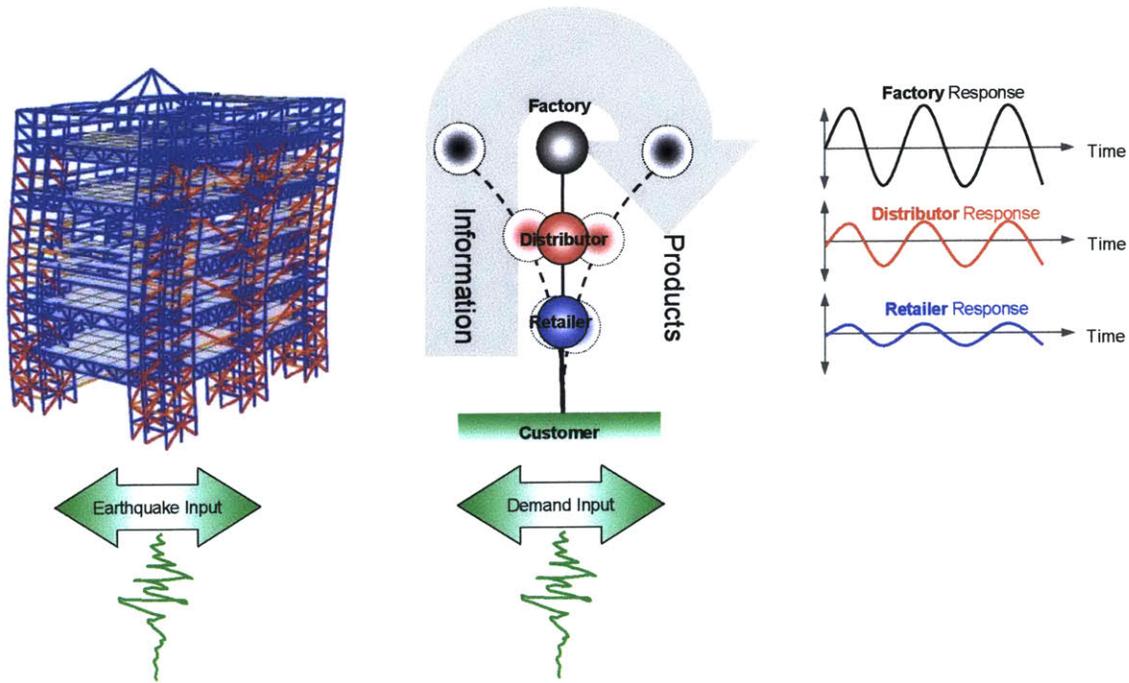
Figure 2.12: Spectrum of Structural Model Complexity



A physical analog using the building metaphor can be quite powerful in understanding the dynamics of human organizations and enterprises. In figure 2.13, each “story” of the structure represents a value chain member who is connected to its “upstream” supplier and its “downstream” customer. In this case, the enterprise is a simple, three-degree of freedom production-distribution system comprising a retailer, a distributor and a manufacturer. Notice that this enterprise structure is resting on the ground that represents the customer base. The changing customer demand is therefore like an earthquake signal that causes the building to oscillate. The speed at which the customer changes her mind (i.e. the “customer clockspeed”) will be discussed in chapter 9, under the lean enterprise name of “Takt”⁹⁷.

⁹⁷ “Takt” is the German word meaning “heartbeat”, and is often used in Lean vocabulary to signify the production speed which will match customer demand.

Figure 2.13: Structural Dynamics of Organizations



It is important to note that there are a variety of different types of possible “earthquakes” or exogenous shocks to an enterprise⁹⁸. Other than changes in customer demand for product, this includes changing demand from the capital markets for corporate profits (which we will discuss later in chapter 8). The optimum structural form is likely to be different when designing the enterprise for the dynamic demand from customers vs. for the dynamic demand from capital markets. Nevertheless, as most enterprises must respond well to both types of shocks, the enterprise design must have design “robustness” to meet the possibly conflicting demands of long-term customer satisfaction and short-term profitability.

Other “earthquakes” include changes in government regulation, waves of mergers and acquisitions or even technological discontinuities that send shocks through an enterprise. Note that these types of shocks tend to cause the enterprise (whether a firm, value chain or even an industry) to evolve its

⁹⁸ Joel Cutcher-Gershenfeld and Eric Rebertisch identify three sources of instability in aerospace enterprises: Technological, Organizational and Economic. See “The Impact of Instability on Complex Social and Technical Systems”, ESD Internal Symposium, April 2002.

structural form, as Fine argues in his work on industrial evolution.⁹⁹ Customer and capital market demand dynamics on the other hand tend to cause “non-emergent” response and do not necessarily lead to enterprise restructuring. Instead, the enterprise as designed responds in real time to the event.

As shown in figure 2.13, in the case of the enterprise responding to changes in customer demand, time-varying customer information is sent upstream through the enterprise (like an earthquake wave) and product is sent downstream through the enterprise (like an earthquake wave reflected back downward). Such input waves cause the building to shake and the enterprise value chain to oscillate like a “bullwhip”, with greater amplification the further along the value chain as depicted in the figure. The larger the earthquake, the greater the amplification will be throughout the enterprise. The greater the amplification throughout the enterprise, the stronger (and typically more expensive) the enterprise must be in order to prevent “damage” or wholesale collapse of the enterprise. In the context of a manufacturing corporation for example, the larger the earthquake and enterprise amplification, the greater the enterprise capacity must be, i.e. the more expensive fixed capital expenditures and variable inventory levels must be.

Each firm in the value chain (i.e. each mass) could also be modeled as having its own inverted pendulum of connected masses representing internal functions. For example, this micro-enterprise could just as easily be a firm having three degrees of freedom in its functions (e.g. marketing, engineering & manufacturing), or more realistically in its “business processes”¹⁰⁰ (e.g. order fulfillment).

Conversely, the above enterprise could be aggregated into a larger macro-model of an industry or a national macro-economy as shown in figure 2.14 below. This three-degree of freedom enterprise structure connects the macro-economy with an industry and ultimately with a firm.¹⁰¹ From this model, one would expect to see three “modes of vibration” in the data and the research literature^{102,103}. We will revisit this macro-economic model again later in this thesis.

⁹⁹ Charles H. Fine, *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*, Perseus, 1998.

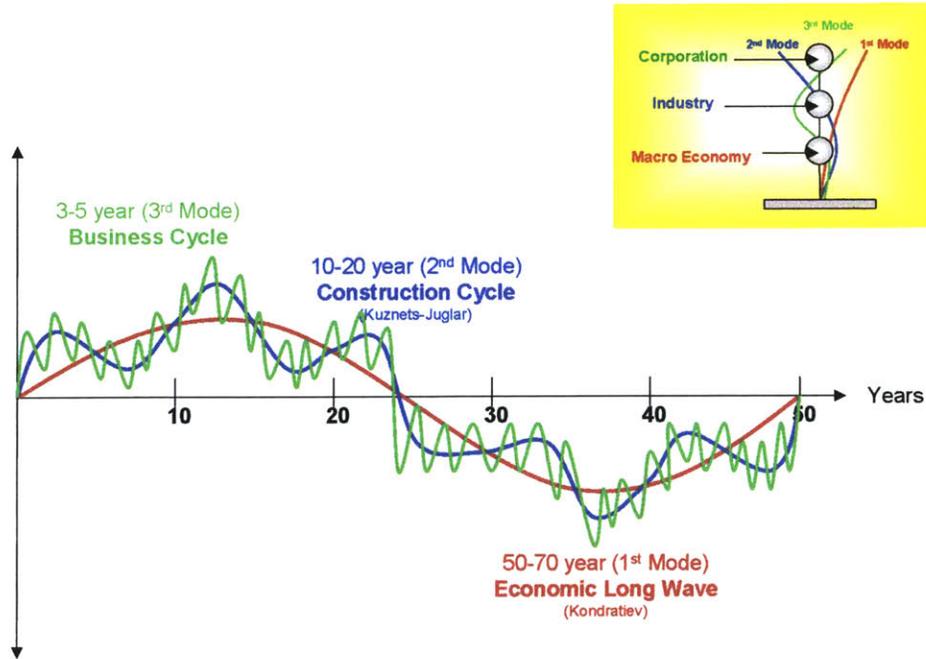
¹⁰⁰ *The Agenda*, Michael Hammer, 2001.

¹⁰¹ There is also an underlying “growth mode” which is excluded from this discussion for the time being.

¹⁰² “Modeling Cycles in the National Economy”, Nathaniel Mass, *Technology Review*, March/April 1976, pg. 43-52.

¹⁰³ “Empirical and Theoretical Evidence of Economic Chaos”, Ping Chen, *System Dynamics Review*, Vol. 4 No. 1-2, 1988, pg. 27.

Figure 2.14: Structural Dynamics of Business Economies



From the data, we can see the period of oscillation as well as the amplitude of vibration; therefore one could theoretically calculate mass and stiffness of each of the three components of the business economy enterprise model. But before we attempt this, let us first map the physical forces to their organizational analogues.

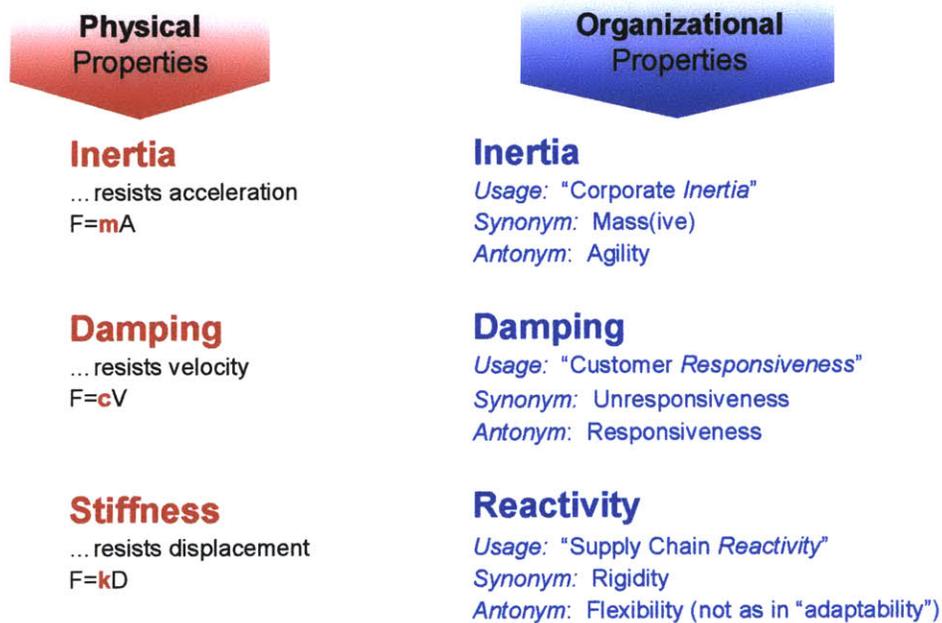
2.3 Three Dynamic Forces on Enterprises

There are three primary physical forces¹⁰⁴ acting on a physical system like a building during an earthquake. They are: inertia (or acceleration-dependent forces), damping (or velocity-dependent forces), and stiffness (or displacement-dependent forces). I am proposing a similar mapping to human organizations and enterprises that use physical analogs and common, everyday management terms and concepts that are summarized in Figure 2.15 below¹⁰⁵:

¹⁰⁴ Although I focus in this thesis on Newtonian *force*-based dynamics, Hamiltonian *energy*-based dynamic formulations could also be used which would lead to additional insights.

¹⁰⁵ Although most of this thesis takes a *deterministic* approach to dynamics for simplicity and instructive ease, I note that this is just an approximation to the uncertain nature of complex human systems which would benefit from a *probabilistic /stochastic* approach.

Figure 2.15: Three Dynamic Properties



It is interesting to note that the three organizational forces are common in the academic literature as well as in business colloquialisms. Organizational *inertia* has for years been researched in the academic discipline of organizational behavior, supply chain flexibility or *reactivity* is well known in the supply chain / operations management disciplines, and customer *responsiveness* is an important topic in the marketing discipline. This thesis attempts however to unify these disparate notions into a unified theory of business enterprise dynamics.

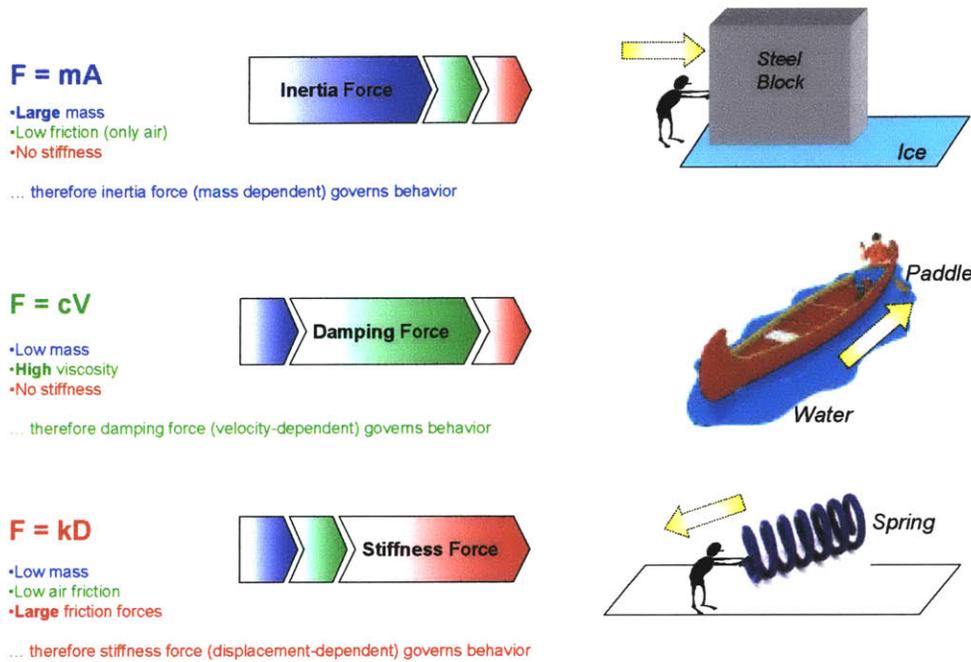
From this we can see that the *inertia* of an organization is a measure of how much resistance to change there is within the organization. Also, I note that organizational *damping* is a measure of how responsive the organization is to the customer (i.e. do they smooth and delay decisions?). And finally, the *stiffness* of an organization is how "reactive" it is to an input.

It is interesting to note that researchers at the *Harvard Business School* and the *Tuck School of Business* have recently published the results of a five-year research program that proposed four

characteristics that distinguish successful companies.¹⁰⁶ One was a corporate structure that is flexible (i.e. related to stiffness) and responsive (i.e. related to damping).

In figure 2.16 below, I propose visual metaphors for each of these three forces, in order to understand conceptually what they mean in the physical and organizational realms. Although all three dynamic forces are always acting on a physical system, one force usually dominates.

Figure 2.16: Visualizations of the Three Dynamic Forces



To consider when inertia dominates, consider a large block of steel sitting at rest on a frozen pond. There is little velocity-dependent air friction to resist movement, and there is little displacement-dependent ground friction to resist movement. The reason that it is so difficult for a person standing on solid ground to move the block is that the block has an endogenous property called “inertia” which resists movement. This force is acceleration-dependent, which means it is very difficult to change the velocity of the block. For example, if the block is at rest, it is difficult to get it moving. Or if the block is sliding across the pond with constant velocity, it is difficult to bring it to rest.

This inertia (or mass) is defined by the size of the block and its density. It would be easy to move this large block if it were made of a low-density material like Styrofoam. Organizationally, this inertia is

¹⁰⁶ “What Really Works”, Nitin Nohria and William Joyce, *Harvard Business Review*, July 2003.

a function of the size of an organization, but more importantly, it is a function of its “density” which manifests itself in its level of vertical integrality or focus on “functional silos”. This will be discussed further later.

To consider when damping dominates, consider a paddling canoe in a lake. There is little acceleration-dependent mass or inertia associated with the lightweight canoe, and there is little displacement-dependent stiffness (e.g. a rope tying the canoe to the shore) resisting movement. The reason that it is so difficult for a person paddling in the canoe is that the water has velocity-dependent viscosity. This means that it is relatively easy to move the paddle slowly through the water – there is little velocity and therefore viscous resistance movement. However, when one tries to move the paddle more quickly, the water’s viscosity makes this effort harder. Note that these velocity-dependent forces would be even more pronounced if the canoe were being paddled in a more viscous fluid like oil or syrup.

Organizationally, this viscosity is a function of the “responsiveness” of the organization, i.e. the speed at which it responds to changes in the environment. Often, this manifests itself as the level of corporate “bureaucracy”. This will be discussed further later.

To consider when stiffness dominates, imagine pulling on a spring. There is little acceleration-dependent mass or inertia associated with the spring itself, and there is little velocity-dependent air friction to resist movement. The reason that it is so difficult to pull the spring is that it possesses elastic stiffness, which is displacement dependent. In other words, it gets harder to pull the farther you pull it. It is not difficult to start pulling it (i.e. not acceleration-dependent), nor is it difficult to pull it quickly (i.e. not velocity-dependent).

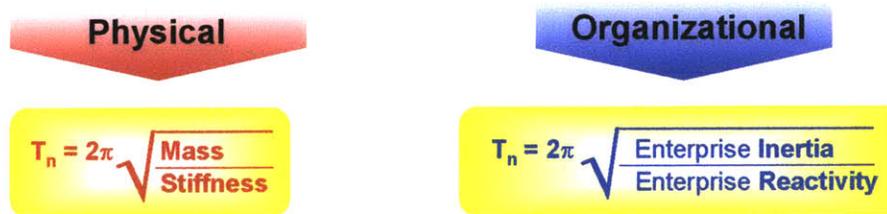
Organizationally, this stiffness is a function of the “reactivity” of the organization i.e. the metaphorical distance an organization moves when it reacts to a customer order. Often, this manifests itself as the level of waste in an organization. This will be discussed further later.

A more in-depth exploration of each of the three forces: inertia, responsiveness and reactivity will be covered in sections 2.6, 2.7 and 2.8 respectively.

2.4 Calculation of Clockspeed

Although researchers have attempted to measure industry clockspeeds based on gathering empirical data based on items like total duration of product lifecycle¹⁰⁷, I am attempting to propose a slightly more analytical framework which could give the enterprise attributes which govern its clockspeed. Figure 2.17 below shows the general equations for calculating the natural period of vibration of a SDOF system.¹⁰⁸

Figure 2.17: General Equations for Natural Periods of Vibration for Systems



As an example of the ease and usefulness of this equation, I observe how an MIT colleague chose to describe his experience at *Dell Computers*¹⁰⁹:

“Dell is the most reactive company I know. They can turn on a dime, and yet they react to every penny.”

In this simple statement, a qualitative assessment of *Dell's* clockspeed was made. “Turning on a dime,” means agility, low resistance to change or low organizational inertia. “React to every penny” means high stiffness, short string length or high enterprise reactivity. Therefore a small numerator (inertia) and a large denominator (reactivity) equal a small natural period of vibration (or fast clockspeed).

But a pendulum is an even simpler specific case. If (as demonstrated in Chapter 1) any dynamic system (whether physical or organizational) can have its dynamic response approximated by treating it as

¹⁰⁷ “Industry Clockspeeds: Measurement and Operational Implications”, Manufacturing & Service Operations Management, 1999.

¹⁰⁸ A more exact formula for natural period of vibration includes the damping factor, however it can be considered to be negligible for most physical or human systems. For a more complete discussion, refer to Appendix D.

¹⁰⁹ Personal communication with Rick Nardo, LFM 2003, April 2003.

an equivalent pendulum having a mass size and a string length, then the clockspeed equation is easy to derive from Newtonian physics.¹¹⁰ For a pendulum, the following simple relationships hold:

$$\text{Mass of a Pendulum} = \text{Pendulum Weight} / \text{Earth's gravity}$$

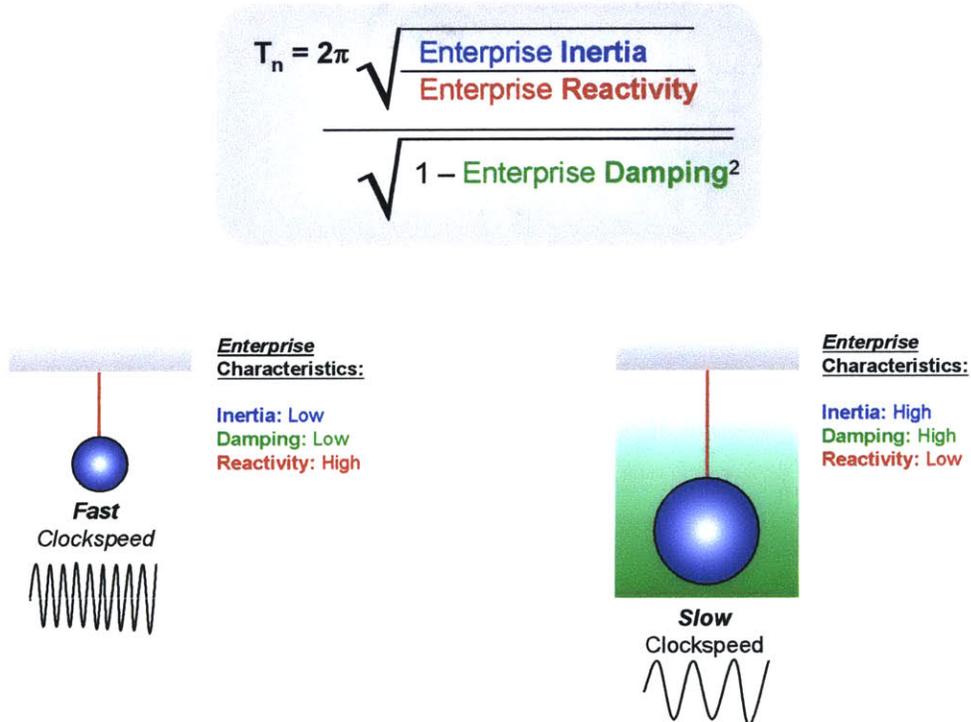
$$\text{Stiffness of a Pendulum} = \text{Pendulum Weight} / \text{Length of Pendulum}$$

Substituting these into the general equations of figure 2.15 (noting that pendulum weight cancels out) results in the following equation:

$$T_n = 2\pi \sqrt{(\text{length of pendulum}/\text{gravity})}$$

It is intuitive to note that the more corporate inertia, the more resistance there is to change, the larger (slower) the natural period of vibration. Also, the less reactive the value chain (i.e. the longer the string), the slower the natural period of vibration. These relationships are shown below in figure 2.18 utilizing the complete equation for clockspeed discussed in Appendix D.

Figure 2.18: The Three Dynamic Properties and the Clockspeed Equation



¹¹⁰ A good website for learning about pendulum dynamics is: “The Pendulum Lab” by Franz-Joseph Elmer at www.monet.physik.unibas.ch/~elmer/pendulum.

In the coming chapters we will explore the strategic positioning of an enterprise's clockspeed. For now I note Senge's observation that "faster is not necessarily smarter... in a world of constant acceleration, while most firms become increasingly *reactive*, the race will go to the few who can think more deeply rather than *react* more quickly".¹¹¹

2.5 The Enterprise "Response Spectrum"

Before I discuss and attempt to quantify inertia and reactivity for organizations, I would like to introduce a powerful concept or visual representation for enterprise design, the "Enterprise Response Spectrum" which will be used throughout this report.¹¹² This concept is used widely in diverse fields like earthquake engineering where engineers need a simple tool to capture complex design issues.¹¹³ As over two million people died in collapsed buildings due to earthquakes from 1900-2000, such a tool was developed quite literally to save lives – if you don't consider the nonlinear dynamic complexity of your enterprise then people die. Can such a simple design aid be used for enterprise designers, where the profits and well being of organizations are at stake?

Quite simply, a response spectrum plots the response on the vertical axis of an infinite number of enterprises, each having a different clockspeed on the horizontal axis to an input signal (e.g. a change in customer demand, a change in interest rates, a global war). As every enterprise has a clockspeed or natural period of vibration, and every input signal has its own clockspeed, the closeness of the two clockspeeds defines the amplitude of dynamic amplification or attenuation that the enterprise will experience.

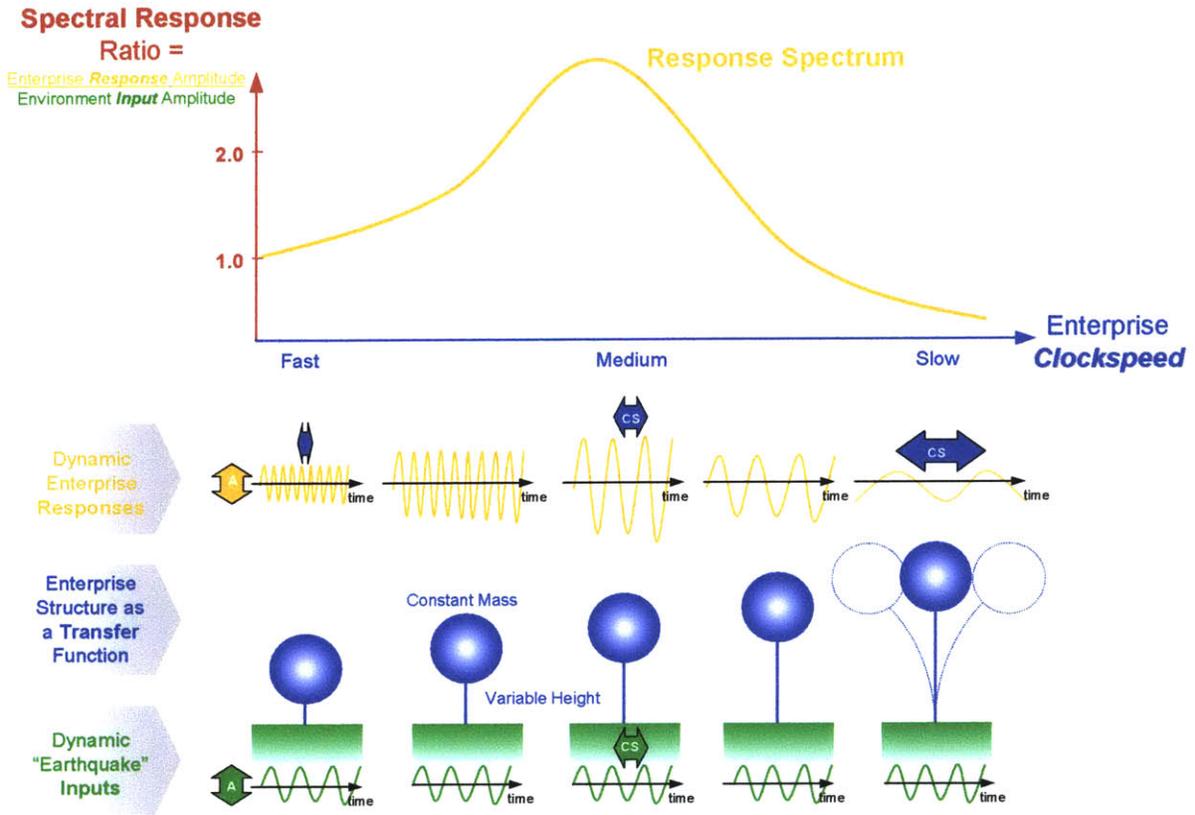
The two figures below illustrate the construction of a response spectrum. In figure 2.19, the clockspeeds or natural periods of vibration are determined by assuming that each enterprise has a constant mass, while the stiffness (represented by height) varies.

¹¹¹ Peter Senge, back cover of *Clockspeed*, by Charles H. Fine, 1998.

¹¹² Although I take the notion of "response spectrum" from structural engineering, it is also known as a "transfer function" in general dynamics theory or as a "bode plot" in acoustics and mechanical vibrations.

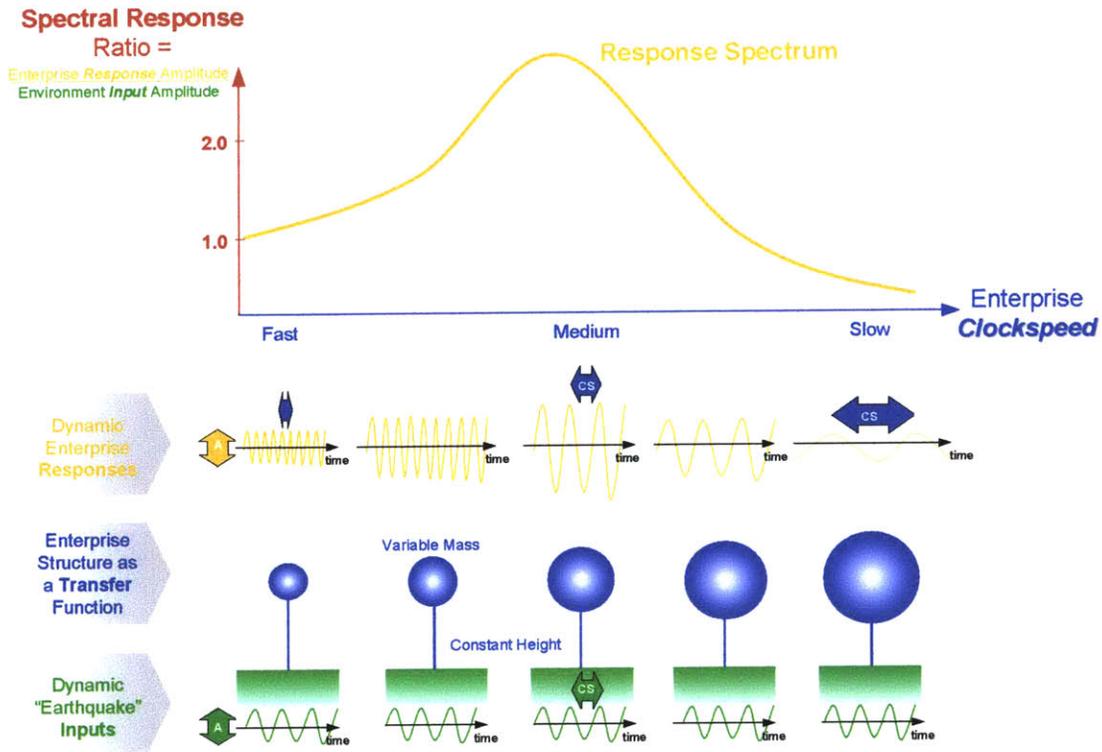
¹¹³ Jay Forrester even introduced the concept in system dynamics for enterprises in one of the appendices in one of his original works, *Industrial Dynamics*, 1961, Appendix I, figure AI-2, pg. 424.

Figure 2.19: Construction of a Response Spectrum (Constant Mass)



In figure 2.20 below, the clockspeeds or natural periods of vibration are determined by assuming that each enterprise has a constant stiffness, while the mass varies. The resulting response spectrum is identical to the previous one, as the clockspeeds of each enterprise are the same, although they are expressed in different ratios of mass and stiffness.

Figure 2.20: Construction of a Response Spectrum (Constant Stiffness)

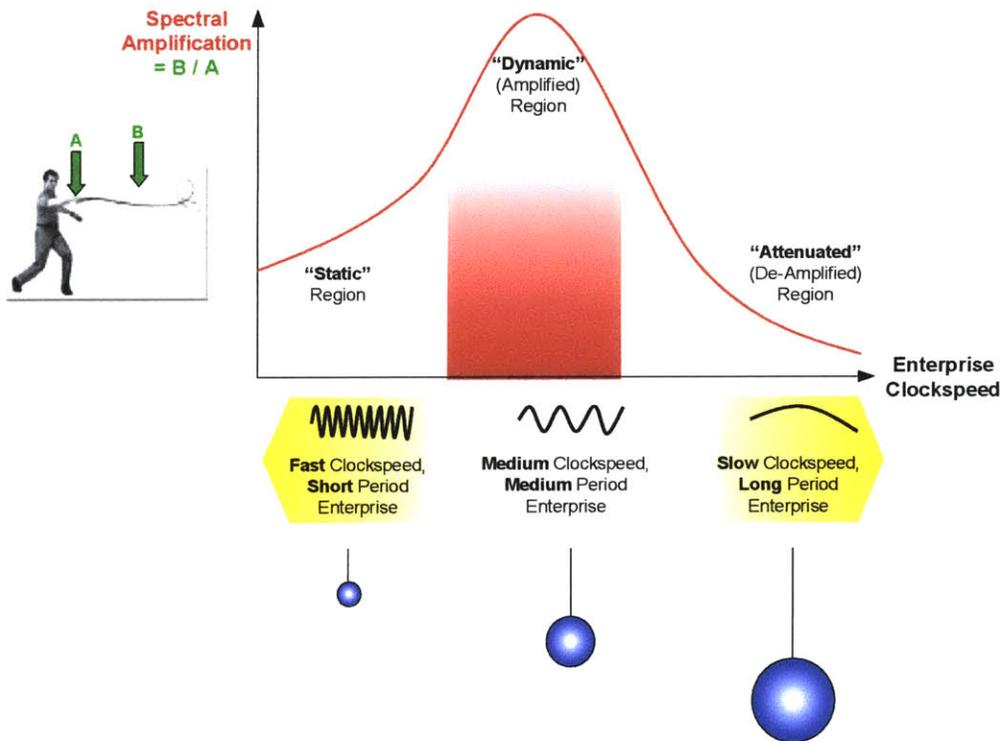


As a response spectrum graphically shows the effects of the beer-game bullwhip on a variety of enterprises having different clockspeeds, I will illustrate this concept using a metaphor of a lion-tamer's bullwhip.

The response spectrum plots the response (e.g. the acceleration of the end of a bullwhip) of a range of bullwhips each having a different length (and therefore different natural period of vibration) to a specified whipping acceleration of the lion-tamer's hand. For example, if we cut the bullwhip off at its handle, leaving only the stump, then the acceleration of the stump is equal to the acceleration of the lion-tamer's hand – i.e. there is no dynamic amplification. We plot this point vertically at the far left of the graph where the period of vibration of the bullwhip stump is zero. If we add back more and more whip, we find that the acceleration of the tip keeps amplifying the motion of the lion-tamer's hand further and further – that is the response spectrum increases as we move further to the right as the whip has a longer and longer natural period of vibration. Note that there is a “magical” length of whip, which maximizes

the amplification of the acceleration of the lion-tamer’s hand. This corresponds to the highest point on the response spectrum, and occurs at the resonant natural period of the whip – i.e. when the natural period of the whip is approximately equal to the period of motion of the lion-tamer’s hand. Finally, as we add more and more length to the whip, making it longer and longer and hence the natural period of vibration longer and longer, the maximum acceleration of its tip begins to diminish, and in fact “de-amplifies” the motion of the lion-tamer’s hand. On the response spectrum, as we move further to the right, the values reduce. The characteristic shape of a “mountain-looking” graph is an acceleration response spectrum as shown in figure 2.21 below.¹¹⁴

Figure 2.21: The Bullwhip and the Enterprise Response Spectrum



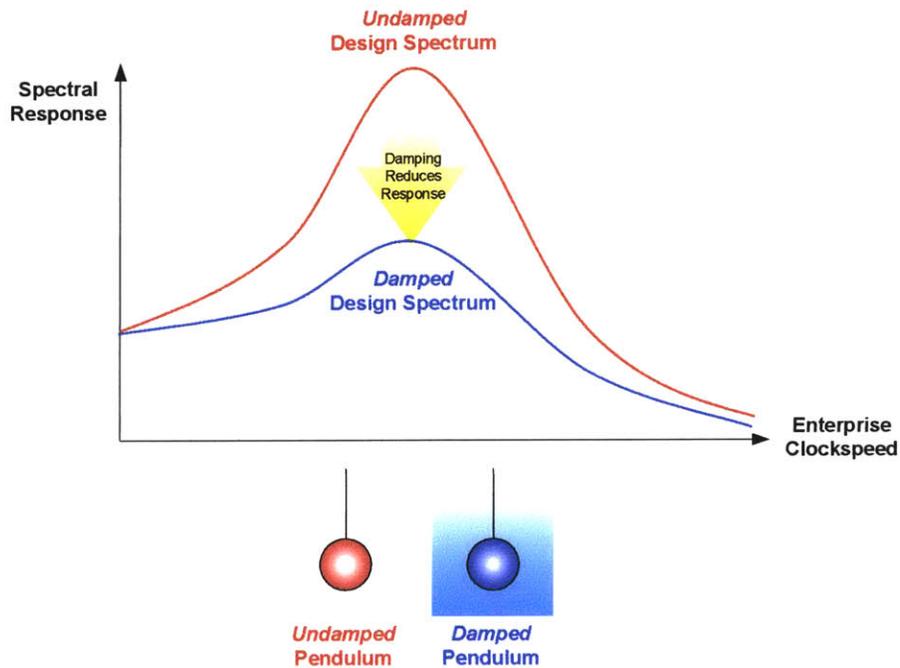
For example, if an enterprise’s clockspeed is the same as the input signal’s clockspeed, the enterprise will experience maximum bull-whip effect – a phenomenon known as ‘resonance’. However, if the clockspeed of the enterprise is much faster than the input clockspeed, the enterprise will not “feel”

¹¹⁴ In the body of this thesis, I focus almost exclusively on the *acceleration* response spectrum. As there are three primary forces in structural dynamics, there are three response spectra, the other two being *velocity* and *displacement* response spectra. For a brief discussion of the three spectra and how they are related, see Appendix E.

the input strongly and it will not amplify its effects (see left side of spectrum). Also, if the clockspeed of the enterprise is much slower than the input clockspeed, the enterprise will also not “feel” the input strongly and it will de-amplify its effects (see right side of spectrum). I shall return to this concept later.

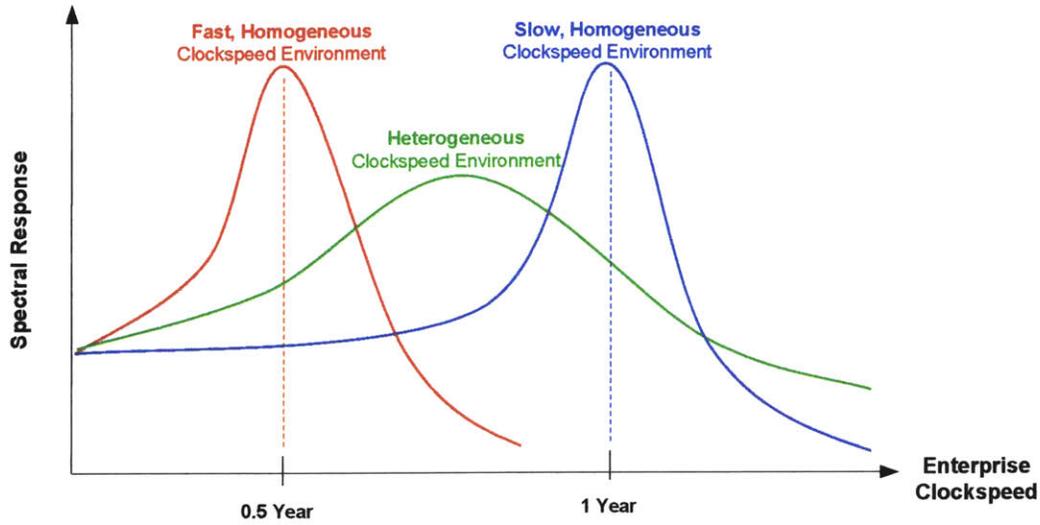
Enterprise damping acts to reduce the response of enterprises. Therefore, there is a different response spectrum for different levels of enterprise damping as shown in figure 2.22 below.

Figure 2.22: Effect of Damping on Response Spectra



The shape of the enterprise response spectrum is also a function of the dynamics of the “earthquake”, that is the dynamics of the changes of customer demand, etc. The peak of the response spectrum occurs near the clockspeed of the customer demand. For example, figure 2.23 below, shows the response spectra of two different simplified markets, where there is only one clear customer signal. On the left (in red) is a market where the clockspeed of the customer demand changes every six months and on the right (in blue) is a market where the clockspeed of the customer demand changes every year. Notice how they both are relatively “pointy” curves.

Figure 2.23: Shapes of the Enterprise Response Spectrum



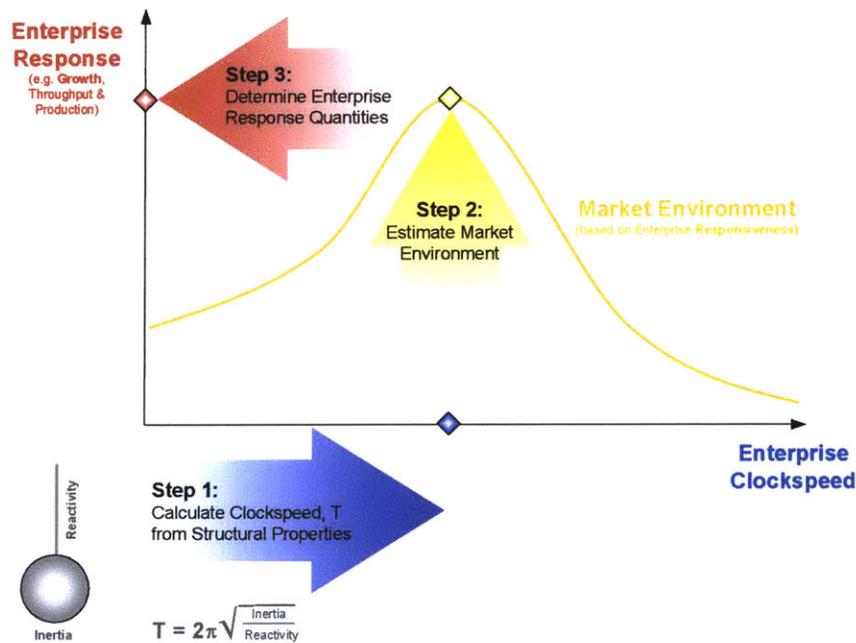
In the field of earthquake engineering, ground motion typically has many complex frequencies or clockspeeds occurring simultaneously – we say that the earthquake signal is “rich in frequency content”. This environment produces a broad-shaped response spectrum as is shown in green in figure 2.23. In the business world, this environment is like the world of real markets, where demand for multiple product and customer segments occurs simultaneously – the business environment is “rich in demand clockspeed content” or heterogeneous.

In fact, only in rare cases does the demand (both in earthquakes and markets) have only one predominant clockspeed. In earthquake engineering, Mexico City proved to be such a rare environment. The city is founded on an ancient lakebed of deep soft soil having a natural period of vibration or clockspeed of 2 seconds. That is if you smacked the ground of Mexico City with a large hammer, it would shake back and forth like a bowl of Jell-O, left-to-right, every 2 seconds. This is extremely relevant, because the majority of building collapses were high-rise buildings also having fundamental periods of vibration of 2 seconds. The buildings went into resonance with the very strong single clockspeed of the ground. If the ground of Mexico City were made of more solid rock which creates a ground motion having more rich, simultaneous frequencies, (like the lower, broader green curve in figure 2.23) those buildings would not have collapsed. Similarly, in the business world, a company that serves

only one customer with one predominant product is subjected to the full dynamic amplification of changes in that demand. However, if there were multiple customer segments, each changing their demand patterns at slightly different times, the dynamic response of the enterprise would be less, requiring less enterprise strength. In fact, as we shall discuss in chapter 9, this “Agile” product offering and production line flexibility, is one of the many key architectural advantages that *Toyota* exploits.

Before leaving the concept of an enterprise response spectrum for the time being, let us summarize the concepts developed thus far that allow describe the three-step process of dynamic enterprise design. I will summarize them in the logical format of: “Enterprise + Environment = Response” as shown in figure 2.24

Figure 2.24: The Enterprise Design Process

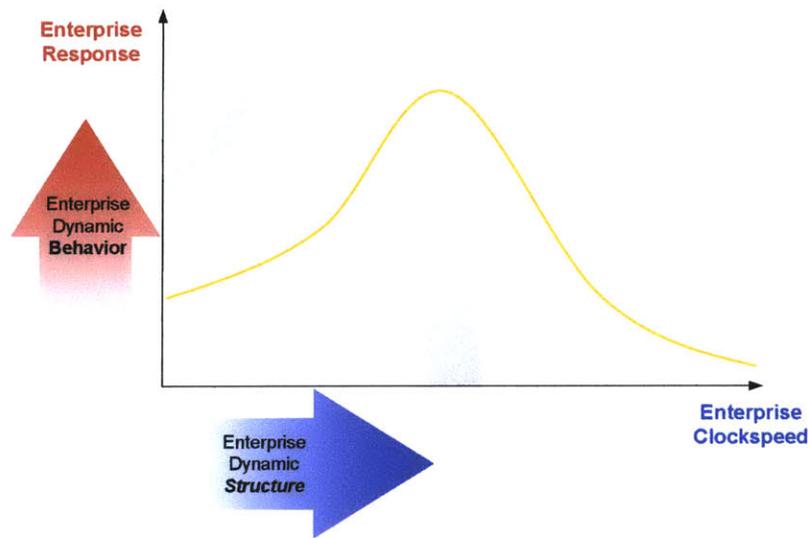


The first step is to estimate the enterprise structural properties (namely the inertia and reactivity) in order to calculate the enterprise clockspeed, which is then plotted on the horizontal axis. The second step is to estimate the market environment spectrum, the shape of which is a function of the market richness, and the amplitude of which is a function of the enterprise damping or responsiveness. The third step is to determine the enterprise response quantity (e.g. growth, throughput or production) by reading up

from the enterprise clockspeed to the environment response spectrum, and then horizontally to the value of the response. In this way, the enterprise design spectrum will indicate the maximum growth that an enterprise of a given clockspeed would experience given a specific market demand dynamic.

The response spectrum not only shows how the response is a function of the enterprise and its environment, but also that the enterprise *structure* drives its *behavior* as shown in figure 2.25 below.

Figure 2.25: Enterprise Response Spectra: Structure Drives Behavior



2.6 Comparing *System Dynamics* and *Structural Dynamics*

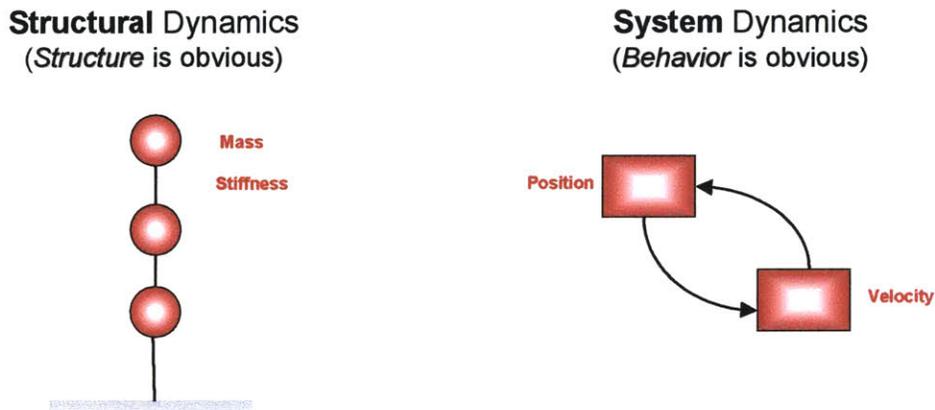
Having defined a response spectrum using the concepts of structural dynamics, it is helpful to reconcile the two different representations of dynamic systems used in this work: system and structural dynamics in order to observe their complementary nature. As shown in figure 2.26 below, the appeal of using structural dynamics is the obvious and transparent representation of an enterprise’s *structure* as captured by the masses etc. – with its response or behavior not readily apparent. Whereas, the appeal of using system dynamics is the transparent representation of an enterprise’s *behavior* as captured by the stocks as state variables – with the structure not readily apparent.¹¹⁵

The mathematical solution of a system’s structural dynamics lies in the numerical integration of the equations of motion which are a system of ordinary differential equations. As pointed out by

¹¹⁵ A comparison of system & structural dynamics within the context of dynamic systems is shown in Appendix B.

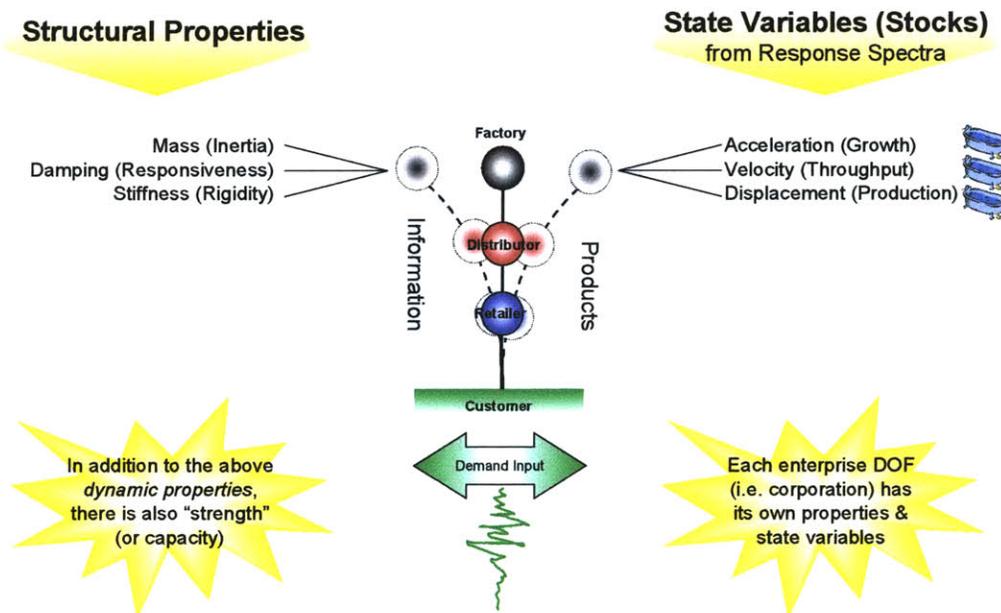
Forrester, the use of integral calculus (e.g. for stocks) is more intuitive because it is easier to assign causality.¹¹⁶ For example in the case of the pendulum, it is clear that integrating acceleration causes change in velocity, and the integration of velocity causes change in displacement.

Figure 2.26: Complementary Representations of a System's Dynamics



One can then map the system's state variables (or stocks) to the structural dynamic model which represents the system's structural properties as shown in figure 2.27 below for a typical enterprise.

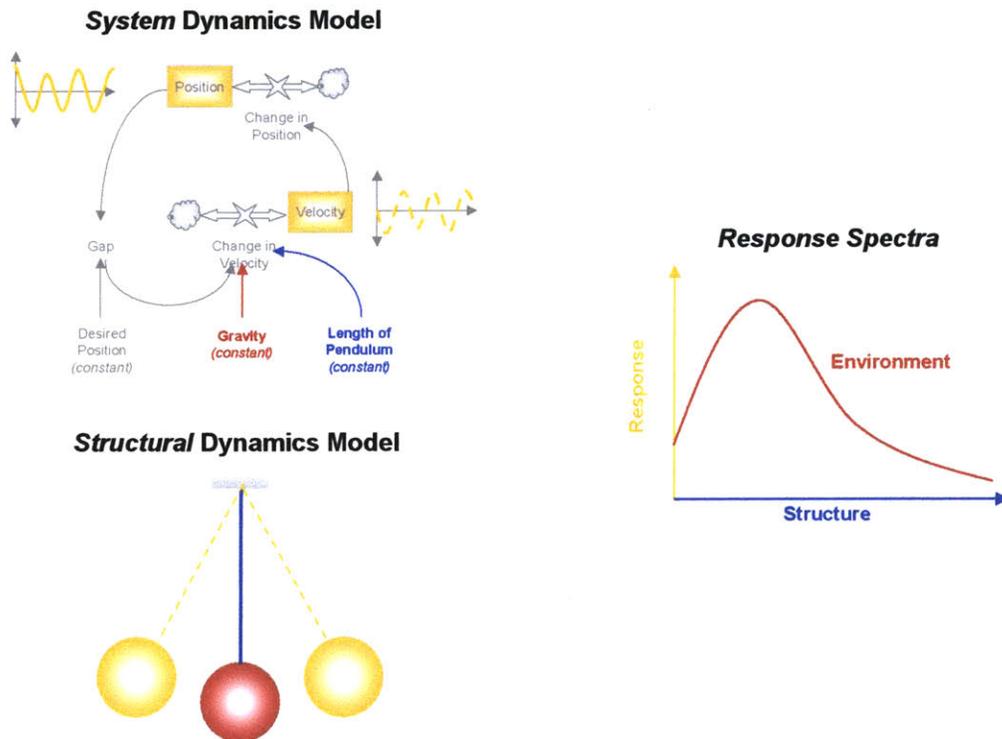
Figure 2.27: Summary of Structural and System Properties



¹¹⁶ Jay W. Forrester, *Principles of Systems*, 1968, pp. 6-11 and 6-12.

Finally, to close the loop between system and structural dynamics and the concept of a response spectrum, one can see in figure 2.28 below the three ingredients of the dynamic analysis color coded for the three figures: red represents the *environment* i.e. the exogenous force of gravity (and its direct impact on the inertial mass), blue represents the *structure* i.e. the stiffness or the length of the pendulum, and yellow represents the *response* i.e. the state variables of displacement and velocity.

Figure 2.28: Relating Response Spectrum to System and Structural Dynamics



From the above comparisons of the complementary nature of system and structural dynamics, it becomes clear that while both describe the structure and behavior of dynamic systems, each has particular strengths in communicating such systems. Structural dynamics works with *strategic* “high-level” aggregated enterprise properties of inertia, damping and reactivity while system dynamics works at a more *operational* level with more refined and discretized details of decision making.

Having defined the concept of a response spectrum that will be used over and over again throughout this report, we now move to an exploration of each of the three dynamic forces that we introduced in section 2.3. We begin with Inertia.

2.7 *Inertia: Dynamic Property #1*

The question now arises as to how one defines and measures the two crucial organizational parameters, Inertia and Reactivity. Let's first focus on "Inertia" which is defined by Newton's second law of motion:

$$F = mA$$

Inertia Force = mass * acceleration

The mass (or inertia) of an organization is an *endogenous* property of the organization (whether a firm or a value chain or a nation) that it can design and control. Physical inertia is a function of the size of the object times its density:

$$\text{Physical Inertia} = \text{Size} * \text{Density}$$

In a classic paper on organizational inertia, Hannan and Freeman note that *structural inertia* is a function of an organization's age, size and complexity.¹¹⁷ They also note that inertia is stronger in the core activities of an organization than in its peripheral activities. One can therefore extend the physical formulation to organizations where organizational inertia can be thought of as a function of the "size" of the organization times "density" of the organization:

$$\text{Organizational Inertia} = \text{Size} * \text{Density}$$

Size can encompass such parameters as number of employees, number of citizens, etc., but the more important "fuzzy" parameter is the density. Density defines the quality of the relationships between the organization's constituents. Some determinants of the density could therefore be hierarchical structure (e.g. vertical vs. virtual integration), age of organization, etc.

¹¹⁷ Hannan, Michael T., and John Freeman, "Structural Inertia and Organizational Change", *American Sociological Review*, Vol. 49, April, 1984, pp. 149-164.

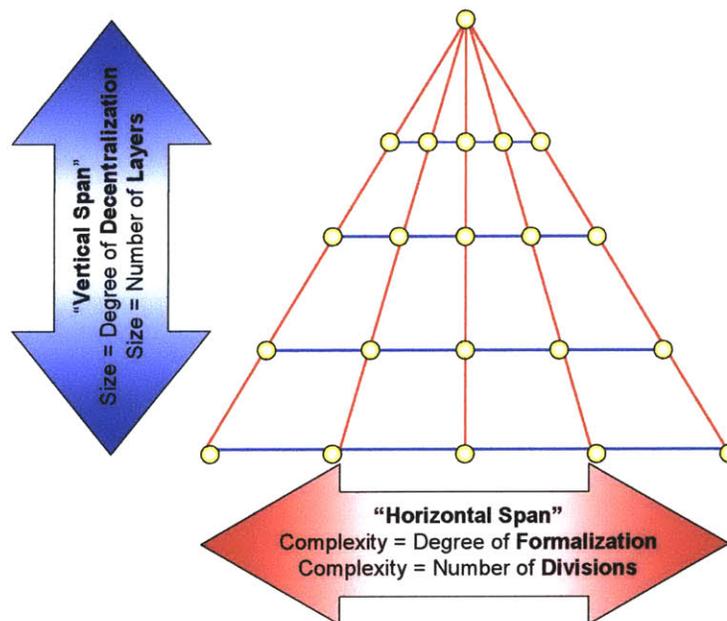
Some of the original “classic” works on organizational design theories define inertia as an “overbounded system”¹¹⁸ or in terms of its synonymous cousin, a “bureaucracy”. Child defines bureaucracy or inertia in a similar way to the above formula:¹¹⁹

$$\text{Organizational Inertia} = \text{Size} * \text{Degree of Complexity}$$

In this formulation, size and complexity can be described as variables of “vertical span” and “horizontal span” respectively as shown in figure 2.29 below, and defined by the following synonymous formula:

$$\text{Organizational Inertia} = \text{Degree of Decentralization} * \text{Degree of Formalization}$$

Figure 2.29: Enterprise Inertia



More recent work defines organizational inertia as being “cultural”¹²⁰. Foster and Kaplan of McKinsey define inertia or “cultural lock-in” as follows¹²¹:

¹¹⁸ Alderfer C., “Consulting to Underbounded Systems,” *Advances in Experiential Social Processes*, Vol. 2, London 1980, Chapter 11.

¹¹⁹ Child, J. (1973). “Predicting and understanding organizational structure”, *Administrative Science Quarterly*, 18, pp. 168-185.

¹²⁰ Pankaj Ghemawat, *Commitment: The Dynamic of Strategy*, 1991, pp. 23-25.

¹²¹ *Creative Destruction*, Richard Foster and Sarah Kaplan, 2001, pg. 16.

“Cultural lock-in – the inability to change the corporate culture even in the face of clear market threats...results from the gradual stiffening of the invisible architecture of the corporation, and the ossification of its decision making abilities, control systems, and mental models. It dampens a company’s ability to innovate or to shed operations with a less-exciting future.”

It is interesting to note that Foster and Kaplan use the other two terms of dynamic forces (stiffness and damping) to define the third force (inertia). They further define the cause of inertia being three general fears – cannibalization of important product lines, channel conflict with important customers and earnings dilution that might result from a strategic acquisition.¹²² Researchers at Stanford University have also defined inertia in terms of an organization’s complexity and opacity¹²³ and in fact, the notion has appeared in the popular business press in books like MacKenzie’s *Orbiting the Giant Hairball*.¹²⁴

The second part of Newton’s equation, “acceleration” defines the “force field” within which the mass or organization moves. This is an *exogenous* property of the environment, however, I will discuss how it too can be designed and controlled. What does “acceleration” mean to a business manager? What notion does it conjure up to a CEO that is intuitive and in language that is meaningful to her? The answer is possibly simpler than one would expect. This “force field”, this “pull of gravity” that brought the falling apple onto Newton’s head, is actually the “force of competition” in the business world – which too can be calculated from Newton’s laws.¹²⁵

Newton’s second law of motion, which defines the motion of the pendulum and the oscillation of the building undergoing an earthquake can be generalized to cover even more amazing dynamics – namely the motions of the heavens, the orbits of the moon around the earth and the earth around the sun (see figure 2.30 below)¹²⁶.

¹²² *Ibid*, pg. 17.

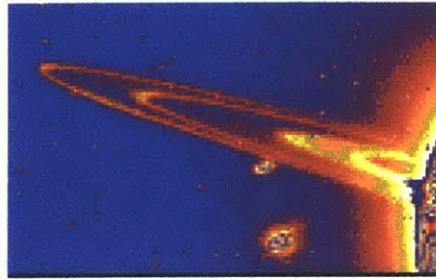
¹²³ “Structural Inertia and Organizational Change”, Michael T. Hannan, Laszlo Polos, and Glenn R. Carroll, Research Paper No. 1734, April 2002.

¹²⁴ MacKenzie, Gordon *Orbiting the Giant Hairball: A Corporate Fool’s Guide to Surviving with Grace*, 1998.

¹²⁵ Others have also supported this insight including: “Understanding the Home Market Effect and the Gravity Equation: The Role of Differentiating Goods”, Robert C. Feenstra, James A. Markusen and Andrew Rose, No. 6804 in National Bureau of Economic Research Working Papers, 1998. Richard Koch, *The Natural Law of Business*, 2000, pg. 119.

¹²⁶ Mirowski (1989) notes that this use of physical metaphor of celestial bodies in the unification of physics and economics was already discussed in Walras’ 1909 article, “Economie et Mécanique”.

Figure 2.30: The Pull of Gravity – The Force of Competition



Newton's Second Law of Motion can be written in its more general form called the "Law of Universal Gravitation":

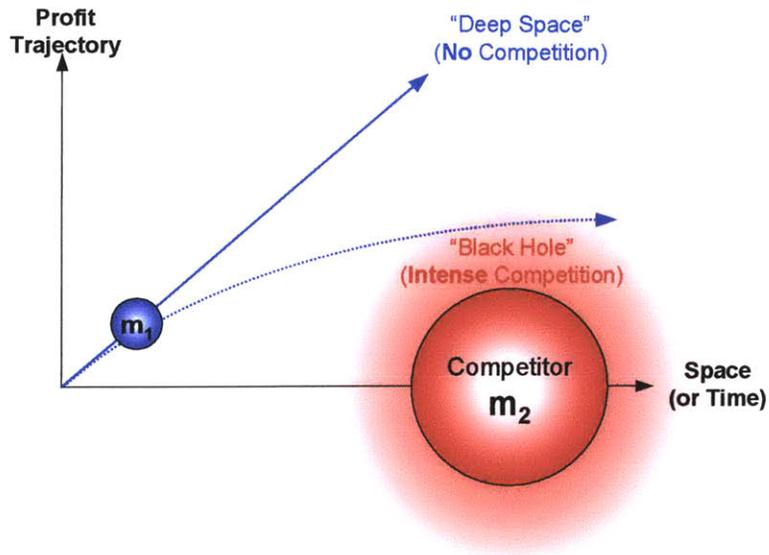
$$F_{\text{gravity}} = G \frac{(m_1 * m_2)}{r^2}$$

Now I have explicitly defined two masses, m_1 and m_2 : ranging from Newton's tiny apple vs. the massive earth to the tiny *Apple Computer* company (of the 1980s) vs. the massive *IBM* (of the same time).

The second and more important parameter is the distance between the two bodies, or more accurately, the square of the distance between the two bodies, r^2 . In business terms, this could be the distance in "market space", between two firm's products or services. This market space could be defined using micro-economic definitions of "cross-price elasticity of demand"¹²⁷. In other words, the closer you get to a rival's product offering, the more intense the competition, the lower the potential profits. If you offer the same product in the same space as a large established competitor (who enjoys economies of scale and possibly network externalities), you will get pulled into it, crashing like a comet to its surface. In the limit, an uncontrolled monopolist is like a "black hole" with infinite gravity where nothing escapes its pull. Conversely, supernormal profits can be earned out in "deep market space" where you are far from competitor's offerings, essentially offering niche, differentiated products. Figure 2.31 below illustrates an organization's "profit trajectory" is unbounded to grow in deep space (that is away from and unaffected by competitors). However the pull of competition, like the pull of gravity, "bends" space and depresses profits.

¹²⁷ *Microeconomics*, Pindyck and Rubinfeld, 2001, pg. 32-33.

Figure 2.31: The Acceleration of Competition



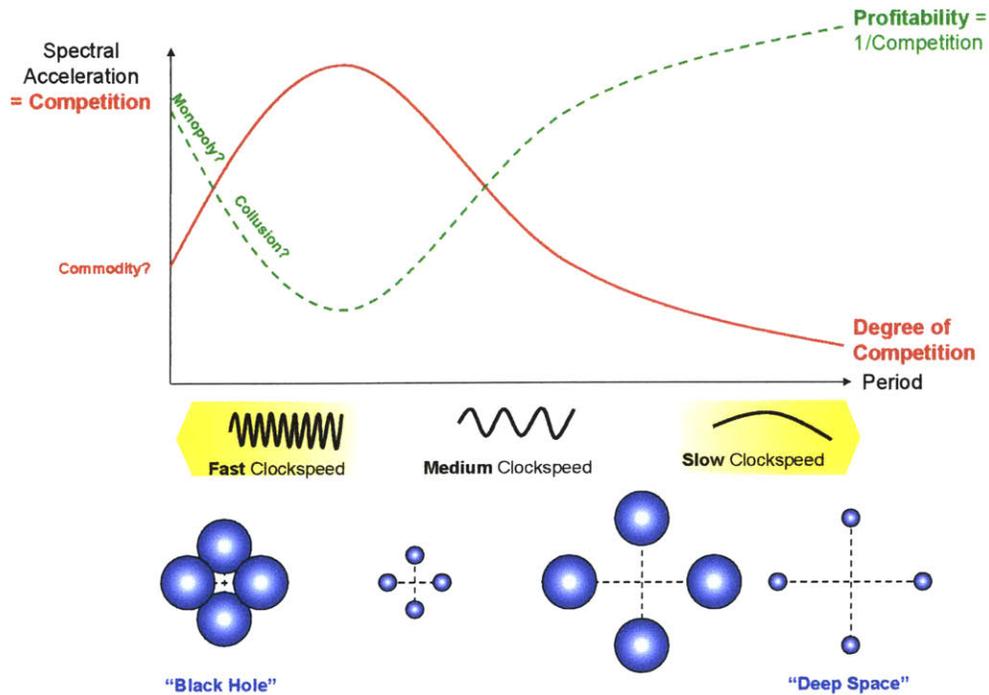
This “Law of Universal Competition” (as it might be called) therefore states that distance and relative mass (= size*density) are both important, but distance is the biggest lever to success. Therefore, although this force field is exogenous to your enterprise or organization, one can design strategies that chart the path, orbit or trajectory of one’s organization to maximize profits in the face of competition.

Now I can re-integrate our concept of clockspeed within the context of a field of gravitation or competition, and plot a spectrum of enterprise on our “enterprise response spectra”. If we recall the natural period (of either a pendulum in the earth’s gravity field, or of a celestial body in space is equal to:

$$T_n = 2\pi \sqrt{(\text{length of string}/\text{gravity})}$$

It is clear therefore that as the strength of the gravity field defines clockspeed, so the strength of the competitive space defines clockspeed. In other words, the speed of oscillation of your enterprise is a function of the relative mass or your enterprise, as well as the distance you are to your competitors. This is shown in figure 2.32 below. *Note that as an approximation, I conjecture that profitability is a function of the inverse of the degree of competition.* As we can see, the keys to profitability lie in the extremes of the spectrum.

Figure 2.32: “Spectral” Competition



At the right, small niche players subject to distant competitors create a weak gravity/competition field like deep space (slow clockspeed environment on the right of the figure) where supernormal profits can be earned. But a note of caution – as you earn supernormal profits in deep space, you are likely to expand by collecting more mass (as you pull-in asteroids through mergers & acquisitions), which in turn attracts other larger competitors into your lucrative space, increasing the gravity of competition and depressing the profitability profile. The business world therefore actually mimics the “big bang” of the universe. The forces of profitability seek expansion into deep space, and yet the same forces cause the accumulation of mass, the attraction of competitors, the reduction of distance, the increase of competition, the depression of profits (towards commodity status) and the final collapse of the universe. To quote the American poet, T. S. Elliot¹²⁸, “... *This is the way the world ends, not with a bang but a whimper.*”

Further to the left, as either competitors get more massive, or closer or both, clockspeeds increase, the amount of competition increases and the profitability decreases. One would expect this trend to increase without limit (and in fact, it may), however, like all dynamic systems, competition would

¹²⁸ “The Hollow Men”, T.S. Elliot, 1925.

tend to fall off settling in on the commodity equilibrium. In the limit, as fewer and fewer larger competitors dominate, the resulting oligopoly (or monopoly) makes supernormal profits possible without exogenous control forces like anti-trust legislation. In reality, without these controls, the world *would* end with a supernova bang.

2.8 *Reactivity: Dynamic Property #2*

Having defined Inertia and Competition, it is now time to turn briefly to the other part of the clockspeed equation, Reactivity and Demand. Let's first focus on "reactivity" which is defined by Newton's third law of motion: "for every action, there is an equal and opposite reaction". In this case I am also interested in how far the system moved when the action was applied.

$$F = kD$$

Spring Force = stiffness * displacement

Again, the stiffness (or reactivity) of an organization is an *endogenous* property of the organization, (whether a firm or a value chain or a nation) which it can design and control. Value Chain Reactivity (like physical stiffness) is a function of the properties of the organization

What is rather interesting is that Newton's "Law of Universal Gravitation" was extended many years later to apply to much larger forces acting over very small distances, like those inside atoms. The Law of Electromagnetism is therefore very similar to Newton's law:

$$F_{\text{electricity}} = k \frac{(Q_1 * Q_2)}{r^2}$$

This law explains how a spring coils back as electrical charges over very small distances oscillate. In the enterprise metaphor, these small but strong forces that cause reactivity can be described in the speed at which information and materials flow throughout the enterprise. As an enterprise is a system with time connecting all the parts, removing such delays forms the basis of "time-based competition"¹²⁹ where direct and responsive links between all customers and suppliers all along the value chain, as well as

¹²⁹ "Time - The Next Source of Competitive Advantage", George Stalk Jr. *Harvard Business Review*, July-August 1988.

minimizing inventory and using just-in-time methods cause a shortening of the supply line. In the pendulum metaphor, this is equivalent to shortening the string. Recall, when the string is shortened, the clockspeed increases. Companies like *Toyota*, *Southwest Airlines* and *Dell* metaphorically have “short strings” (or short delays in their value chains) which means that they are very reactive to customer demands.

2.9 Responsiveness: Dynamic Property #3

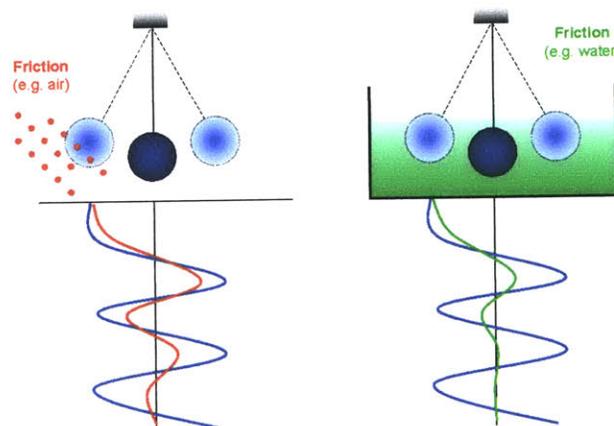
Having defined Inertia and Reactivity, the two parameters that define clockspeed, it is time to briefly discuss the third of the dynamic forces on an enterprise that is the “friction” in the enterprise that is responsible for bringing the enterprise to stop oscillating over time. It is known as the Damping Force or Responsiveness.

$$F = cV$$

Damping Force = viscosity * velocity

Again, the viscosity (or responsiveness) of an organization is an *endogenous* property of the organization, (whether a firm or a value chain or a nation) which it can design and control! Customer Responsiveness (like physical viscosity) is a function of the properties of the organization and its immediate environment. In the pendulum example, viscosity or responsiveness is analogous to the medium through which the pendulum oscillates whether it is air (in which the pendulum swings for a long time) or whether it is water or oil (in which case the pendulum motion comes to rest more quickly) as shown in figure 2.33 below.

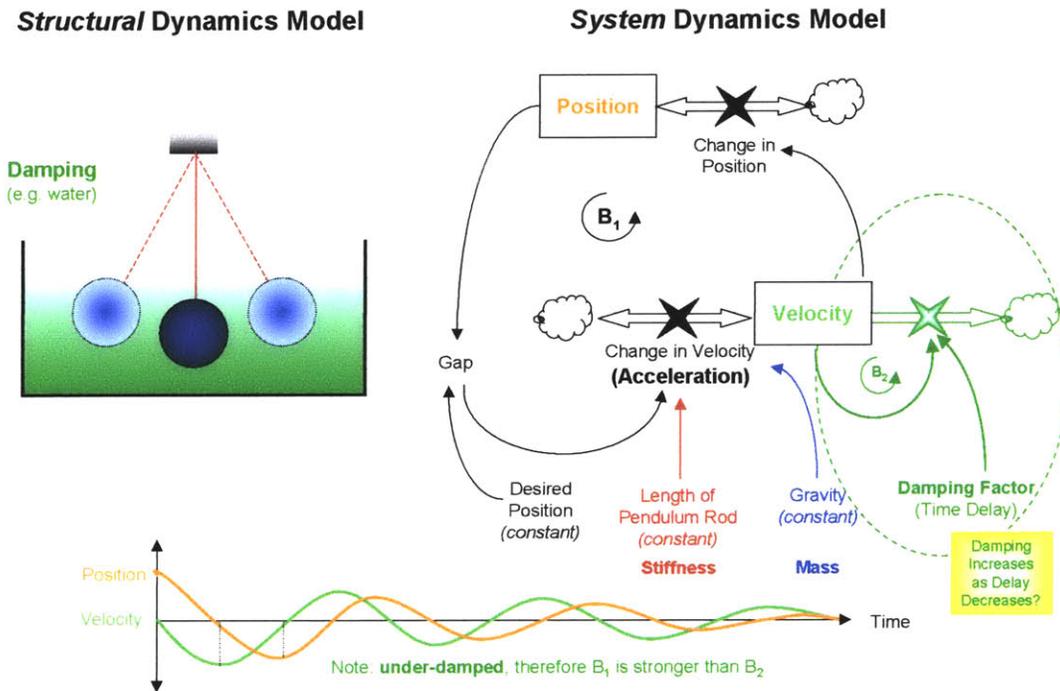
Figure 2.33: The Effects of Viscosity (Responsiveness) on a Dynamic Enterprise



The underlying physics of the damped pendulum is the addition of another balancing loop (a “minor” loop¹³⁰) to the primary pendulum balancing loop as shown in figure 2.34 below. This additional loop (shown in blue) acts to drain velocity away from the system¹³¹.

The speed at which the system comes to equilibrium depends on the system’s degree of damping, which is governed by the damping factor (or time delay). The smaller the time delay, the faster the system comes to rest. In the case shown below, balancing loop B₁ is stronger than balancing loop B₂ as the response is oscillatory and the system is under-damped.

Figure 2.34: Underlying Physics of the Damped Pendulum



Management policies that delay response or average information over time have the effect of reducing variation and therefore reducing oscillation of the enterprise. This will be discussed later¹³².

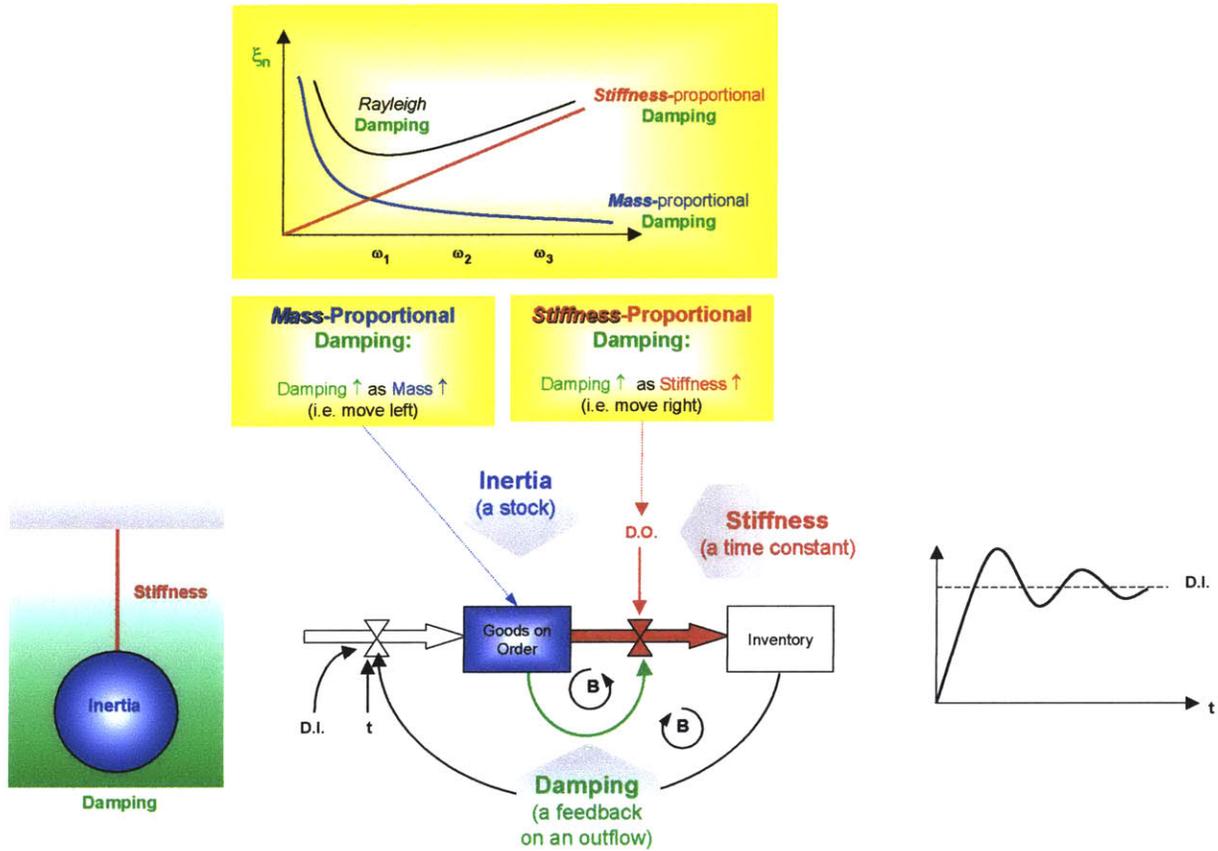
¹³⁰ “Principles on the Relationship Between Structure and Behavior of Dynamic Systems”, Alan K. Graham, MIT PhD thesis, 1977.

¹³¹ “Properties of Damped Oscillations”, Helen Zhu, MIT System Dynamics in Education Project, document D-47-67, June 3, 1998.

¹³² “Generic Structures: Exponential Smoothing”, Kevin M. Stange, MIT System Dynamics in Education Project, document D-4782, 1999.

Finally, before we leave the topic of damping, one might note that enterprise damping has a frequency-dependence which can be expressed in linear combinations of mass and stiffness as shown in figure 2.35 below.

Figure 2.35: Mass & Stiffness Proportional Damping

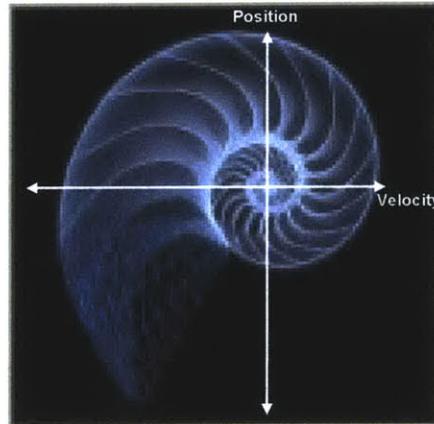


As the damping mechanism is seen to be a feedback loop connecting a stock (i.e. inertia) with an outflow controlled by a time constant (i.e. stiffness), it is clear that damping can be expressed as *mass-proportional*, *stiffness-proportional* or any linear combination of these two (e.g. *Rayleigh damping*).¹³³

¹³³ For a more detailed description of the formulations of damping, see Chopra, pp. 418-419.

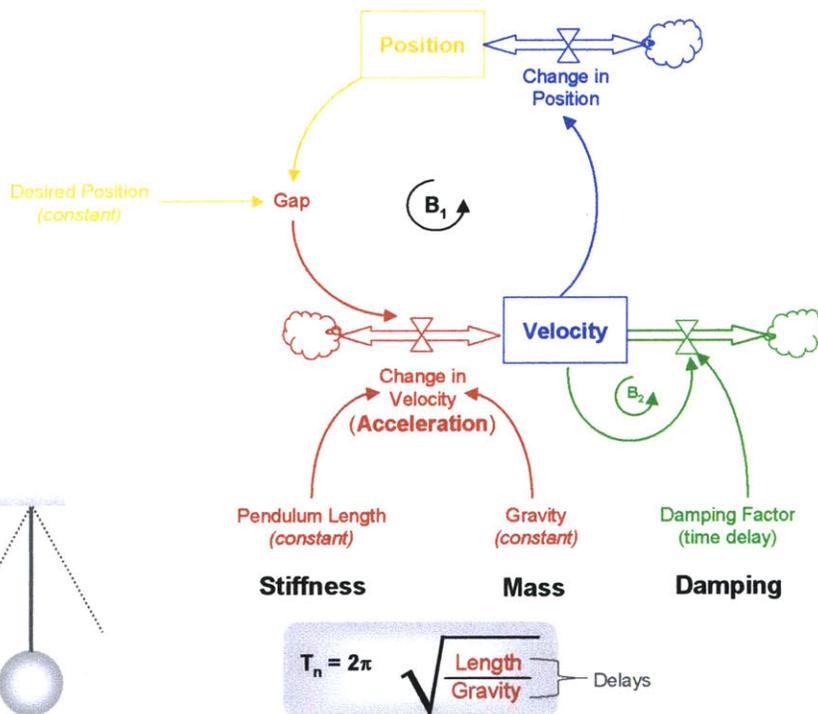
Recall that the two “states” which define the dynamics of the pendulum are velocity and position, therefore the “state-space” diagram for an undamped pendulum is a circle, while the state-space diagram for the damped pendulum is a spiral as shown in figure 2.36 below.

Figure 2.36: State-Space Diagram of the Damped Enterprise



Having defined the three structural properties of enterprises (inertia, damping and reactivity) as well as the three response quantities or state variables (displacement, velocity and acceleration), we can now summarize them on the pendulum archetype in figure 2.37 below.

Figure 2.37: Summary of Three State Variables and Three Structural Properties



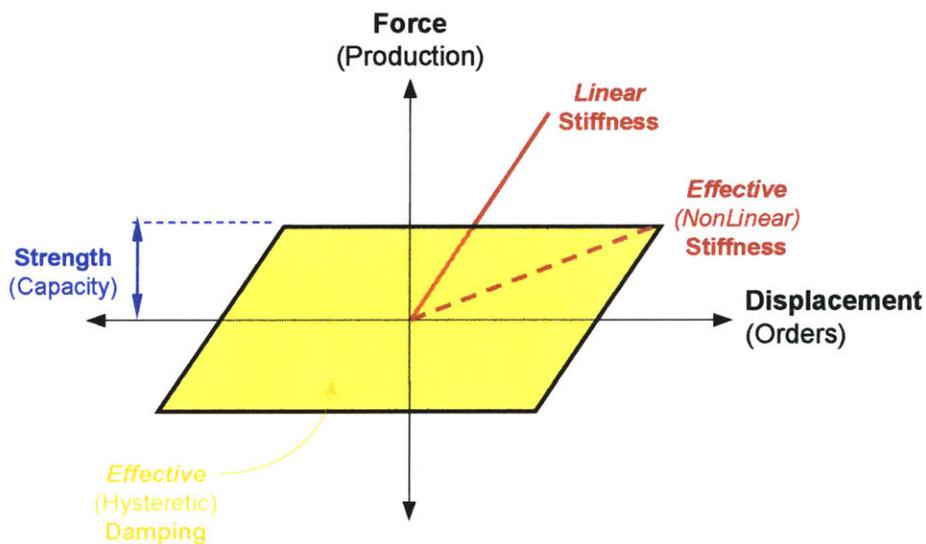
2.10 Strength & Toughness: Dynamic Properties # 4 & 5

The three primary dynamic properties of organizations (inertia, responsiveness and reactivity) are those required to describe the dynamics of enterprises that are confined to the *linear* range of response. However, often in the real world, organizations have finite capacities, and thus exceedance of these properties leads to *nonlinear* behavior.

The fourth dynamic property of enterprises, which applies only in the nonlinear range, is enterprise *strength* (or “carrying capacity” in system dynamics parlance). The most obvious example of organizational capacity is a manufacturing firm’s production capacity, which will be discussed and explored in more detail in chapter 3.

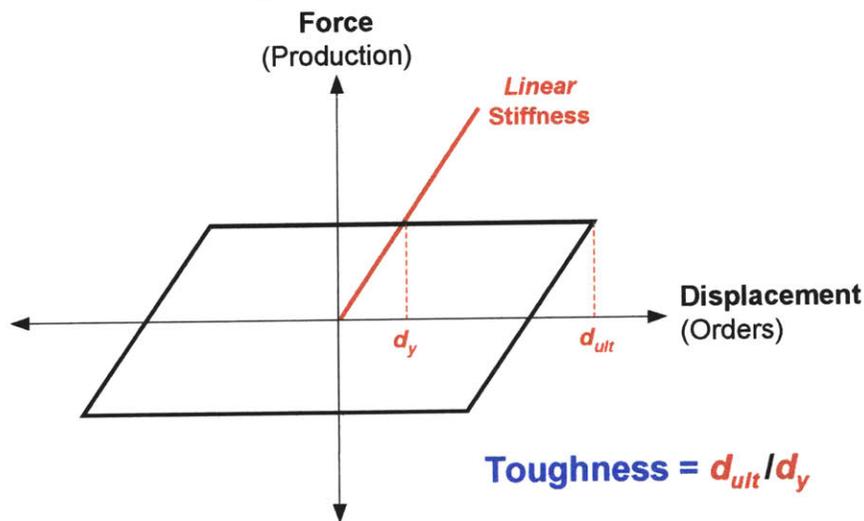
Enterprise strength is intimately connected with the linear dynamic properties of reactivity (stiffness) and responsiveness (damping). As shown in figure 2.38 below, the exceedance of enterprise strength has two effects: decreasing the effective enterprise reactivity (stiffness) and decreasing the effective enterprise responsiveness (increasing the effective damping). The effective damping is the area (in yellow) under the force-displacement curve, also known as enterprise *hysteresis*. This hysteretic damping supplements the linear damping that exists in the system.

Figure 2.38: Enterprise Strength and Effective Enterprise Stiffness and Damping



The notion of the exceedance of strength (or capacity) without collapse reveals another enterprise property: enterprise *toughness* (or ductility). Toughness is the ability to deform inelastically without collapse. As shown in figure 2.39 below, it is the ratio between the ultimate displacement and the linear elastic displacement at strength. It is interesting to note that enterprise strength and toughness are important properties that define how cost-effective an enterprise is. This will be discussed further in chapter 9.

Figure 2.39: Enterprise Toughness

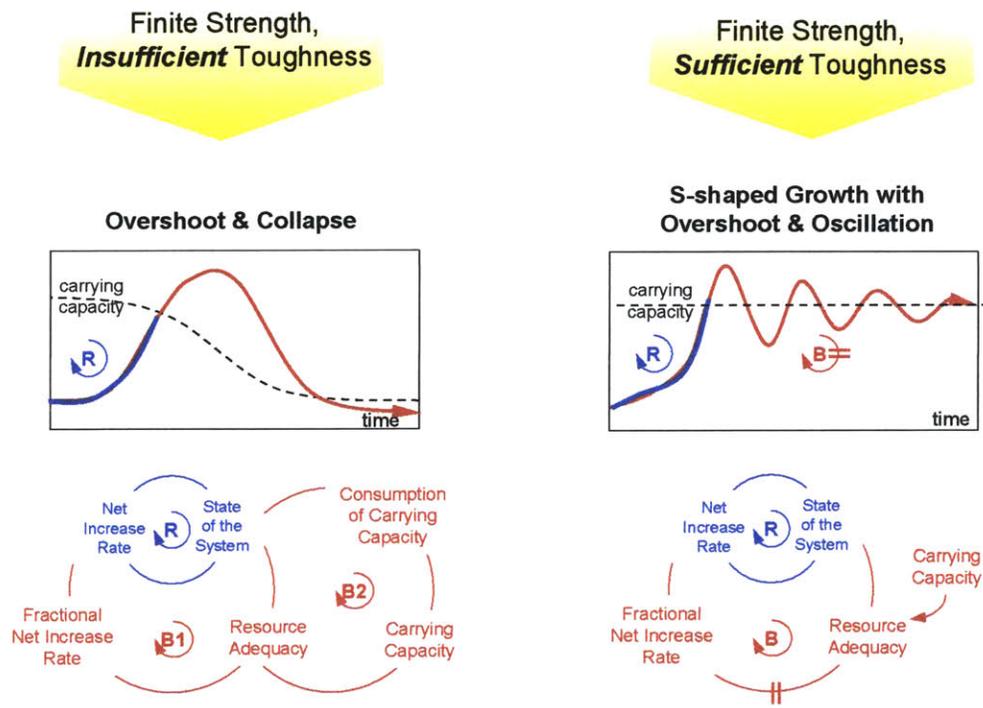


Finally, it is interesting to note that enterprise strength is synonymous with enterprise *carrying capacity*. If the carrying capacity is exceeded, and secondary effects take over, the result can be “overshoot and collapse”. As shown below in figure 2.40, both strength and toughness are needed to define the potential for collapse.¹³⁴ These concepts are both rooted in the physics of structural dynamics as well as in system dynamics as demonstrated in socio-environmental systems like the earth’s natural carrying capacity.¹³⁵

¹³⁴ When loading is near-static, toughness does little to help prevent collapse, based on the ratio of t_d/T_n . However, when loading is dynamic, toughness is an essential property for economic enterprise performance.

¹³⁵ *World Dynamics*, Jay W. Forrester, 1971, and *Limits to Growth*, Meadows et al., 1972.

Figure 2.40: Enterprise Strength and Toughness Prevent Collapse



To summarize this chapter so far, we have demonstrated that the dynamic response of an enterprise is dependant upon two things:

- the clockspeed of the enterprise relative to the clockspeed of the environment (as introduced by the concept of the response spectrum), and
- the strength (or carrying capacity) and toughness of the enterprise.¹³⁶

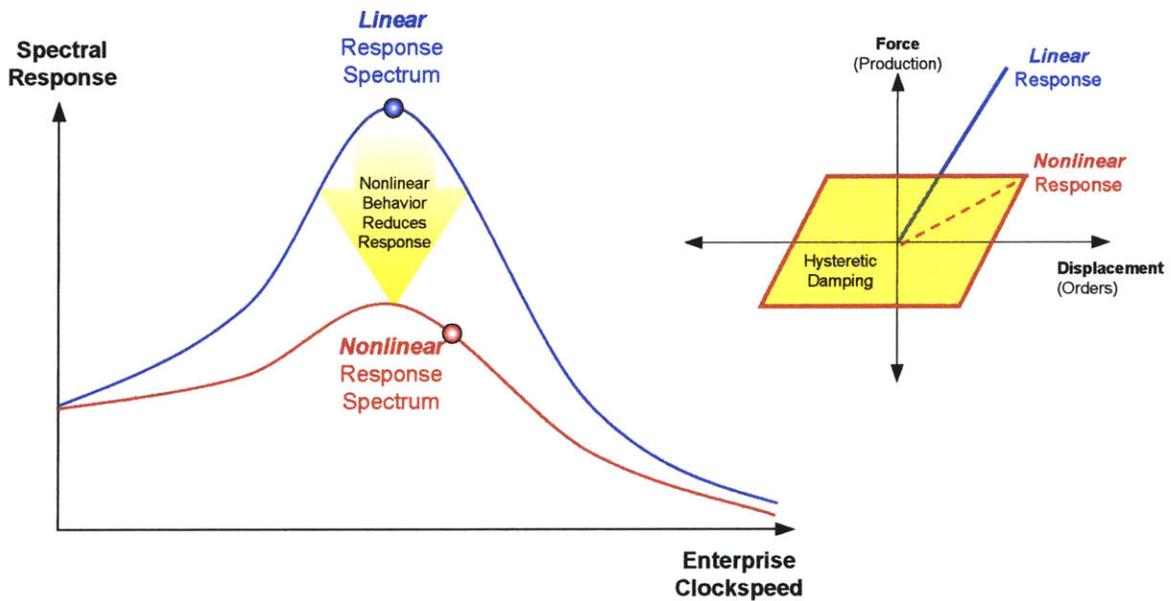
We will next extend the concept of an enterprise response spectrum (which illustrates the relationship between enterprise & environment dynamics) to include the effects of relative strength of the enterprise relative to the environmental demands.

¹³⁶ Note that strength and ductility are important quantities in quantifying the dynamic response of structures to earthquakes (response spectra) and blast loading (shock spectra).

2.11 *Strength-Modified Enterprise Response Spectra*

A strength-modified response spectrum is a response spectrum which takes into account the finite carrying capacity of most enterprises. In essence, we are modifying the previously discussed linear elastic response spectra by factors which are a function of their ability to deform inelastically without collapse. As discussed above, exceedance of the finite enterprise capacity creates an enterprise with lower effective stiffness and higher effective damping. On our linear response spectrum, this equivalent to a shift in enterprise response to the right and downward respectively as shown in figure 2.41 below.

Figure 2.41: Strength-Modified Enterprise Response Spectra



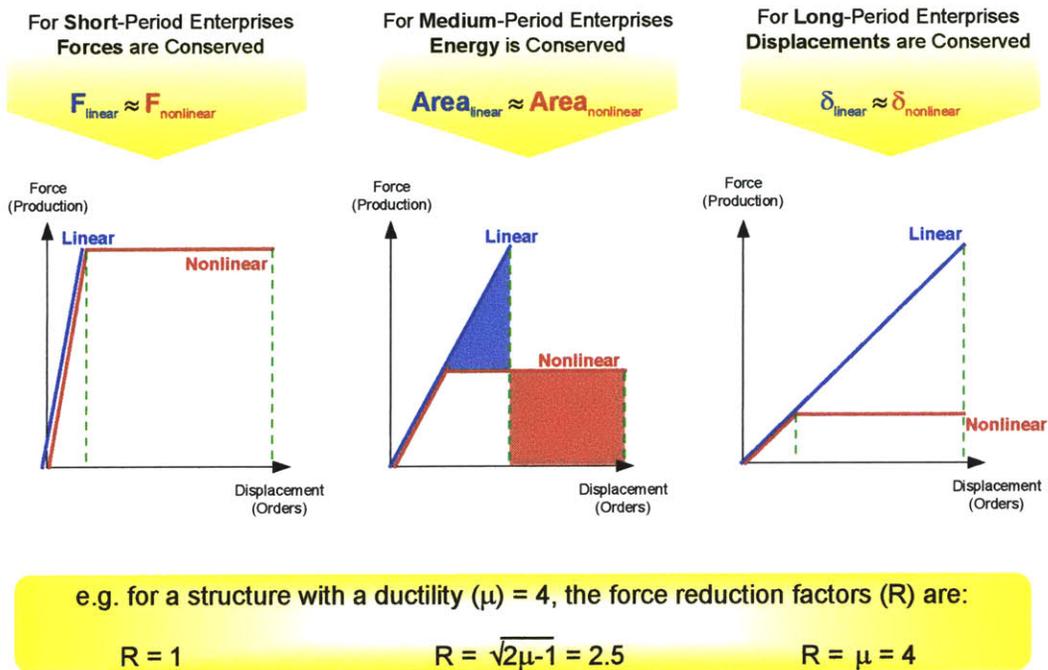
Preliminary parametric studies on the system dynamics model with varying period and varying degrees of capacity appears to reveal the following trend:

- For short-period enterprises (relative to the forcing period), production is conserved.
- For intermediate-period enterprises (relative to the forcing period), energy is conserved (i.e. the difference between the areas under the linear and nonlinear curves).
- For long-period enterprises (relative to the forcing period), orders are conserved.

These three heuristics (shown in figure 2.42 below) were derived from the field of nonlinear structural dynamics taken from earthquake engineering.¹³⁷

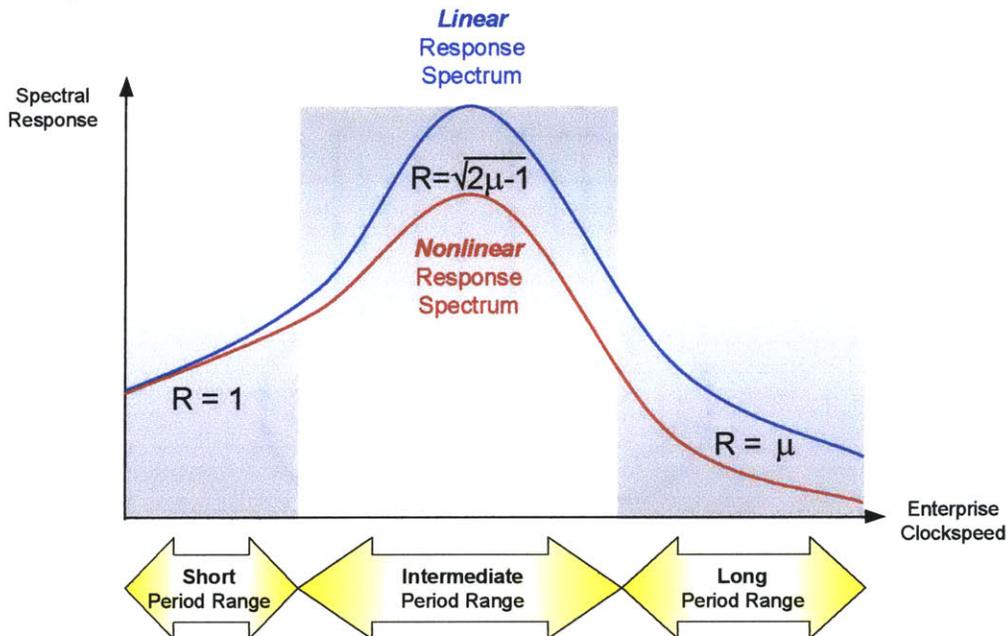
¹³⁷ Nathan Newmark and Emilio Rosenbleuth, *Fundamentals of Earthquake Engineering*, 1971.

Figure 2.42: Newmark's Method for Constructing Nonlinear Response Spectra



These application of these heuristics for force reductions on nonlinear spectra are shown below in figure 2.43.

Figure 2.43: Strength-Modified Reductions for Enterprise Response Spectra

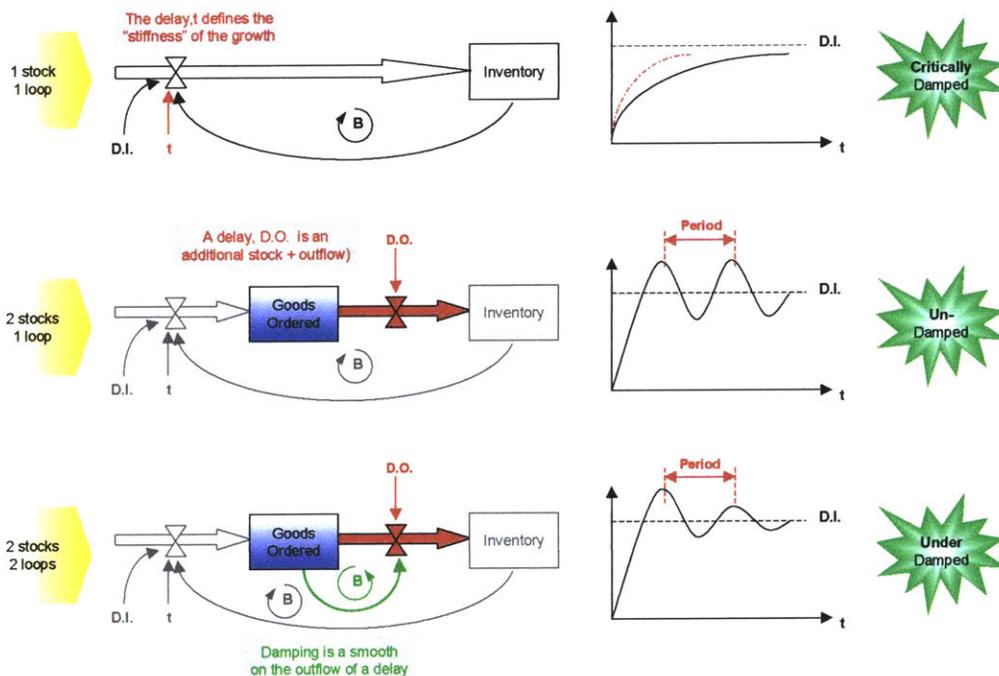


2.12 The Mechanics of Time, Delays and *Time-Based Competition*

We will conclude the theoretical part of “Physics 101” by discussing the mechanics of time. Managing dynamic complexity is essentially about mastering an enterprise’s most precious commodity, time. This is a difficult and challenging task, as time (or delay) is hiding in almost every technical or physical aspect of an enterprise and more importantly in almost every social or behavioral aspect of an enterprise. What makes it more difficult is that time (or delay) is sometimes harmful to an enterprise’s competitive advantage, and sometimes it is helpful. As Sterman notes: “Some delays breed danger by creating instability & oscillation. Others provide a clearer light by filtering out unwanted variability and allowing managers to separate signals from noise.”¹³⁸

In the discussion that follows, I attempt to uncover the nature of delays in socio-technical systems using both the system dynamics and structural dynamics methodologies.¹³⁹ I begin by exploring three simple structures shown in figure 2.44 below and identifying the dynamic components of each. (Note that inertia is shown in blue, stiffness is shown in red and damping is shown in green.)

Figure 2.44: Impact of Delays on Mass, Stiffness and Damping



¹³⁸ John Sterman, *Business Dynamics*, pg. 409.

¹³⁹ Much inspiration for this endeavor is taken from Forrester’s *Principles of Systems*, 1968.

The top part of the figure shows a simple one stock, one loop system with a balancing loop controlling the inflow. This type of behavior leads to goal-seeking growth. Using a physical analogy, it is like a ball rolling down a hill in a very viscous environment (like molasses). The time delay defines the “stiffness” or severity of the growth curve. As there is no overshoot or oscillation, the system contains a lot of damping – in fact (as the system eventually attains its growth goal), it is “critically damped”.

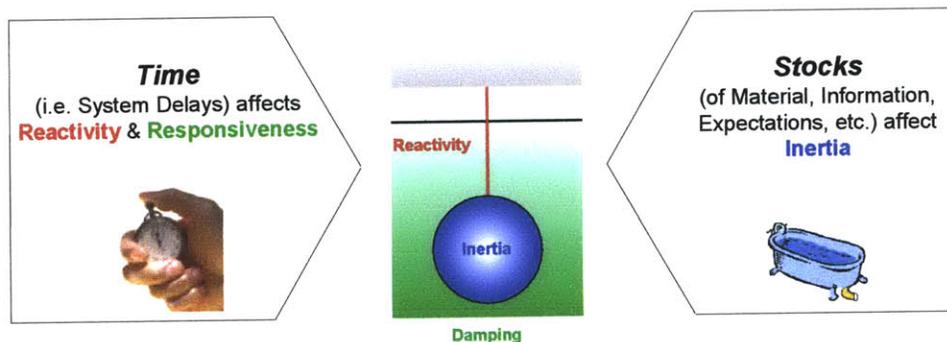
In order to produce oscillatory behavior, we need to introduce another piece of structure into the main balancing loop. As we know that oscillation arises from a delay on a balancing loop, we must introduce a *delay structure* which can be seen in the middle part of the figure as an additional stock and outflow. We now have a two-stock, one loop system. Note that the response now has a clear periodicity – which we defined before as being a function of both inertia and stiffness. Therefore we know that we must have introduced both a “piece” of inertia as well as a “piece” of flexibility (which is the inverse of stiffness). As is shown in the figure, the inertia is actually the stock and the flexibility is actually the time controlling the outflow. To be clear, the new inertia is not actually due to the existence of a new stock (i.e. metaphorically a new bathtub), but more correctly the amount of material or information (i.e. water) in the bathtub. So when Sterman notes that, “delays give systems inertia”¹⁴⁰, he means more precisely that *delay structures* give systems inertia. Delays themselves give systems reduced stiffness (i.e. flexibility) and stocks of material or information give systems inertia. Together, the two (stocks and associated controlling time delays) give systems their inertia and flexibility and therefore their periodicity. Finally note that we have gone from critically damped behavior to completely undamped behavior.

In order to produce damped oscillation, we must add a second minor loop on the outflow. As shown in the bottom portion of the figure, we now have a two-stock, two-loop system. Damping is actually a smooth on the outflow of the delay. Note that we now go from undamped to underdamped behavior.

¹⁴⁰ John Sterman, *Business Dynamics*, pg. 423.

To summarize therefore, *time* (the governing mechanism controlling rates) is the source of two enterprise properties: enterprise stiffness (or reactivity) and enterprise damping (or responsiveness). *Stocks* (e.g. material, information or perceptions) are the source of enterprise inertia. *Delay structures* involve the addition of a stock with an outflow controlled by a delay time. The stock (of the delay structure) therefore gives the system inertia or memory, while the delay time (of the delay structure) gives the system flexibility or possibility damping. Returning to Sterman’s observation about the “schizophrenic” nature of delays, we can now add some more clarity: “Some delays breed danger by creating instability & oscillation (*i.e. by reducing stiffness like adding to a pendulum’s length*). Others provide a clearer light by filtering out unwanted variability and allowing managers to separate signals from noise (*i.e. by adding damping*).” See figure 2.45 below.

Figure 2.45: Enterprise “Mechanics of Materials”



$$T_n = 2\pi \sqrt{\frac{\text{Enterprise Inertia}}{\text{Enterprise Reactivity}}} \sqrt{1 - \text{Enterprise Damping}^2}$$

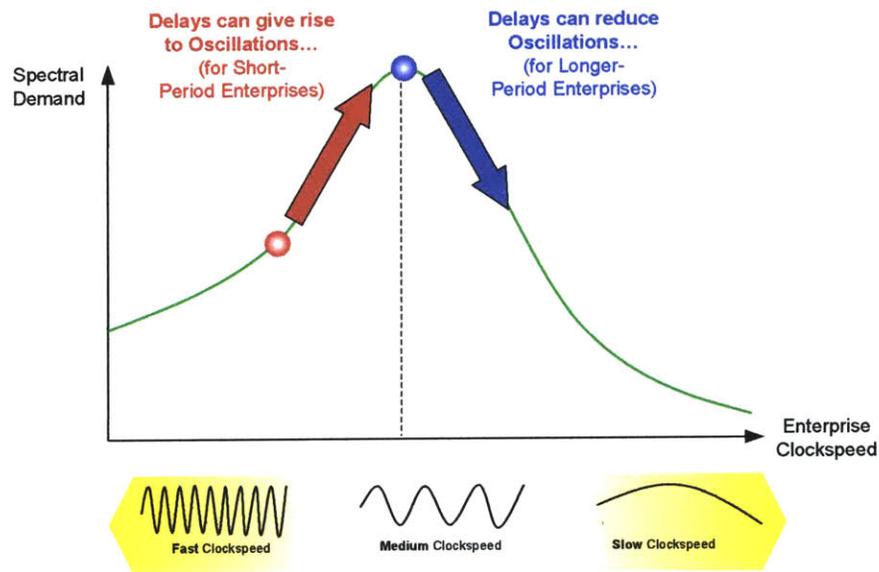
The management application of this theory of the mechanics of time became known as “time-based competition”.¹⁴¹ In the late 1980s, *Boston Consulting Group’s* George Stalk took Forrester’s 1961 work on *Industrial Dynamics* to note one of the reasons why Japanese companies were so dominant. He

¹⁴¹ Stalk Jr. G., “Time: The Next Source of Competitive Advantage,” *Harvard Business Review*, July-August 1988, pp. 41-51.

observed that they took an integrated view of the system or enterprise, and reduced the consumption of time throughout the system. By focusing on the delays in the system, Stalk was exploring only one of the dynamic structural properties, the stiffness or reactivity. He noted that by removing the delays, one could shorten the pendulum length, speed up the clockspeed and gain competitive advantage.

While this is an important observation, it does not present a complete picture of the full dynamics of the problem – i.e. it considers only the dynamics of the enterprise and not that of the environment. As shown in figure 2.46 below, depending on where the enterprise is on the response spectrum (i.e. where its dynamics lie relative to the dynamics of its environment), delays can either give rise to oscillations (for short-period enterprises) or they can reduce oscillations (for long-period enterprises).

Figure 2.46: The “Relativity” of Time



For example, we must explain why *Airbus* has become such a formidable competitor to *Boeing*, when its strategy does not explicitly embrace time-based competition via the compression of delays, but conversely by slowing down its clockspeed via the increase of enterprise inertia. This will be discussed in later chapters.¹⁴²

¹⁴² A more detailed discussion of delays is given in Appendix C.

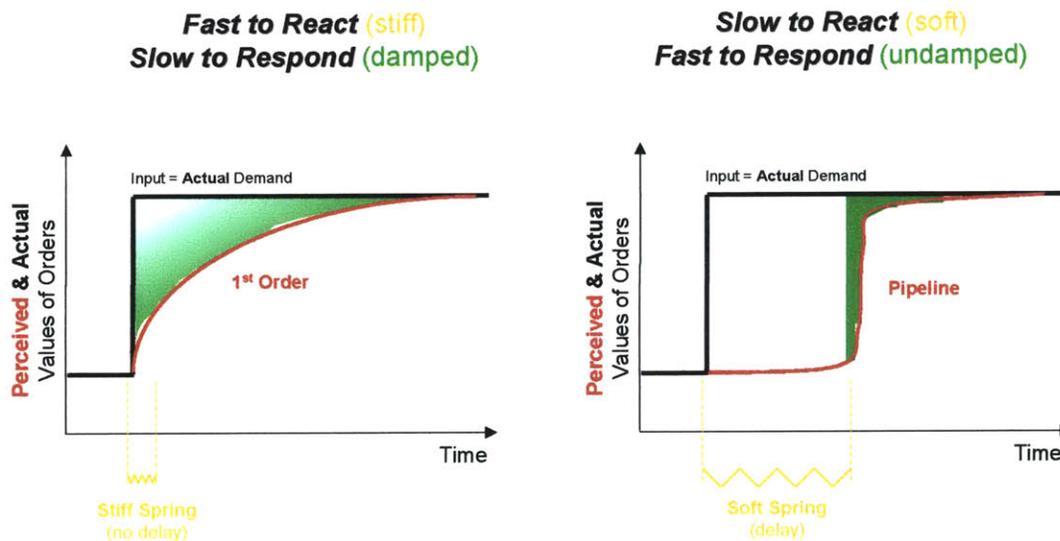
2.13 Enterprise Physics Example: *Decision Dynamics*

I will now briefly examine a few management insights attempting to capture some or all of the concepts of enterprise physics. I begin with an exploration of the dynamic effects of delays in managerial decision-making.

When changes are presented to management, like a change in customer demand for products, there are delays in management's ability (or desire) to make decisions on these changes. Delays therefore slow things down, increasing an enterprise's clockspeed. The question remains, are these delays a function of an enterprise's inertia, responsiveness or reactivity? The answer is: all of these.

As Sterman notes, these delays give rise to *inertia* in the enterprise.¹⁴³ Forrester demonstrates that the way in which a delay is represented (either as a single stock or as a series of multiple stocks) impacts the amount of high-frequency *damping* exists in a system.¹⁴⁴ See Appendix C for a further description of this. Finally, the delay obviously injects a static time offset, and therefore reduces the enterprise stiffness or *reactivity*. Figure 2.47 below summarizes the dynamics embedded in the representation of delays.

Figure 2.47: The Physics of Decision Dynamics



¹⁴³ Sterman, John, *Business Dynamics*, 2000, pp. 423.

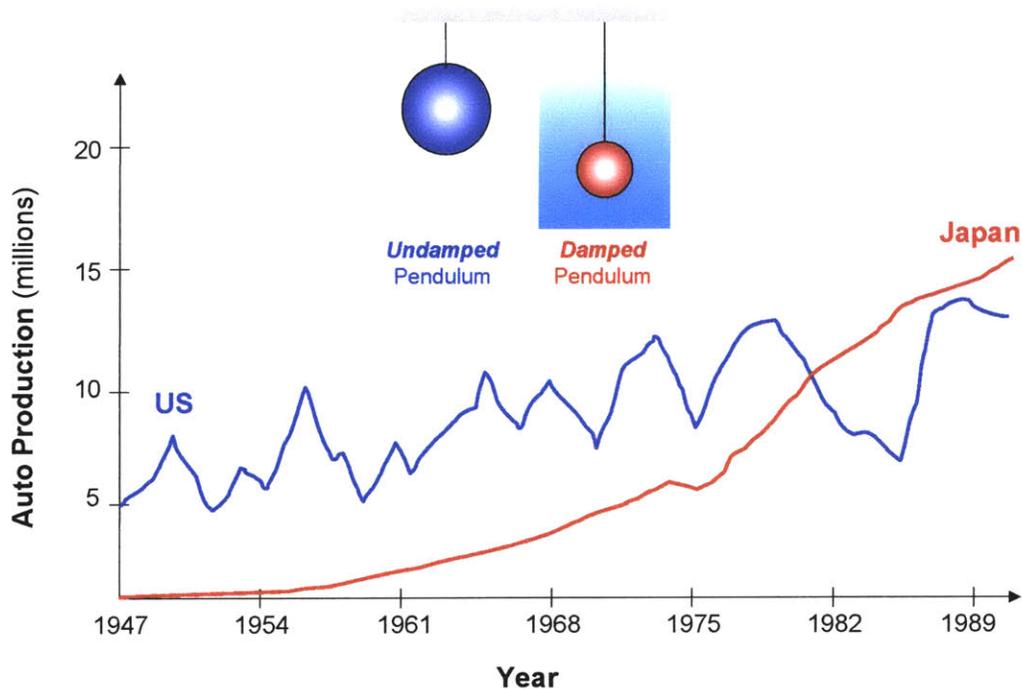
¹⁴⁴ Forrester, Jay, *Industrial Dynamics*, 1961, pp. 419.

2.14 Enterprise Physics Example: *Mass(ive) Production*

Next, we will examine the notion of “mass” production – a term used to characterize a dominant microeconomic industrial strategy in the U.S. in the majority of the 20th century, but also playfully, a term that uses the inertial force (or mass) to describe its underlying dynamics. The term “mass” production was originally intended to relate that production was for the “masses” of people, and was therefore created in “mass” quantities. It is an interesting linguistic coincidence to note that the physics of “mass” production is largely based on the fact that the enterprise structure has large amounts of inertial “mass”.

A review of figure 2.48 below shows a comparison of U.S. mass production-style with Japanese lean production-style outputs in the global automotive industry. I will reiterate and expand on a few of the points made by the original researchers.¹⁴⁵

Figure 2.48: The Dynamics of Mass(ive) Production



¹⁴⁵ Womack, Jones & Roos, *The Machine That Changed the World*, The Free Press, 1990, pp. 246-250.

“Westerners are resigned to the idea of the business cycle. Like gravity, its simply there, although no one quite knows why... Mass production is, in fact, a system ideally suited to the survival of large enterprises in a highly cyclical economy. Both workers and suppliers are considered variable costs. When the market goes down, the assembler companies jettison their human and organizational ballast and expect to find their workers and suppliers pretty much where they left them once conditions improve.”

A General Motors executive, was reported as commenting on the data in figure 2.48:

“When the Japanese [meaning lean] producers encounter these gigantic market waves, they will quickly become as mediocre as we are. They will have to start hiring and firing workers along with suppliers and will end up as mass-producers in short order.”

The researchers go on to conjecture:

“... widespread adoption of lean production may dampen both inflation and the business cycle. If mass production is ideally suited to the survival of big companies through deep cycles in demand, it may also be cycle-enhancing. That is, its penchant for massive inventories, both of in-process parts and finished units, would seem to exacerbate the cycle: As inflation builds, stocks are built up against expectations of yet higher prices. This move pushes prices up farther. Then, when the economy suddenly falters, the built-up stocks are worked off, deepening the slump upstream in the production system.

Some observers have even wondered if the lack of a cyclical market in durable goods in Japan is a direct result of lean production: an inventoryless, highly-flexible system may significantly damp cyclicity.

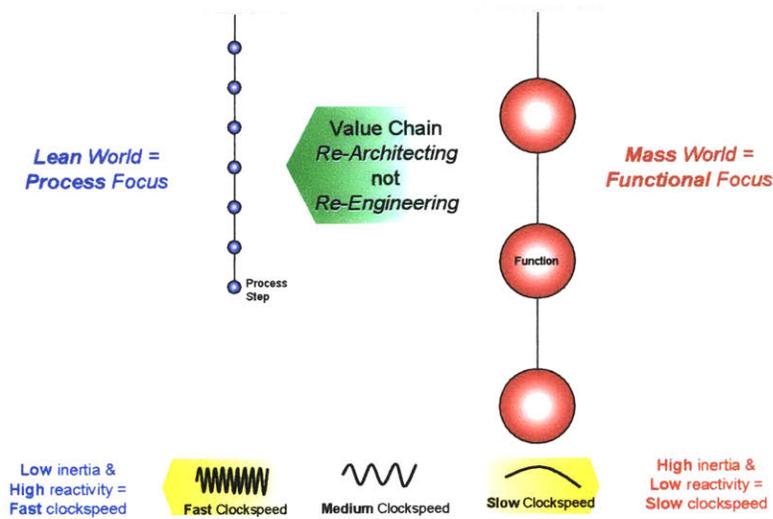
The Japanese have another cycle damper in their arsenal in the form of flexible compensation. Most employees at all levels in Japanese companies receive a large part of their compensation – up to a third – in the form of bonuses are directly tied to the profitability of the company. So when a market drops, at least in theory, the company can dramatically slash prices due to lower operating costs and restore production to its former level.

These observations can shed some light on the underlying dynamics of each system. For example, mass production is like an undamped pendulum with a larger mass and shorter (less flexible) length which can produce a faster clockspeed than lean production, as is evidenced by the five year business cycle periodicity. The absence of a period of oscillation in lean production is possibly due to a combination of the above-mentioned highly-damped, more-flexible (longer length) and less massive pendulum. The massive mass production pendulum swings with rapid, powerful oscillations, while the lean production pendulum swings with slower, controlled movements.

2.15 Enterprise Physics Example: *Value Chain Reengineering*

By way of another quick example, I will use the laws of enterprise physics to demonstrate that Business Process Reengineering¹⁴⁶ can have the simple effect of increasing the enterprise’s clockspeed – which by definition makes it more competitive. Business Process Reengineering “obliterates” value chains by disaggregating mass from vertical functional silo-based organizations into less massive, value streams focused on a customer and a specific product/service offering. In addition, it eliminates Non-Value Added activities that act to shorten the supply line, in effect stiffening up the pendulum by making the string shorter. Both the reduction of inertia and the increasing of reactivity work to increase the organization’s clockspeed. Figure 2.49 below illustrates schematically how reengineering works.

Figure 2.49: Dynamics of Reengineering the Enterprise

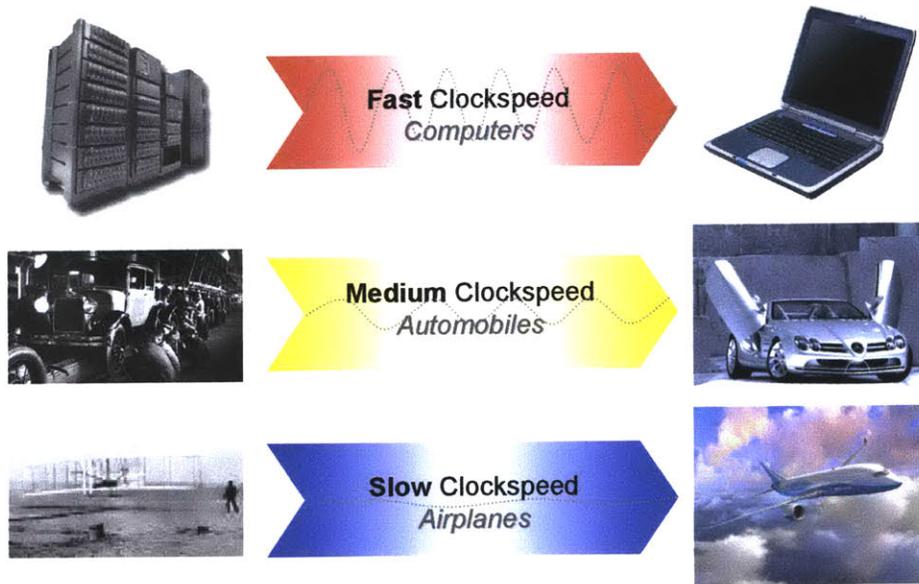


2.16 Enterprise Physics Example: *The Machines that Changed the World*

Having laid out the basic “laws” of enterprise physics, one can then assemble an example matrix of industries having differing clockspeeds and investigate the dynamics of their responses to various inputs. Consider for example, three technological artifacts that have shaped economic development over the past century: the airplane, the automobile and the computer as shown in figure 2.50 below.

¹⁴⁶ *Reengineering the Corporation: A Manifesto for Business Revolution*, Michael Hammer and James Champy, 1993.

Figure 2.50: *The Machines that Changed the World*



One could estimate the clockspeeds of each industry, and Fine¹⁴⁷ has proposed a disaggregation of industry into its product technology, process technology and organizational clockspeeds as shown in figure 2.51 below.

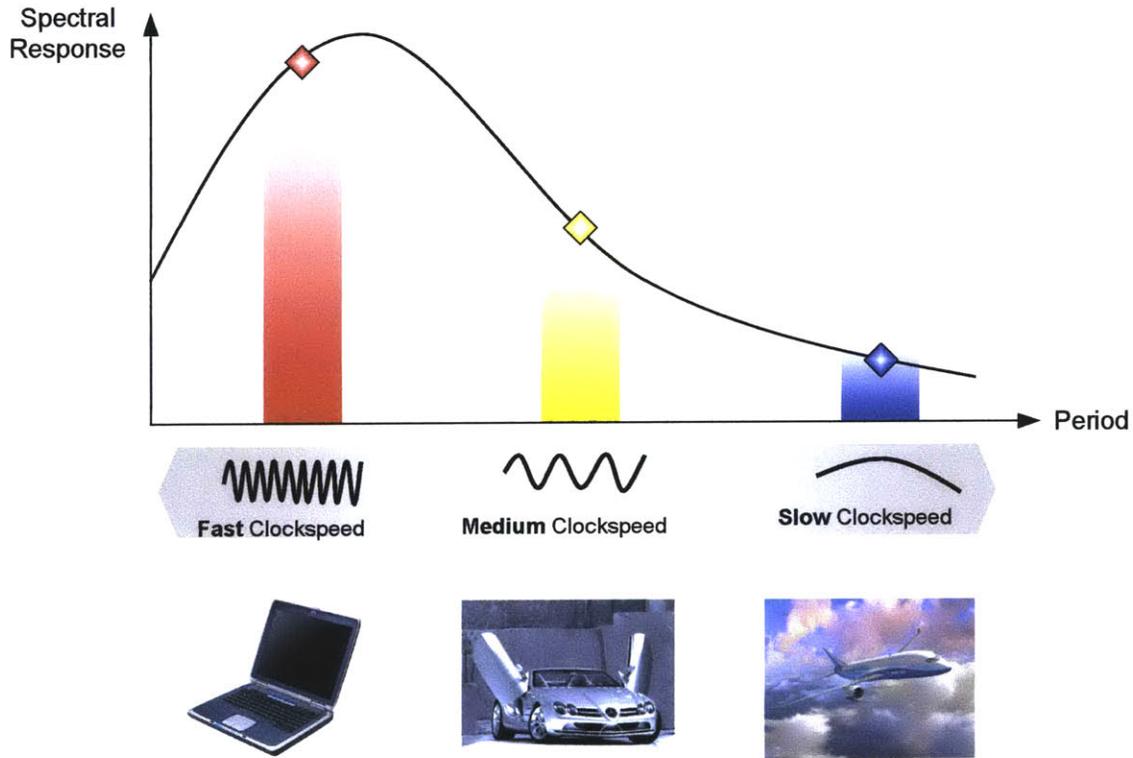
Figure 2.51: Clockspeeds of *The Machines that Changed the World*

	Product Technology Clockspeed (years)	Process Technology Clockspeed (years)	Organization Clockspeed (years)
Fast Clockspeed Computers	<1	5	10
Medium Clockspeed Automobiles	5	10	15
Slow Clockspeed Airplanes	10	15	20

¹⁴⁷ Charles H. Fine, appendix to *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*, 1998, pg. 239.

Finally, one could plot these clockspeeds on a typical macroeconomic design spectrum in order to observe the relative maximum responses of each industry to a dynamic input like the five year business cycle as shown schematically in figure 2.52 below.

Figure 2.52: Response of *The Machines that Changed the World*



2.17 Enterprise Heuristics

Now that I have defined some of the key dynamic “laws” of enterprise physics, we can now develop insights, or heuristics (or “meta-laws”) that govern the behavior of enterprises. For example:

*Just because you are in a slow clockspeed industry,
does not mean that you can behave slowly.*

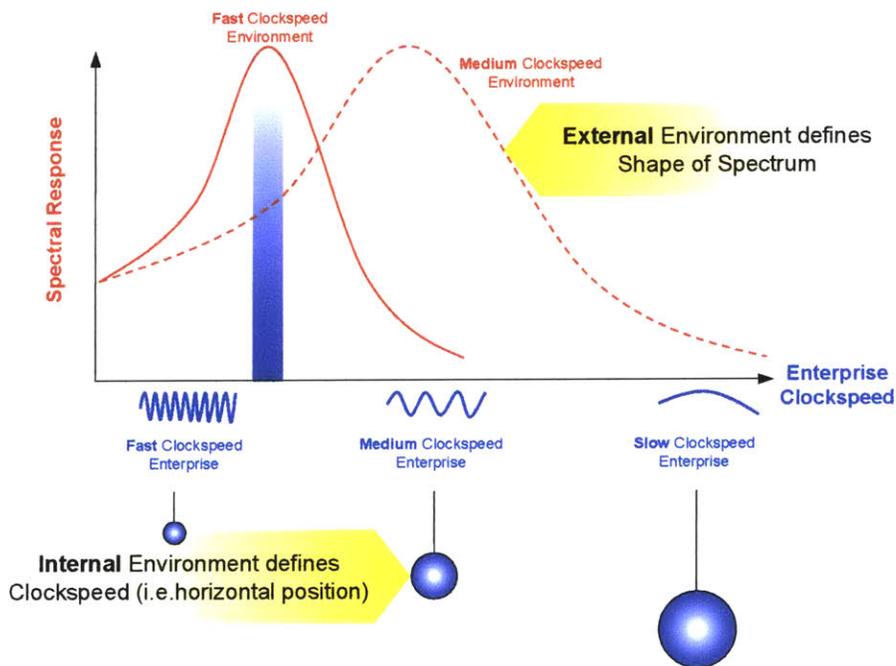
What is embedded in the equation of organizational clockspeed is the recognition that a lot of organizational inertia creates a slow clockspeed, however it for this very reason that if you want to move that organization, you must begin now with a slow but sustained force. If you wait and then try to push all at once, the required force will be too large.

A follow-up enterprise heuristic arises from the definition of an enterprise design spectrum as discussed in section 2.5:

An enterprise's clockspeed is an endogenous, controllable quantity.

A SWOT analysis¹⁴⁸ reveals that a firm's performance is a function of both its external (exogenous) environment in the form of opportunities and threats as well as its internal (endogenous) core capabilities in the form of its strengths and weaknesses. This is represented graphically as shown in figure 2.53 below as the shape of a response spectrum is governed largely by its external environment, while the horizontal position along the response spectrum is governed by the internal core capabilities, namely inertia and reactivity.

Figure 2.53: SWOT and the Enterprise Response Spectrum



¹⁴⁸ SWOT (which stands for Strengths, Weaknesses, Opportunities and Threats) is a strategic model to frame a firm's competitive position.

2.18 Chapter Summary

This chapter introduced the physics underlying an enterprise's dynamics. Learning by analogy from the dynamics of a simple [pendulum](#), we extended this generic structure to understand the dynamic behavior of other human enterprises.

We then examined the three [forces](#) (mass, damping and stiffness) that act on any physical enterprise, from which we then derived the equation of the enterprise's [clockspeed](#), finally drawing analogy to the clockspeed of human organizations.

Having defined this clockspeed, or enterprise natural period of oscillation, we then introduced the concept of a rapid design and visualization tool, called an "enterprise [response spectrum](#)" which allowed us to quickly develop intuition about the dynamic behavior of an enterprise based on the relative clockspeed between it and the supporting structure.

We then began to explore the possible extensions of the three physical forces to human organizations being: corporate [inertia](#), value chain [reactivity](#) and customer [responsiveness](#). Finally, we postulated some meta-laws or [heuristics](#) that could lead to the future design of enterprises.

Having covered the fundamentals of enterprise physics in this chapter, in the next chapter we will study a classic enterprise "structure", namely an industrial production-distribution enterprise which is represented as a three-story building being shaken in an earthquake. This will allow us to use the concepts of enterprise clockspeed and response spectrum that we developed in this chapter to understand the dynamic response of a well-known enterprise.

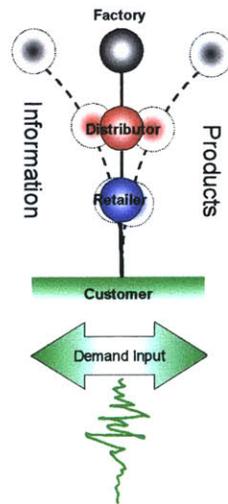
Chapter 3: The Dynamics of Value Chains

The primary focus of this chapter is to explore the fundamental dynamics of a typical enterprise. Later in chapter 9, we will discuss how an enterprise might achieve high-performance using “Lean” enterprise principles. Therefore, I briefly introduce here the important Lean concept of “stability” in order to be aware of the causes of enterprise oscillations. As we perform experiments on the enterprise, we should begin to think about strategies and policies to mitigate such instabilities.

3.1 Enterprise Description

I will now run a series of dynamic experiments on the three-degree of freedom enterprise shown below in figure 3.1, which represents a typical enterprise value chain. This is the original “classic” production-distribution model that Jay Forrester used in 1961 to demonstrate the field of system dynamics¹⁴⁹.

Figure 3.1: Three-Degree of Freedom Enterprise Model



Like a three-story building being shaken by a horizontal earthquake ground motion, the production-distribution model can be thought of as a three degree-of-freedom system that has three sectors consisting of retailer, distributor and manufacturer. Within each sector (i.e. each colored sphere),

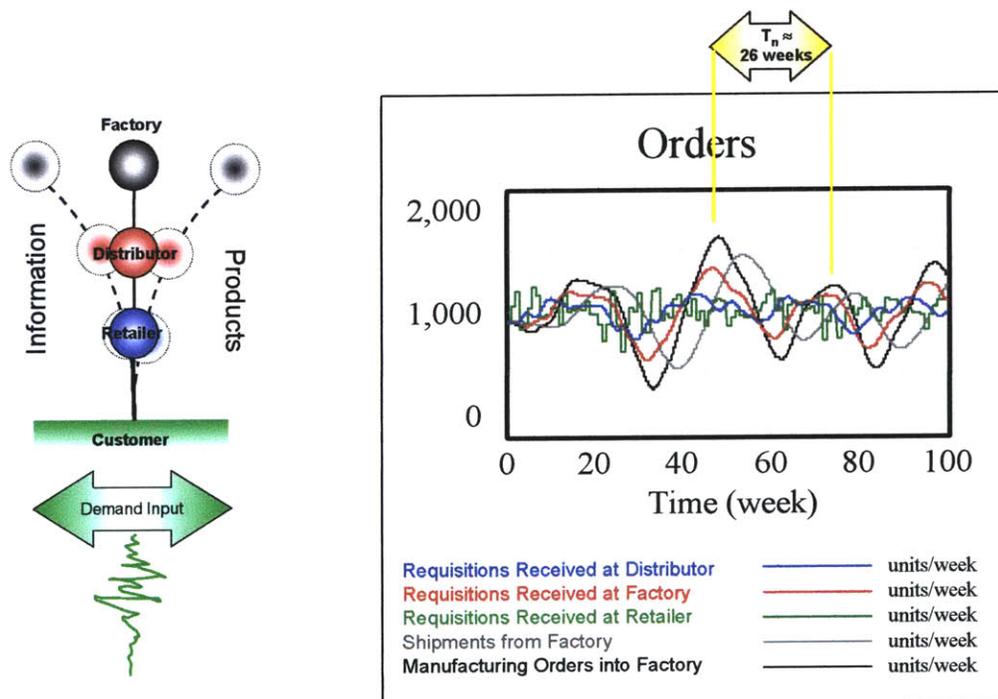
¹⁴⁹ *Industrial Dynamics*, Jay Forrester, 1961, pg. 137-186.

3.2 Enterprise Natural Period of Oscillation

First, I will subject the enterprise to a random noise signal and monitor the inherent dynamics embedded in the enterprise. From Figure 3.5 below, we can observe first hand the nature of the “bull-whip”. The blue, red and black lines corresponding to the orders for the retailer, distributor and manufacturer are each larger in amplitude, signifying that the orders are being amplified up the value chain, just like a building’s top floor moves more than its lower floors when subjected to an earthquake. I also note that there is a phase shift (or a delay) from the black line to the gray line that indicates the manufacturing lead-time in the factory from orders received to products delivered.

Finally, and most importantly, one can observe the clockspeed or natural period of vibration of this enterprise as the random noise causes the system to react in the dynamic way that it naturally wants to. This enterprise has a natural period of vibration of about 26 weeks or one half year.

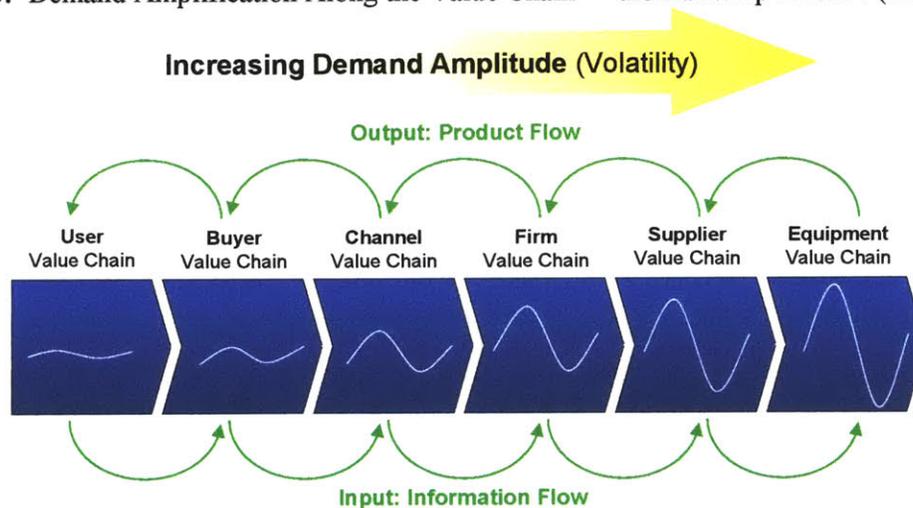
Figure 3.5: Enterprise Natural Period of Vibration (from Random Noise)



3.3 Demand Amplification along the Supply Chain

From figure 3.5 above, we can see that there is a demand amplification as you move further up the supply chain, that is as you move from customer to retailer to distributor to manufacturer. This demand amplification is shown in figure 3.6 below. This phenomenon is well-documented^{151,152} and in fact various management simulations like “the Beer Game” have been developed to demonstrate this effect^{153,154}. Recently Fine noted that this bull-whip effect is a characteristic of a “fulfillment” supply chain, as distinct from “technology” and “architecture” supply chains¹⁵⁵.

Figure 3.6: Demand Amplification Along the Value Chain – “the Bullwhip Effect”. (source: Fine)



3.4 Developing Enterprise Response Spectra

From this model, we can begin to derive the Enterprise Response Spectrum – the concept that we introduced in section 2.5. In the following four analyses, I subjected our “26-week period” enterprise to four different dynamic customer demand sinusoidal inputs: 13-week period, 26-week period (matching the enterprise period), 52-week period and 104-week period. The results are shown in figure 3.7 below.

¹⁵¹ *Industrial Dynamics*, Jay Forrester, 1961.

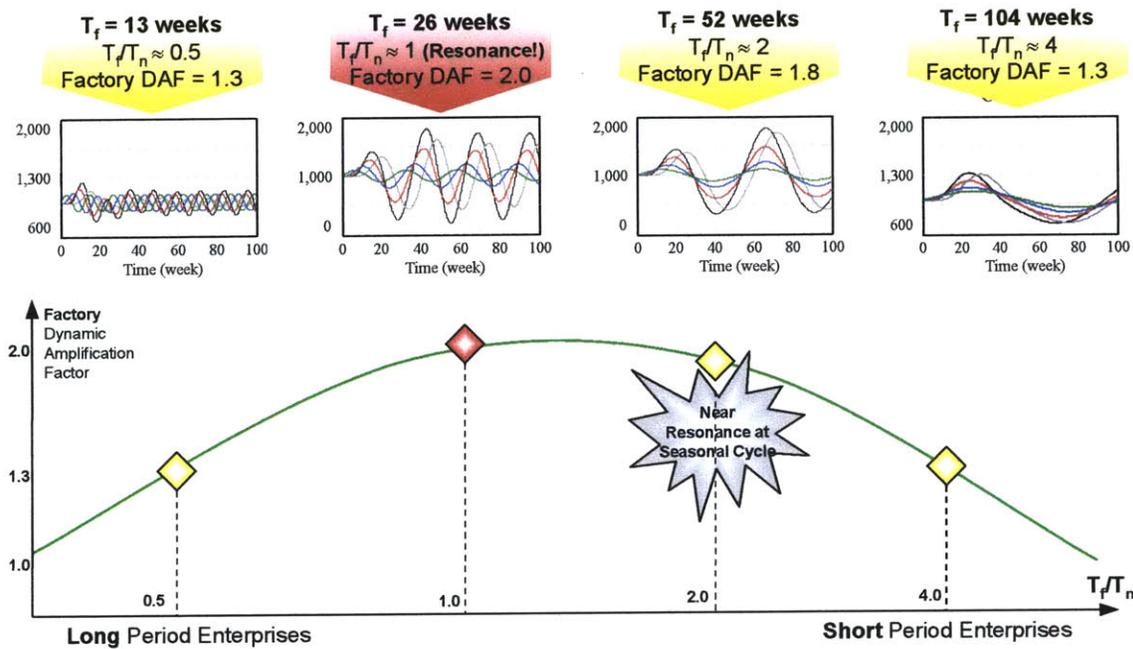
¹⁵² *Business Dynamics*, John Sterman, 2001.

¹⁵³ *The Fifth Discipline*, Peter Senge, 1990.

¹⁵⁴ *Business Dynamics*, John Sterman, 2001.

¹⁵⁵ *Clockspeed*, Charles Fine, 1998.

Figure 3.7: Enterprise Response Spectra and the Bullwhip Effect



Note that for each case, one can plot the maximum “bullwhip amplification”, or Dynamic Amplification Factor (DAF) defined as the ratio between the peak customer amplitude (i.e. “the ground” in the building metaphor) and the manufacturer (i.e. “the roof” in the building metaphor). Note that when the forcing period of 13 weeks is faster than the 26-week enterprise period, (i.e. the structure *behaves* as if it were slow clockspeed) then the maximum amplification is only 1.3. What is happening is that the customer demand is changing so rapidly that the enterprise does not have time to adjust resulting in small waves being sent up the value chain. This is called “hyper-dynamic” response.

When the forcing period begins to slow down to 26 to 52 weeks (i.e. the structure *behaves* as if it were medium clockspeed), it starts to go into resonance with the enterprise’s own inherent dynamics. This causes the maximum amplification of approximately 2.0. This is called resonant dynamic response – the bullwhip is in full effect. Note as an aside, if this enterprise were in an annual or bi-annual seasonal/cyclical business (like the construction industry) then the enterprise would be in a perpetually bad state, unless it designed its dynamics to lie outside the seasonal cycles – more on that later.

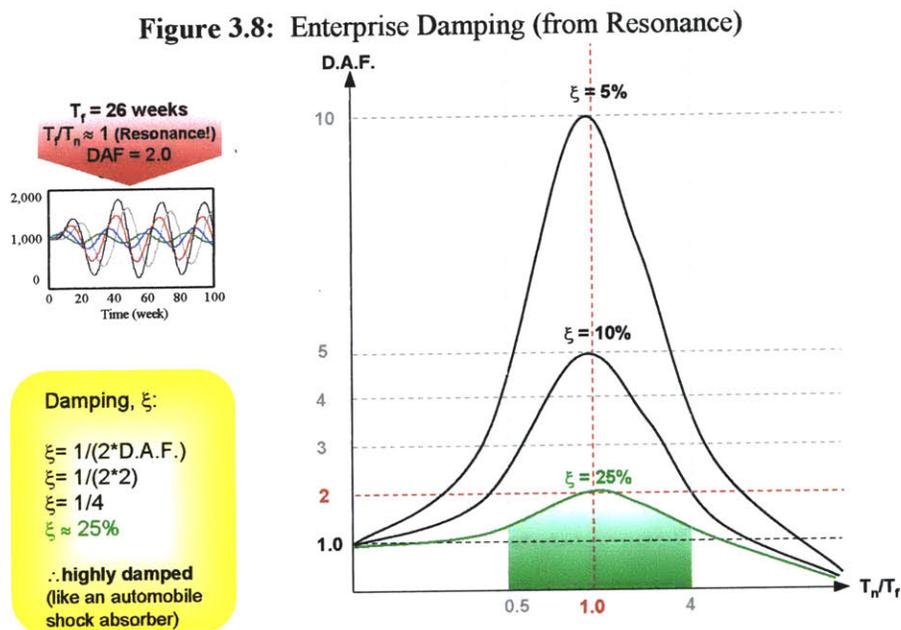
Finally, when the forcing period begins to slow down much further to say 104 weeks (i.e. the structure *behaves* as if it were fast clockspeed), it doesn’t even create dynamic energy, and the enterprise

moves with the customer demand signal as if it were a static problem. This causes the maximum dynamic amplification to approach 1.0 in the limit.

When I plot these four points and fit them to a curve, I have created an enterprise response spectrum, which managers and designers can then refer to and make decisions on without having to run expensive, time-consuming analyses. Another name for such curves in the engineering and physics world are “transmissibility curves”, which we will continue to discuss below in the context of enterprise damping (or responsiveness).

3.5 Determining Enterprise Damping

One can now estimate the amount of damping inherent in such a complex human enterprise. Figure 3.8 below plots the enterprise response spectra for the production-distribution system that we are studying having differing amounts of damping (or responsiveness).

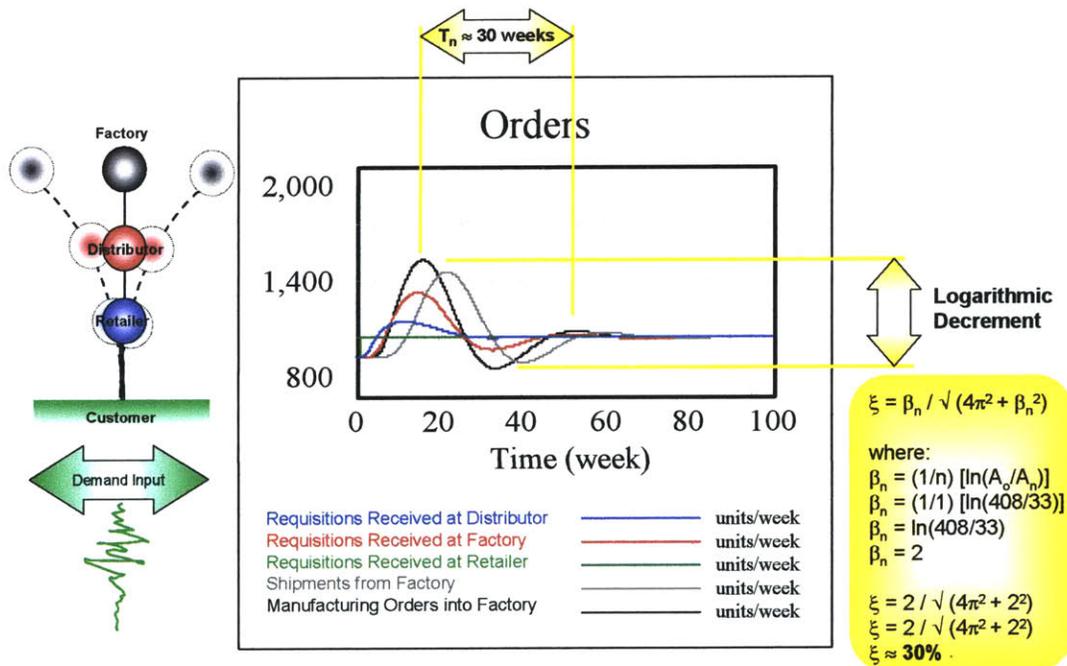


From this I first note that the green line and green shaded area shown above in figure 3.8 is the same as that shown in figure 3.7. We are now merely looking a larger solution space. A simplified equation for damping is shown in the yellow box in figure 3.8. From this one can calculate that our

enterprise, which has a natural period of ½ year, also has approximately 25% damping. In order to put it into perspective, a physical enterprise like a 10 story building shaking in an earthquake has a 1 second natural period and 2-3% damping. A complex human enterprise therefore moves much more slowly and much less responsively. In fact, at 25% damping, our value chain has as much damping as an automobile shock absorber.

Another means to estimate fundamental period of vibration and damping is to shock the enterprise by hitting its base with a metaphorical hammer. Figure 3.9 below shows a one-time 10% increase in customer orders, and the response of the enterprise to that shock. The period of vibration again is about ½ year. Again we see the presence of the bullwhip, and we see the oscillations die down rapidly due to the large amounts of damping. A second way of estimating the amount of damping is to observe the amount of decay between successive peaks of the response. This is known in the structural dynamics literature as “logarithmic decrement”. As shown in the yellow box below, the damping is estimated to be approximately 30% from the logarithmic decrement method.

Figure 3.9: Enterprise Damping (from Logarithmic Decay)



3.6 Strategy #1: Modifying Enterprise Inertia

Having explored the effects of enterprise amplification, we will now use the three firm production-distribution model to explore different strategies for designing effective enterprises. We will look at each modifying each of the three linear dynamic properties in turn: inertia, damping and stiffness, (in sections 3.6, 3.7 and 3.8 respectively) followed by an exploration of the nonlinear dynamic property of strength or capacity (in section 3.9).

One way to explore the effects of enterprise inertia is to remove one of the firms in the production-distribution chain – for example, by changing Forrester’s three-degree of freedom supply chain¹⁵⁶ to a two-degree of freedom enterprise by removing the distributor. Intuitively, the removal of a link in the chain should increase the enterprise clockspeed – recalling from chapter two the analogy of bullwhip in which a system with distributed mass and stiffness has a longer natural period of vibration with longer length. In addition to a modest decrease in natural period of vibration, one would expect a significant drop in force¹⁵⁷ which is not a function of relative clockspeed as is evidenced in a response spectrum but merely a function of total mass. In other words, if $F = mA$, the force is reduced due to the direct decrease in mass, not necessarily due to a dynamic reduction in acceleration.

Note in the following analyses, that the forcing function is a sinusoid having a natural period of one year. As the natural period of vibration of the base case enterprise is less than one year, we are left of the peak on the elastic response spectrum.

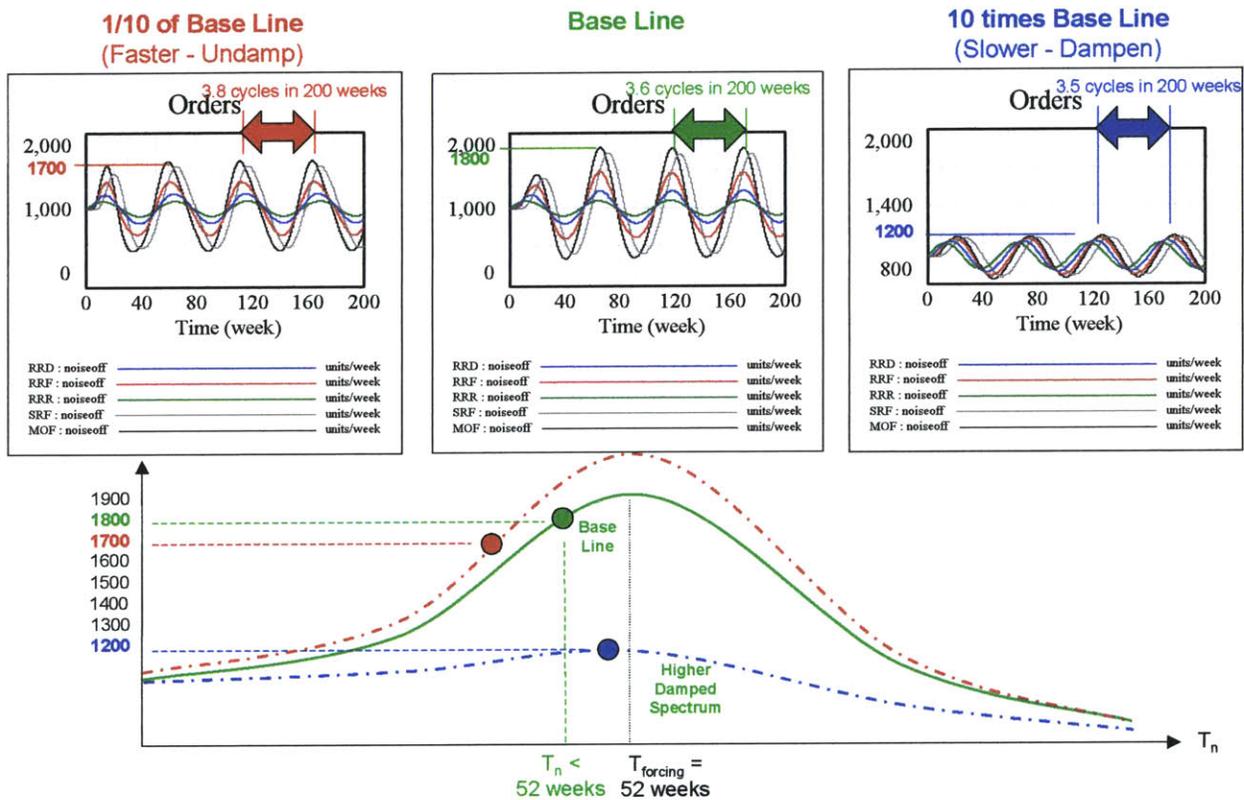
¹⁵⁶ Forrester, Jay W., *Industrial Dynamics*, 1961.

¹⁵⁷ In structural engineering vocabulary, “force” is known as “base shear” or force at the base of the enterprise.

3.7 Strategy #2: Modifying Enterprise Damping

Next, we can examine the effects of modifying enterprise damping. In the production-distribution system, this is done by modifying the speed of inventory adjustment, i.e. by modifying the velocity of flow rates through the supply pipeline. In figure 3.10 below, I explore the effects of varying the inventory adjustment time by a factor of ten times faster and ten times slower than the base case.

Figure 3.10: Effects of Modifying Enterprise Damping



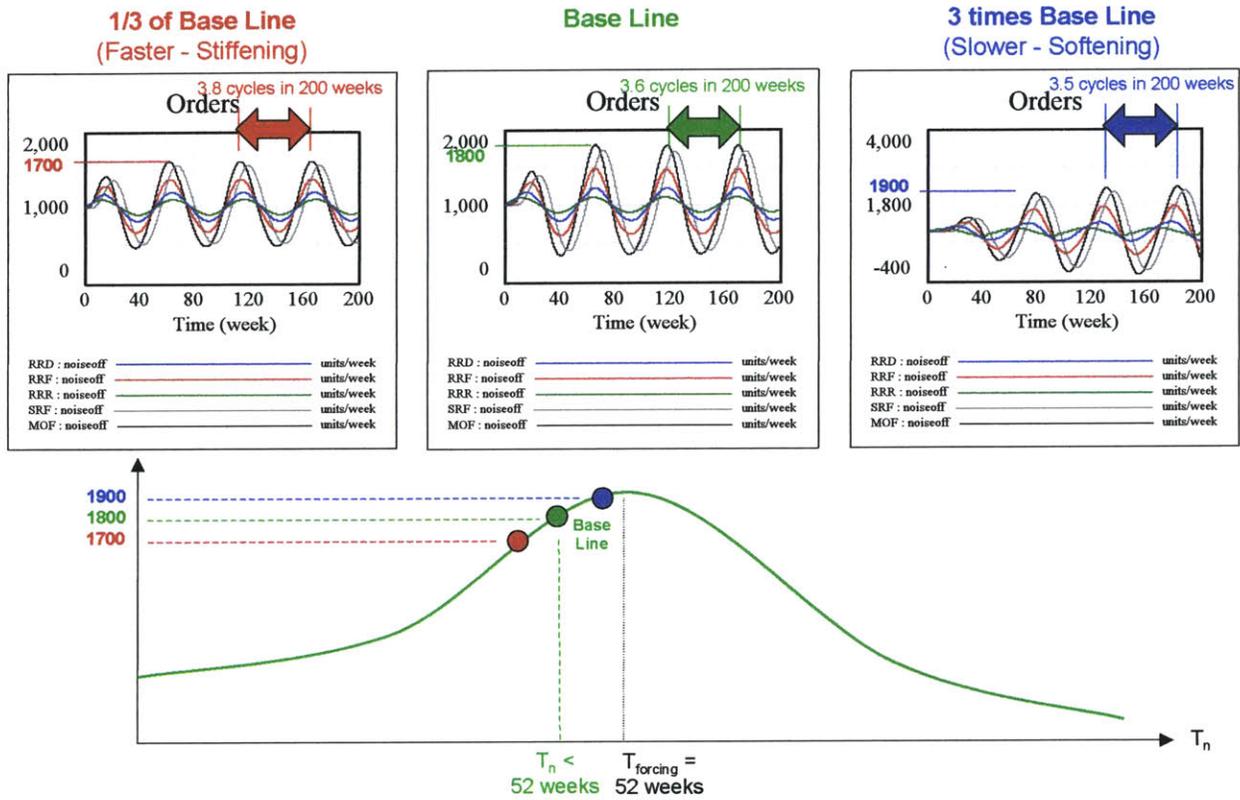
As expected, speeding up flow rates through the reduction of inventory adjustment times decreases the damping (shown in red above). Less damping for a given frequency results in amplification, however, less damping also results in a slight decrease in natural period of vibration, which for this model results in a reduced amplification.

Conversely, slowing down the flow rates through the increase of inventory adjustment times increases the damping (shown in blue above). More damping should both slightly increase the natural period of vibration as well as more importantly decrease the amplification though increased damping.

3.8 Strategy #3: Modifying Enterprise Stiffness

Finally, we can examine the effects of modifying enterprise stiffness. In the production-distribution system, this is done by modifying the clerical delays (i.e changing the order handling times). In figure 3.11 below, I explore the effects of varying the order handling time by a factor of three times faster and three times slower than the base case.

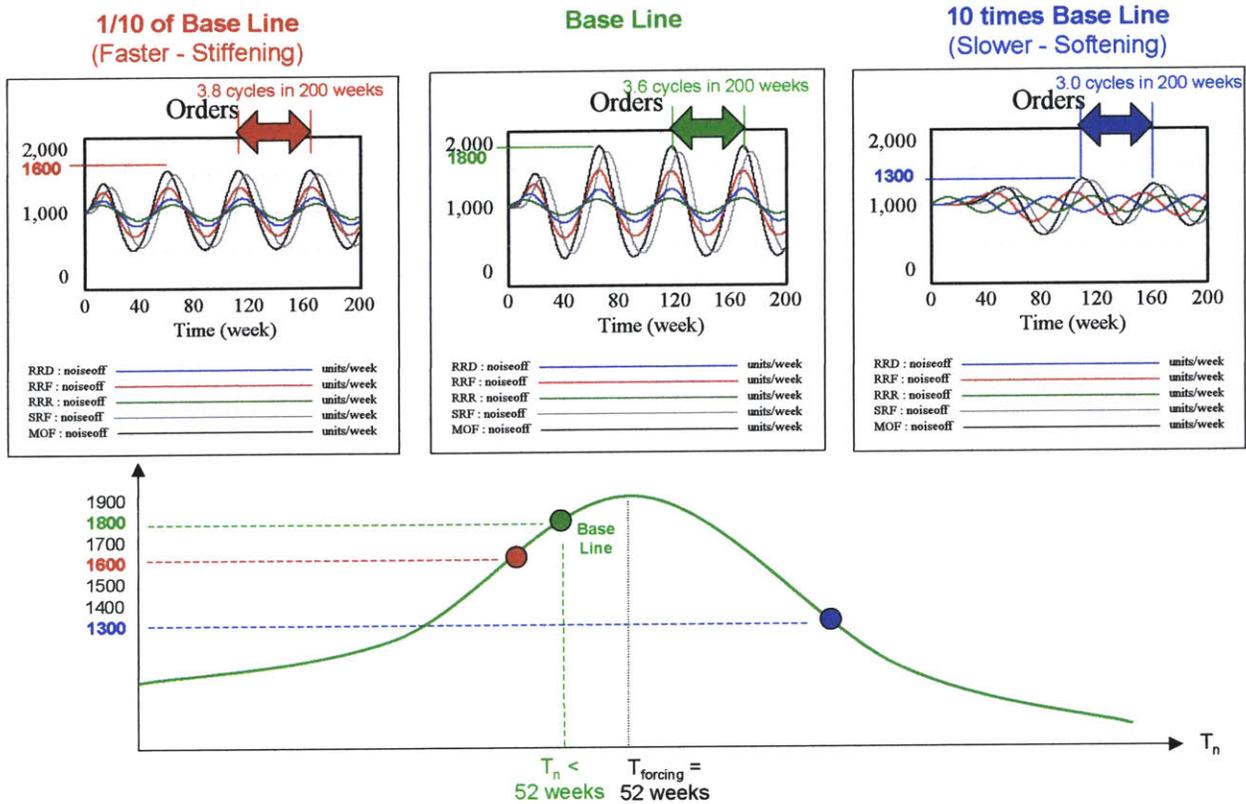
Figure 3.11: Effects of Modifying Enterprise Stiffness (3x)



As expected, stiffening up the enterprise results in a slight reduction in natural period of vibration, which corresponds in a slight reduction in amplitude (shown in red above). Conversely, decreasing the stiffness results in a slight increase in the natural period of vibration which corresponds to a slight increase in amplitude (shown in blue above).

In addition, these effects can be verified by varying the range of enterprise stiffness even further using factors of ten times on the order handling times as shown in figure 3.12 below.

Figure 3.12: Effects of Modifying Enterprise Stiffness (10x)



Again, stiffening up the enterprise results in a further reduction in natural period of vibration, which corresponds in a slight reduction in amplitude (shown in red above). Conversely, decreasing the stiffness results in a further increase in the natural period of vibration which corresponds to a decrease in amplitude (shown in blue above).

In summary, as shown in figure 3.13 below, enterprise clockspeed can be increased by decreasing time delays (i.e. supply line length), by decreasing stocks (e.g. inventory accumulation) and by increasing the velocity of inventory adjustment (i.e. by reducing the time to reduce inventory adjustments).

Figure 3.13: Summary of Modifying Enterprise Dynamic Properties

Decreasing time **Delays** (e.g. supply pipeline length) increases **Stiffness (Reactivity)**

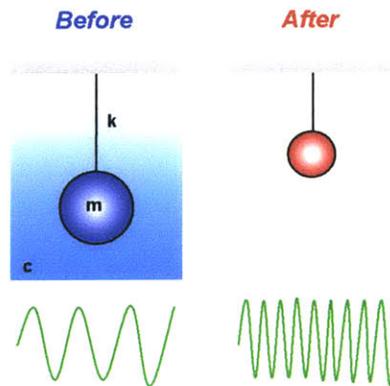
In The Beer Game, this is shipping delays

Decreasing **Stocks** (e.g. inventory accumulation) decreases **Mass (Inertia)**

In The Beer Game, this is inventory

Increasing **Velocity of Inventory Adjustment** (i.e. flow rates through the supply pipeline) decreases **Damping (increases Responsiveness)** – potentially very effective

In The Beer Game, this is decision to smooth information



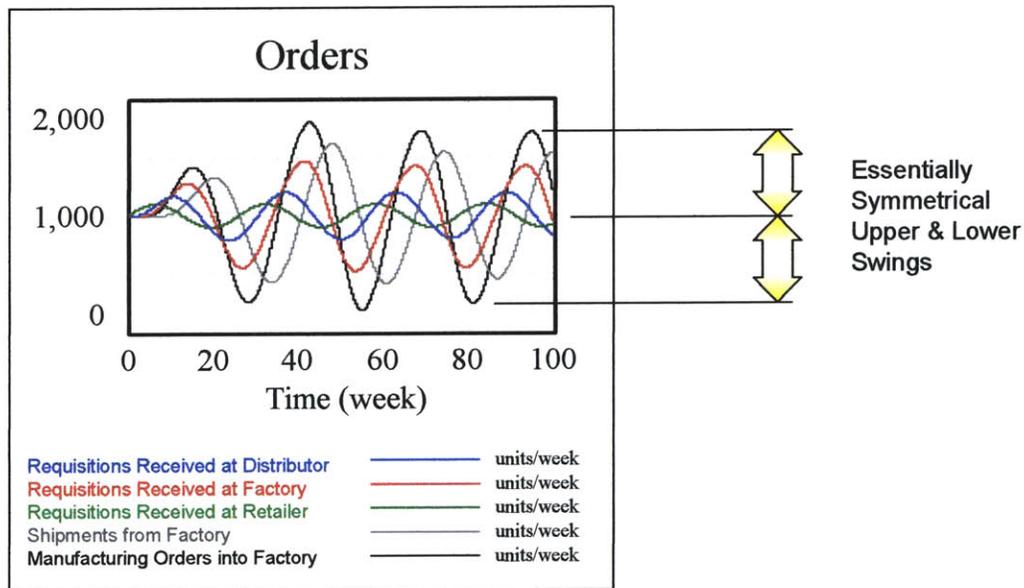
All three act to increase enterprise **clockspeed** (decrease period of vibration)

3.9 Strategy #4: Modifying Enterprise Strength

The enterprise under consideration exhibits essentially linear response as can be seen in figure 3.14 below. We can see that the enterprise is oscillating around an equilibrium of 1,000 orders, with the upper and lower peaks being approximately constant and symmetrical. Note that although the customer demand (the green line) is only oscillating by ± 100 units, because of delays in the enterprise, the orders reach ± 800 units – and the factory is producing ± 500 units!

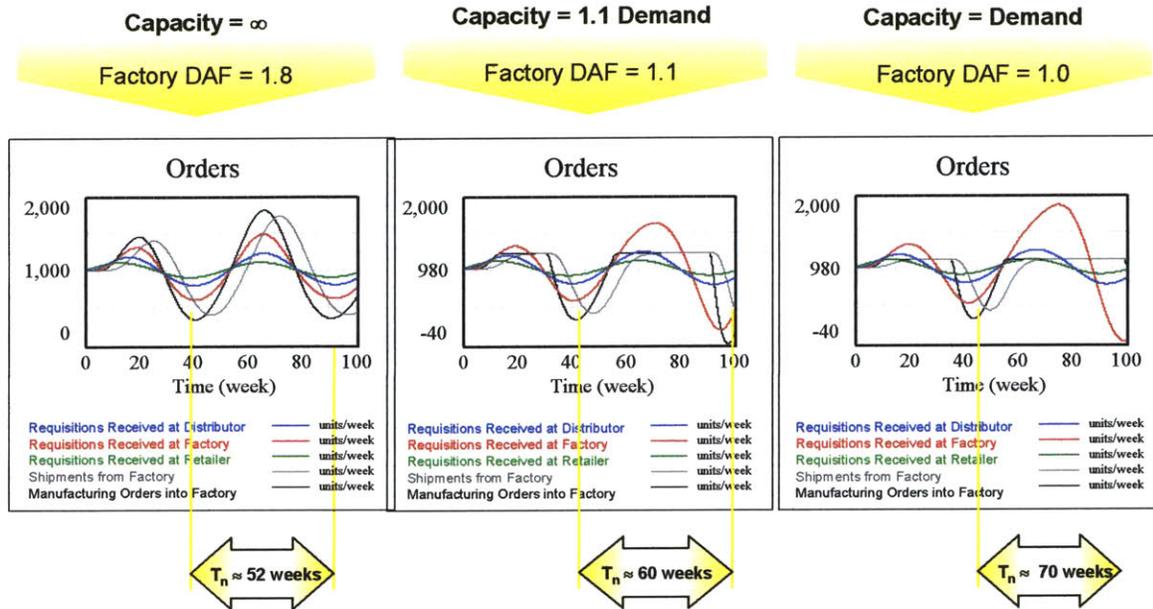
There is an assumption in the model however that is forcing this linear behavior, namely that the capacity (or strength) of the enterprise to meet any dynamic demand is infinite. This is obviously unrealistic.

Figure 3.14: Linear Response of Enterprise



If one limits the capacity of the enterprise at the manufacturer, that is, we “fuse” the system by installing a constraint we can observe the behavior in figure 3.15 below. In the diagram on the left, the enterprise has infinite capacity, the period of oscillation is 52 weeks and the maximum amplification is 1.8.

Figure 3.15: Nonlinear Response (from Capacity Constraint)

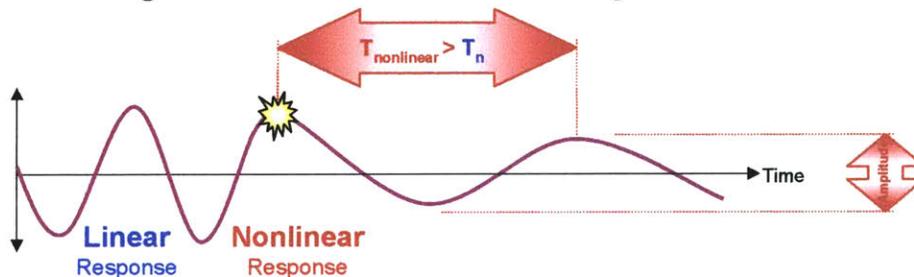


If however, one makes the enterprise weaker and weaker, then by definition, one limits the amplitude of the oscillation more and more. Note, however that we trade uncertainty in production for ever-growing backlogs (as shown in the red line). Finally note that the effective period of oscillation elongates to 60 and 70 weeks as the system gets weaker.

This departure from a fairly regular period of oscillation can be a signal that some portion of the system has begun to behave in a nonlinear fashion, as was discussed in Chapter 2.

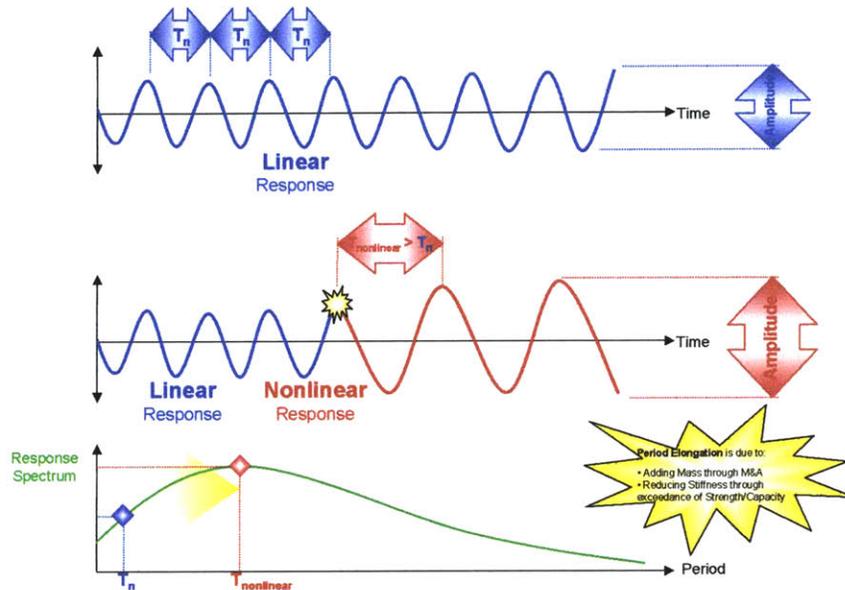
As can be seen in figure 3.16 below, a varying period and/or amplitude may indicate nonlinear behavior.

Figure 3.16: Nonlinear Period and/or Amplitude Shift.



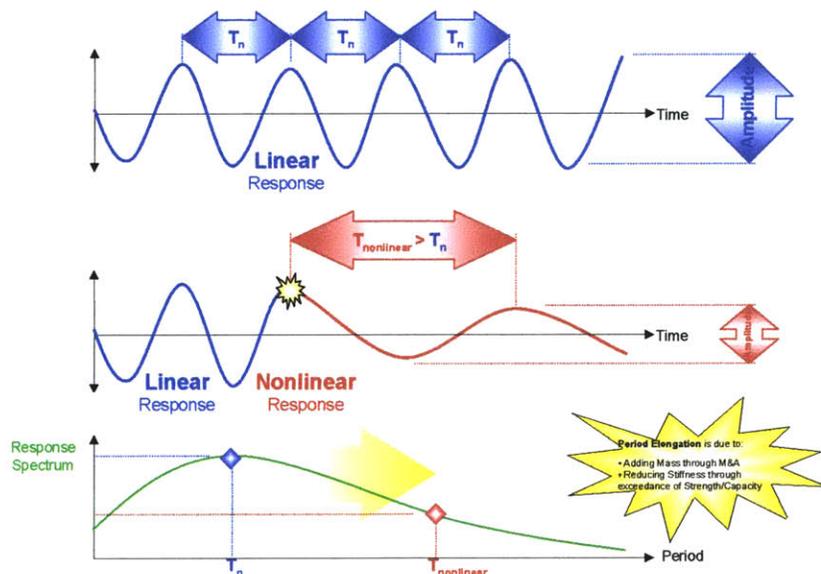
An example of a fast clockspeed company softening and increasing its response is shown in figure 3.17 below. This could arise from a merger or acquisition or if the enterprise's effective stiffness was decreased through an exceedance of its capacity.

Figure 3.17: Nonlinear Slowing and Increasing



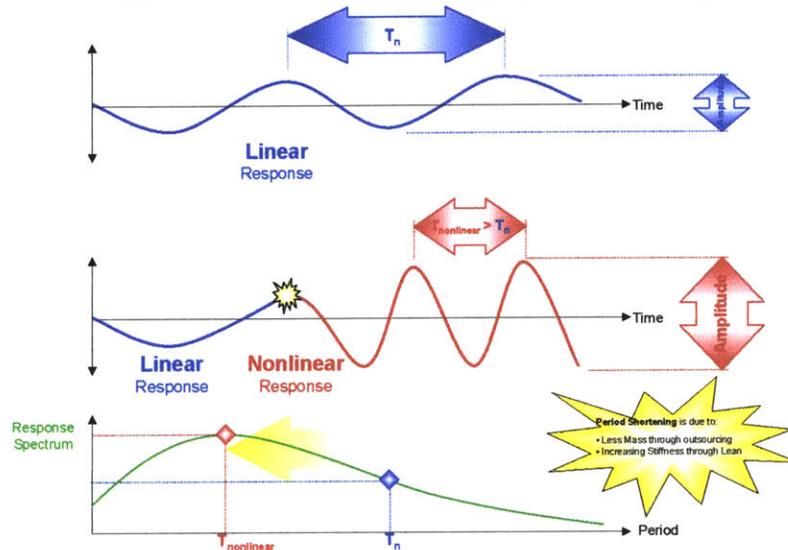
Conversely, an example of a medium clockspeed company softening and decreasing its response is shown in figure 3.18 below.

Figure 3.18: Nonlinear Slowing and Decreasing



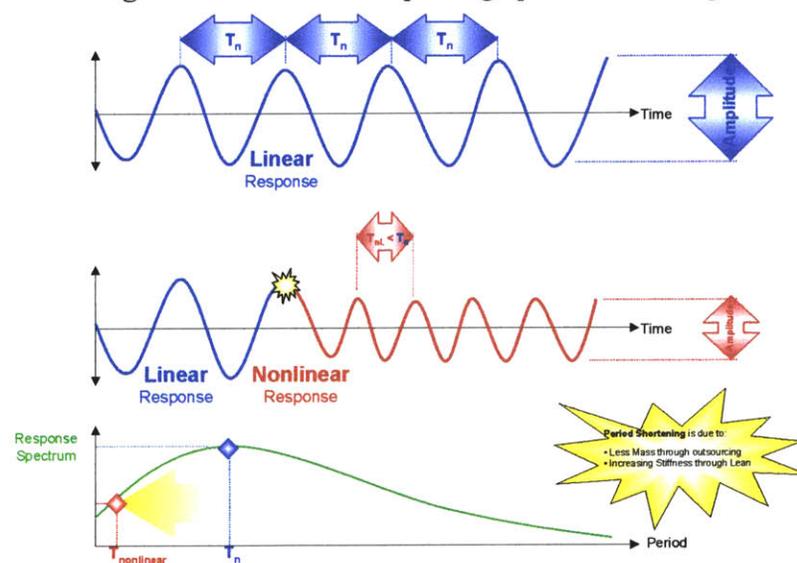
Moving in the other direction, one can examine what happens when a slow clockspeed company stiffens to become a medium clockspeed company, as shown in figure 3.19. This could arise through the shedding of mass via a divestiture, outsourcing, or simply “leaning up” processes.

Figure 3.19: Nonlinear Speeding up and Increasing



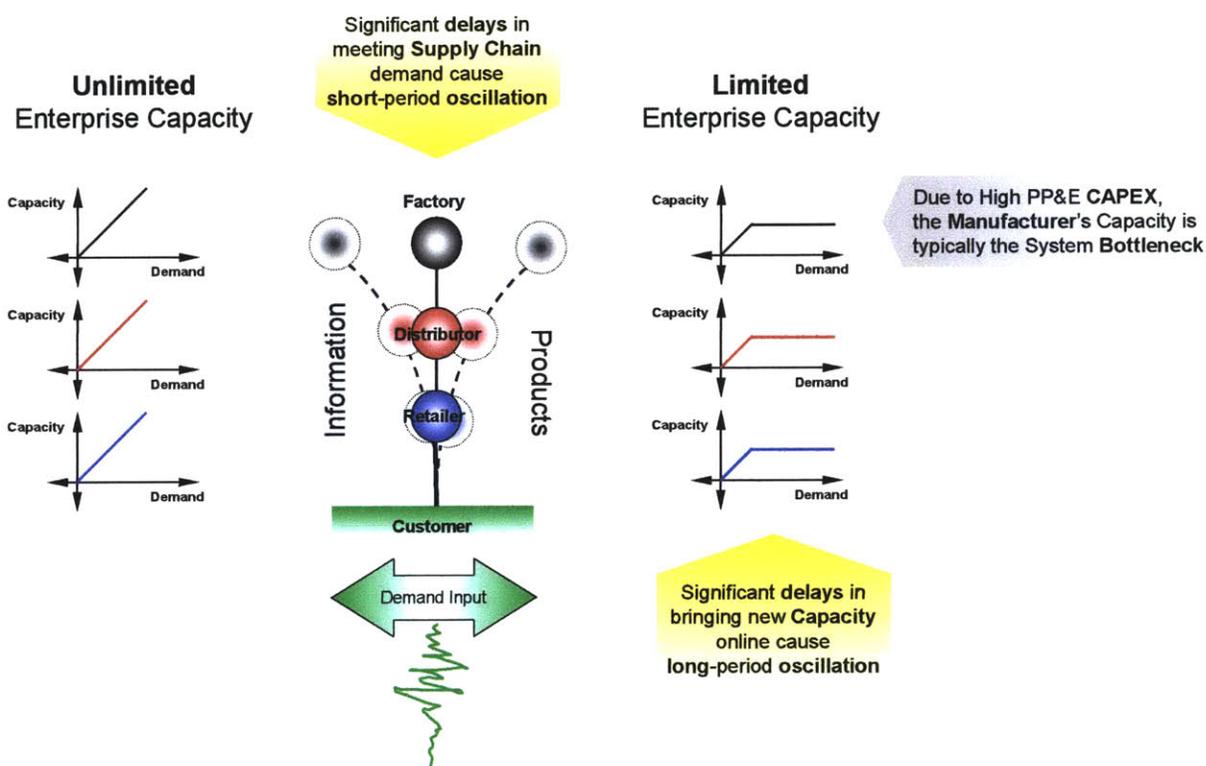
Finally, one can examine what happens when a medium clockspeed company stiffens to become a fast clockspeed company as shown in figure 3.20 below. Again, this could arise through the shedding of mass via a divestiture, outsourcing, or simply “leaning up” processes.

Figure 3.20: Nonlinear Speeding up and Decreasing



In fact, the ability of an enterprise to evolve its properties (whether they be mass, reactivity, responsiveness or strength) over time leads to nonlinear “evolutionary” behavior. If an enterprise decides to increase its capacity, significant time delays and capital outlays can be involved. This can introduce another longer period dynamic well documented in commodity markets¹⁵⁸. As shown in figure 3.21 below, the supply chain dynamics leads to a relative short period of oscillation (in this case, about ½ year).

Figure 3.21: Capacity-Constrained Enterprise



The three-degree of freedom enterprise can therefore be given more evolutionary “life” as the strength of the enterprise (i.e. its capacity) can grow based on demand for the enterprise’s goods / services, or more directly, based on the equilibrated price demanded and received for these goods / services.

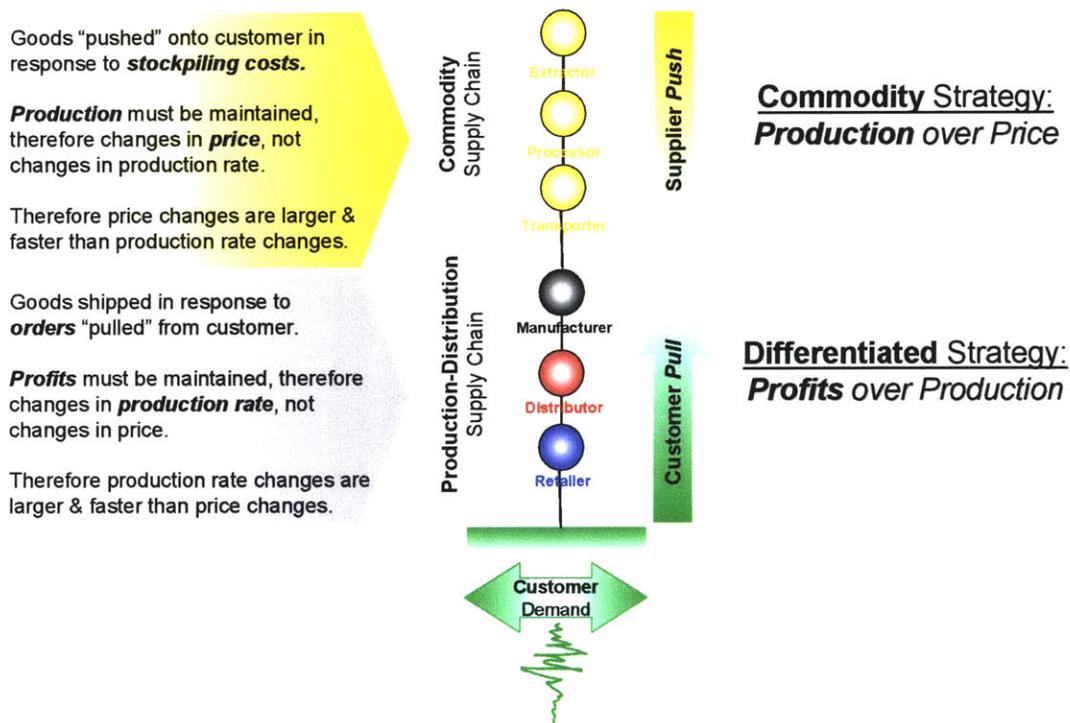
¹⁵⁸ *Dynamics of Commodity Production Cycles*, Meadows, D.L., Pegasus Communications, 1970.

3.10 Manufacturing vs. Commodity Value Chain Dynamics

Having spent the best part of this chapter studying the physics of a typical value chain, namely a production-distribution enterprise which implicitly produces differentiated products, I will now briefly introduce its cousin, the commodity value chain.

While the governing structural dynamics of the commodity value chain is not different from other value chains (i.e. the rules of clockspeeds and bullwhips still exist), Forrester pointed out that the underlying strategic architectures driving the dynamic behavior are inherently different.¹⁵⁹ To be more specific, commodity value chains “push” their product downstream, while manufacturing value chains have their products pulled from customers in the form of orders. In order to keep their undifferentiated flow processes flowing, commodity value chains typically protect production rates at the expense of price stability, while differentiated product value chains typically protect profits at the expense of production stability as shown in figure 3.22 below. We will return to commodity strategies (even for complex high-tech products) later.

Figure 3.22: Manufacturing vs. Commodity Value Chain Dynamics



¹⁵⁹ Forrester, Jay, W., *Industrial Dynamics*, 1961, pg. 322.

3.11 Enterprise Integration

Before we leave the analysis of an inverted pendulum-as-enterprise discussion, let us conclude with an observation of the opportunity to design the enterprise as a system, that is in its entirety. Lyneis observed:

“...for a major U.S. manufacturing firm, the policies of engineering, production and capacity expansion interacted to cause a loss of market share. Each of the policies looked at in isolation is reasonable, however together they contribute to declining performance. The best policy or plan of action for each functional area was not the best policy set for the company as a whole. Interactions tend to be more important than components – policy design by functional area is not always effective.”¹⁶⁰

Forrester notes that responsibility for making important corporate decisions should not reside solely within one functional silo. For example, production managers should not decide production rates and sales managers should not set prices. Price setting for example is one of the system policies that ties together everything a corporation does. These decisions affect the corporate system far outside their own departments.¹⁶¹

The problem with the functional mindset of “doing things right” as opposed to “doing the right things”, is when one takes a systemic or enterprise view¹⁶². It is very difficult to change an organization that is *doing the wrong things ‘righter’*, whereas it is much easier to correct an organization that is *doing the right things ‘wronger’*.

As will be shown in chapter 8, this approach will yield uncommon competitive advantage. But managing the feedbacks requires considerable re-architecting of the enterprise, that is, re-configuring the boundaries around the existing business processes, and the subsequent interactions between the new processes. As Ackoff eloquently noted, “no system is ever simply the *sum* of the behavior of its parts, it is the *product* of the interactions.”¹⁶³

¹⁶⁰ Corporate Planning and Policy Design: A System Dynamics Approach, James M. Lyneis, MIT Press, 1980, pgs. 5 & 9.

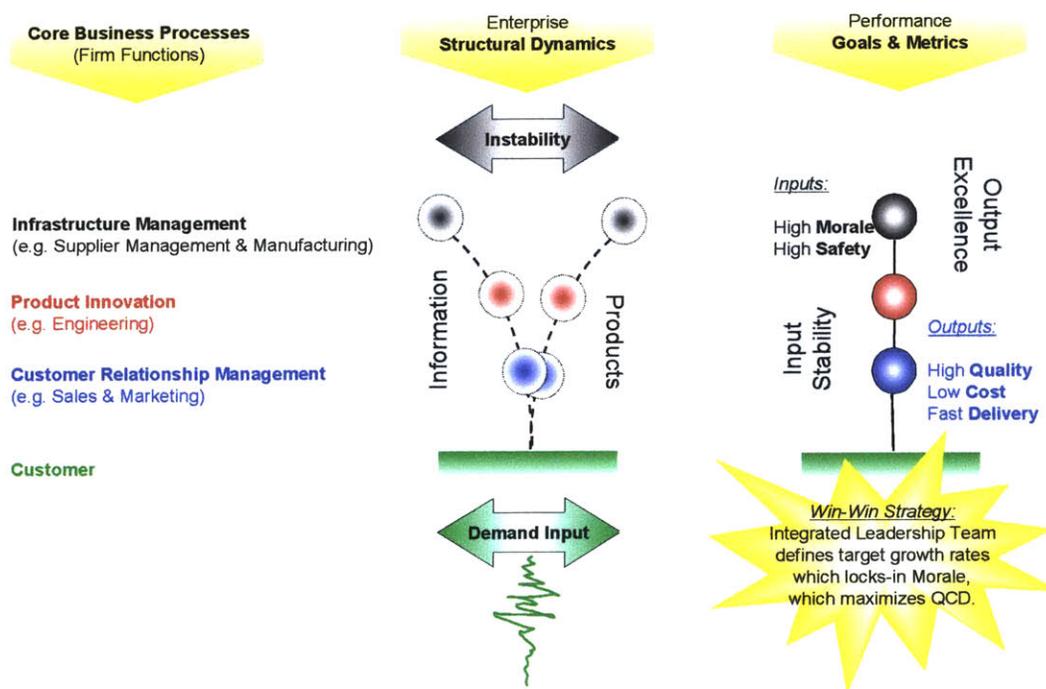
¹⁶¹ Keough, Mark and Doman, Andrew, “The CEO as Organization Designer: An Interview with Prof. Jay W. Forrester”, *The McKinsey Quarterly*, 1992 Number 2, pp. 3-30.

¹⁶² *Lean Enterprise Value*, Earll Murman et al., Palgrave Publishers, 2002.

¹⁶³ Ackoff, Russell L., *Ackoff's Best: His Classic Writings on Management*, 1999.

If the goal of an enterprise or firm is to produce excellent products and services, then the performance metrics should provide incentives for all business processes (or firm functions) to behave in a coordinated, integrated way as seen in figure 3.23 below. If the traditional output metrics of Quality, Cost and Delivery will ensure success with the customer, then an integrated leadership team (ILT) should collectively agree on the optimum growth rate that will provide appropriate levels of input metrics of Morale and Safety, which will in-turn ensure excellent QCD output.

Figure 3.23: End-to-End Enterprise Integration



3.12 Predictive Enterprise Design

As stated at the very beginning of this thesis, one of the questions that inspired this work was an answer to the question, “can enterprises be predictively architected?”¹⁶⁴ Having established the basis for enterprise engineering, we are half way to answering the question.

This chapter has explored the structure and behavior of a rather complex socio-technical system – a value chain. Notice that the technical details of the product technology or production system

¹⁶⁴ This is a fundamental research question from MIT’s Engineering Systems Division.

technology of the value chain have not been discussed. Instead, all of the focus has been on the dynamics of human complexity that is the value chain's inertia, damping and reactivity as operationalized by the embedded decision dynamics of the enterprise. In this way, we have de-coupled the human complexity from the technical complexity. Whether the value chain was manufacturing and distributing complex commercial jet airplanes or cases of beer¹⁶⁵, it is not the technical complexity that tends to make socio-technical enterprises unpredictable.

Before we begin to design enterprises in Part II of this thesis, we can decompose the above question into: "can we predict the behavior of a complex human enterprise?" The work of this chapter seems to show that analytically, complex human enterprises exhibit a dynamic response that is predictable using the laws of enterprise physics. In fact, the empirical evidence seems to support the analytical findings. For over 10 years, MIT's Prof. John Sterman has been administering a version of Jay Forrester's Industrial Dynamics model to graduate business students and executives in the form of an educational simulation called "The Beer Game". With hundreds of simulations using thousands of participants, he has assembled a dataset with remarkable conclusions: complex human enterprises are indeed predictable. They exhibit the same dynamics discussed in this chapter. He has shown that there is a predictable enterprise oscillation, amplification and phase lag. It appears that the question should not be, "is it possible..." but more to the point, "how do you design enterprises to ensure predictable performance." This will be tackled in Part II.

3.13 Chapter Summary

This chapter focused on the dynamic behavior of a typical "extended" human enterprise: the **value chain** (or conversely, the vertically-integrated corporation), by applying the "laws" of enterprise physics derived from the previous chapter.

¹⁶⁵ This refers to MIT's famous "beer game", a management simulation which teaches system dynamics for a manufacturing-distribution enterprise.

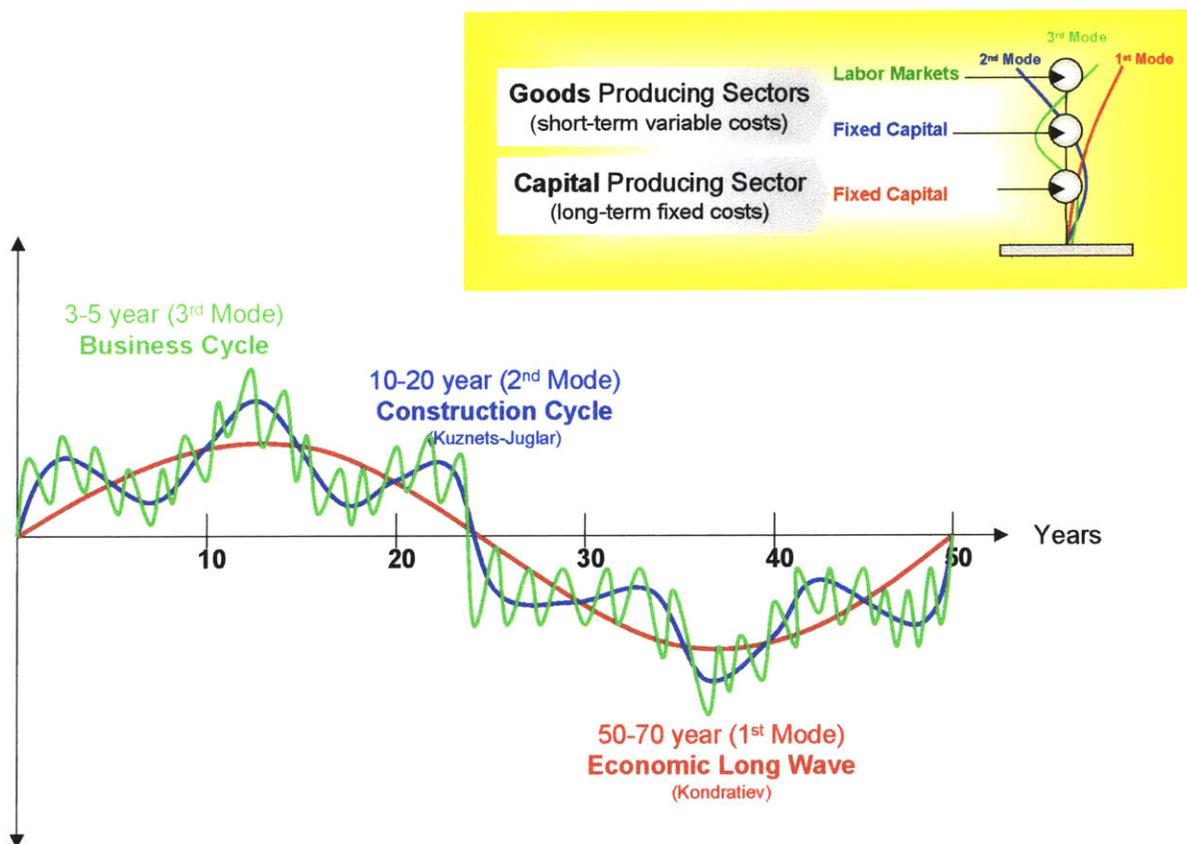
Using the [system dynamics](#) methodology, we examined the dynamic response of the enterprise to an input excitation, represented as customer order volatility. Using this methodology we studied the dynamic characteristics of the enterprise (including its [natural period](#) of vibration, its [damping](#) and its strength or [capacity](#)).

Chapter 4: The Dynamics of Macro-Economies and National Enterprises

4.1 The Dynamics of Macro-Economic Cycles

From the microeconomics of the value chain enterprise, I now turn our attention to the dynamics of a macro-economic enterprise. As introduced in chapter 2, macro-economic cycles can be described using a three-degree of freedom enterprise structure shown in figure 4.1 below.

Figure 4.1: Structural Dynamics of Macro-Economic Cycles



As can be seen above, there are three well-defined modes of dynamic behavior superimposed on each other. First is the well-known “business cycle”¹⁶⁶ which has a 3-5 year period of vibration. Second

¹⁶⁶ *Business Dynamics: Systems Thinking and Modeling for a Complex World*, John D. Sterman, McGraw-Hill, 2001, pg. 782-785.

is the underlying 10-20 year “construction cycle”¹⁶⁷ which was proposed by Juglar and Kuznets. And finally, there is the underlying 50-70 year “economic long wave”¹⁶⁸, proposed by Kondratiev. Macroeconomists refer to these three cycles as “the short run”, “the medium run” and “the long run” respectively¹⁶⁹.

Jay Forrester attributed the short-term business cycle to the over-building and under-building of *consumer durables*, while the economic long wave can be largely attributed to the over-building and under-building of *capital plant*.¹⁷⁰ He also noted that although there are theoretically dozens of fluctuating modes in an economy, only two or three dominant modes appear because most modes are “entrained” to synchronize with each other.¹⁷¹

Similarly, Nathaniel Mass demonstrated that the business cycle is the result of policies relating to the management of labor and production (i.e. those inputs associated with short-term variable costs), while the construction cycle is the result of policies relating to the management of fixed capital (i.e. those inputs associated with long-term fixed costs), and finally that the economic long wave is the result of the capital equipment sector of a national economy diverting a portion of its output for its own use in producing capital equipment.¹⁷² Mass noted that a common structure underlies both the short-term business cycles and the longer-term capital cycles. The primary difference between the two lies in the time-based differences between labor and capital markets – namely their average lifetimes and delivery delays.

When one applies the concepts of response spectra from chapter 2 to the economic cycles described above, one can see the relative effects of each of the three cycles on enterprises having their own dynamic characteristics as shown below in figure 4.2.

¹⁶⁷ Ibid, pg. 782-785.

¹⁶⁸ Ibid, pg. 782-785.

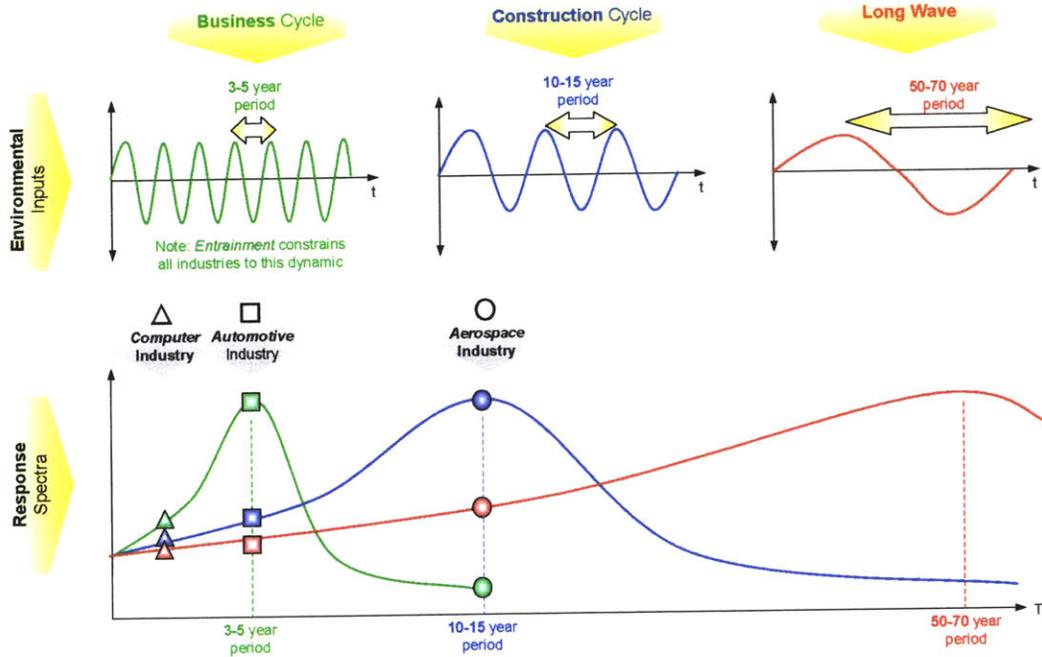
¹⁶⁹ *Macroeconomics*, Olivier Blanchard, 2000, pg. 19.

¹⁷⁰ “The Beginning of System Dynamics”, *The McKinsey Quarterly*, 1995 Number 4.

¹⁷¹ Keough, Mark and Doman, Andrew, “The CEO as Organization Designer: An Interview with Prof. Jay W. Forrester”, *The McKinsey Quarterly*, 1992 Number 2, pp. 3-30.

¹⁷² “Modeling Cycles in the National Economy”, Nathaniel Mass, *Technology Review*, March/April 1976, pg. 43-52.

Figure 4.2: Response Spectra of Economic Cycles



From above, we can qualitatively see that the three main economic dynamics affect industries differently. For example the computer industry (which have a clockspeed of around 1-3 years¹⁷³) moves so quickly that movements of the slower business cycle, construction cycle and long wave are hardly amplified (i.e. the computer industry lies in the pseudo-static region of all three response spectra). Therefore time-based strategies for computer companies who wish to reduce demand volatility, would be simply to speed-up its clockspeed (i.e. move to the left). A similar trend occurs in the automotive industry which has a clockspeed of around 5 years.

The aerospace industry however is a more in an interesting case. With its clockspeed of around 10 years¹⁷⁴, the aerospace industry finds itself near resonance with the construction cycle, but out of phase with the business cycle¹⁷⁵. Interestingly, aerospace companies wishing to speed-up their clockspeed, find themselves worsening the effects of the hire-fire business cycle.

¹⁷³ Charlie Fine, *Clockspeed*, pg. 239.

¹⁷⁴ *Ibid.*

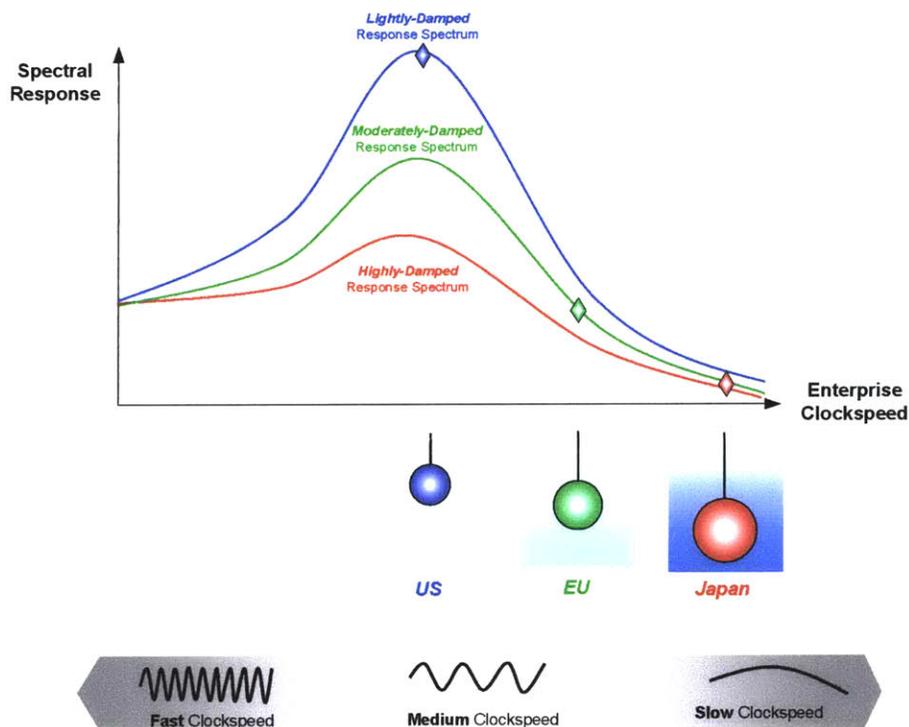
¹⁷⁵ Note that the concept of *Entrainment* (covered elsewhere in this thesis) offers an interesting additional challenge to this theory.

4.2 The Dynamics of Global Macro-Economies

From the macroeconomics of national enterprises, I now turn our attention to a comparison of global macro-economic enterprises. Let us begin with a rapid assessment of the underlying clockspeeds of the world's three largest economic blocks: the US, Japan and the European Union.

Intuitively, one would expect the US to have the fastest clockspeed, driven by its short-term capital markets, its willingness to abandon sluggish industries for newer more innovative high growth industries, and its relatively flexible labor policies¹⁷⁶. Likewise, one would expect Japan to have the slowest clockspeed, driven by its risk-aversion and the long-term view of its debt markets, the strength of its vertically-integrated *keiretsu*, its ability to embrace mature industries and drive more value out than the initiators of those industries, and its long-term social policies (e.g. life-time employment). Finally, one would expect the EU to have an intermediate clockspeed, as shown in figure 4.3 below. The question is, does the dynamics embedded in the data support this?

Figure 4.3: Hypothetical Dynamics of Global Economic Powers



¹⁷⁶ Professor Lester Thurow, MIT course 15.012 *Macroeconomics*, Spring 2002.

In fact it is important to note that these three dynamic systems do not oscillate independently from one another. Researchers have conjectured that there are cross-country ties which act to dynamically couple these enterprises as shown in figure 4.4 below.¹⁷⁷

Figure 4.4: Dynamic Coupling of International Economic Enterprises

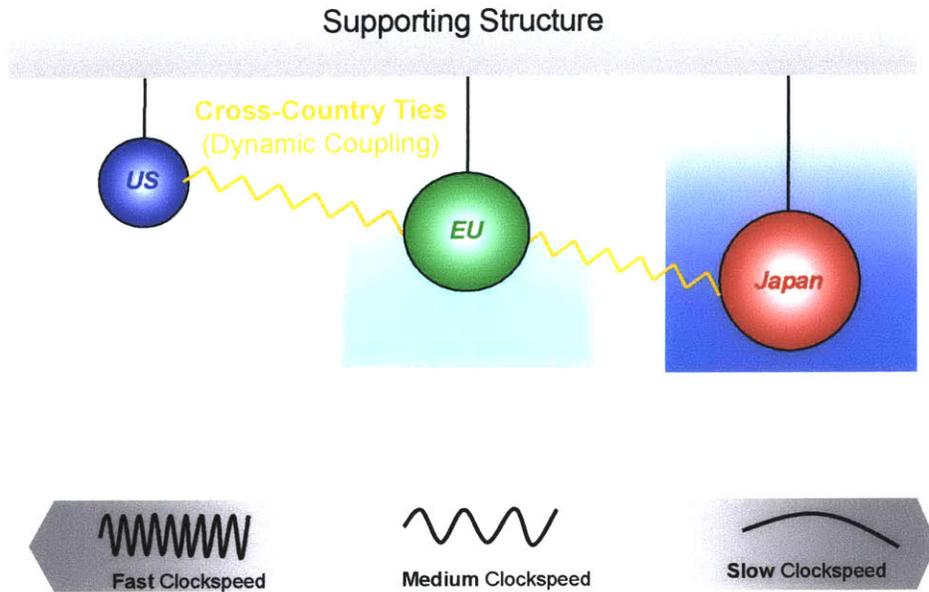
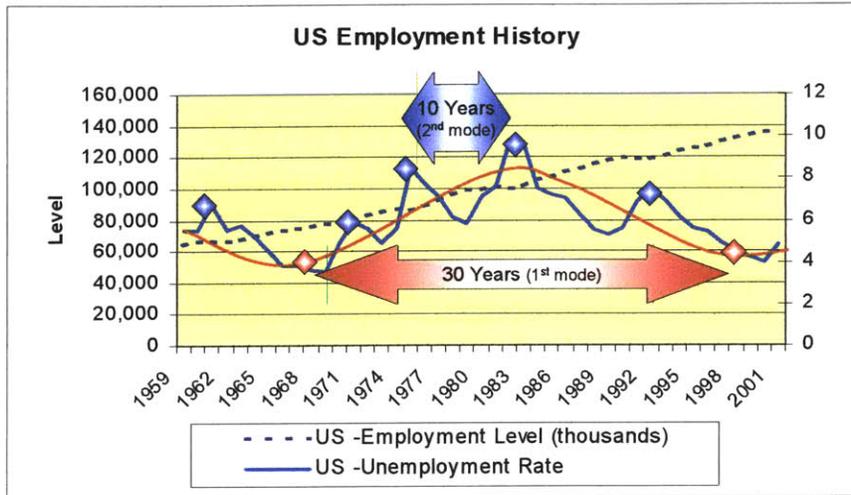


Figure 4.5¹⁷⁸ below shows the long-term unemployment trends in the US over the past 40 years. The first thing that we note is that there appears to be a pronounced periodic oscillation approximately every 10 years, and an underlying (fundamental) one of approximately 30 years. These appear to be the first two modes of vibration of the US economy. It appears therefore that one measure of the US macro economy might indicate that the US has a fundamental period of vibration of approximately 30 years. But what would one expect from Japan? From the EU?

¹⁷⁷ Anderson, Heather M. and Ramsey James B., "U.S. and Canadian Industrial Production Indices as Coupled Oscillators", *Journal of Economic Dynamics and Control*, Vol. 26, No. 1, January 2002, pp. 33-67.

¹⁷⁸ Taken from Charlie Fine's Spring 2003 Operations Strategy final class project with Brian Bowers, Lou Rassey and Eric White..

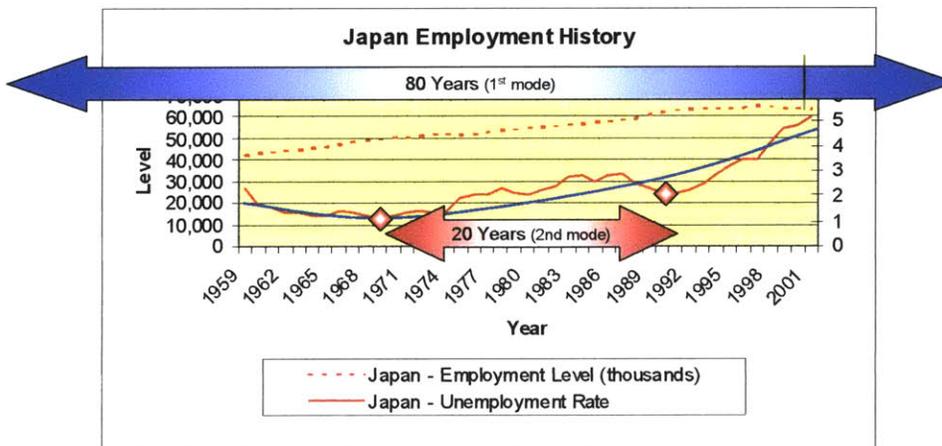
Figure 4.5: US Unemployment



Using the basic principles of enterprise pendulum physics, one might intuit that Japan has a slower clockspeed than that of the US. Although they have fewer citizens than the US, they seem to organize their nation, their keiretsu, their society etc. as a more unified, “massive” structure. In addition, they seem to have a longer string, that is they seem to be less reactive, as reflected in their governmental bureaucracies, etc. Finally, they seem to be less responsive to changes in the environment, that is they smooth their expectations over longer time horizons. This gives them greater damping.

One would expect Japan’s clockspeed to be slower than the US, and figure 4.6¹⁷⁹ below supports that conjecture. We can see that Japan has an 80-year fundamental mode of vibration.

Figure 4.6: Japanese Unemployment

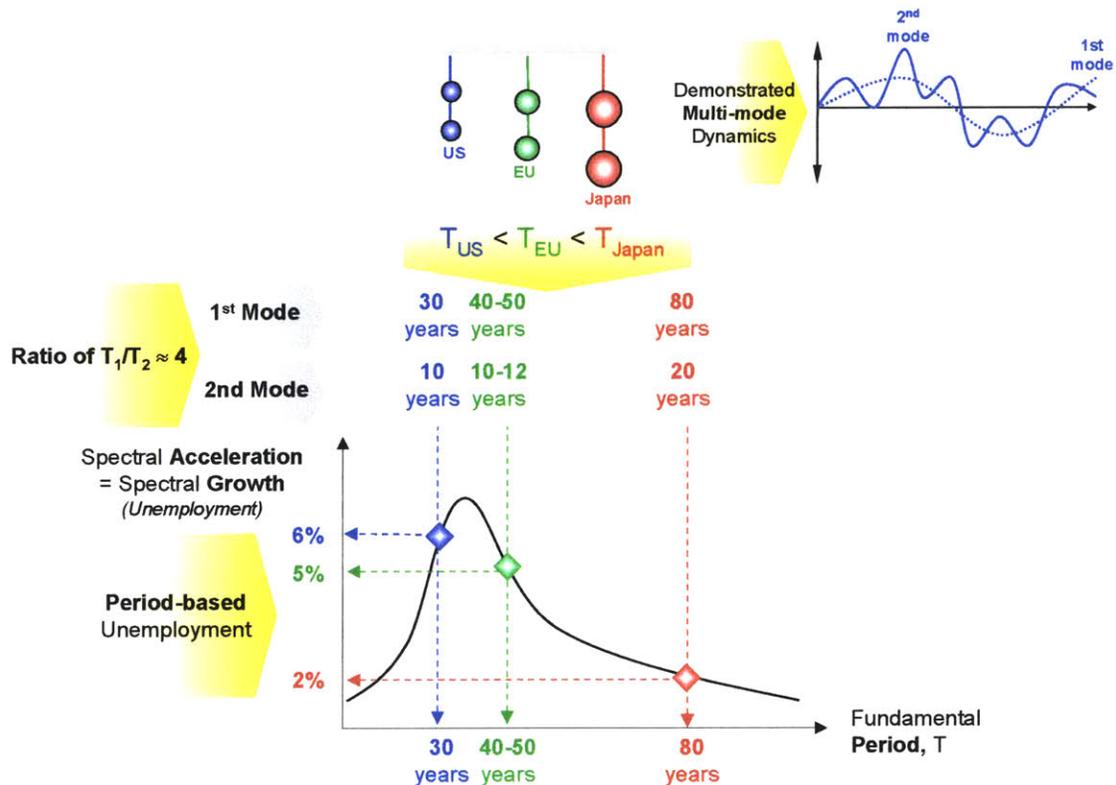


¹⁷⁹ Ibid.

On the international spectrum of clockspeeds, the European Union would be expected to lie somewhere between the two, and the data supports this. The fundamental period of vibration lies in the region of 40-50 years. But what can knowledge of these national clockspeeds do to help us understand a nation's dynamics? Again, I invoke the concept of the Enterprise Response Spectrum as discussed in figure 2.10.

Figure 4.7 below plots the fundamental periods of vibration for each of the three nations. If one were to map a typical response spectrum curve over the data, one would expect to find “period-based unemployment”. That is, one would expect to find less unemployment in Japan than in the EU and the US. In fact, when one plots the real average unemployment data, one can see that the classic spectral growth curve describes the behavior well. Also, as an aside, I note that the ratio of the first to second mode periods of vibration is approximately 4:1. This relationship also exists in the dynamics of building structures.

Figure 4.7: Global Enterprise Dynamics



I would like to make one final note before leaving international competitive dynamics. It is interesting to note that the colloquial language used to express competition at a national level has its own vocabulary to reflect the meta- or super-business issues. When two corporate enterprises are engaged in competition, we use the term “competition”. However, when two national enterprises are engaged in competition, we use the term “wars”, whether “trade wars” or “military wars”. They are not “trade competitions” or “military competitions”. As Victor Hugo wrote:

“A day will come when you, France; you Russia; you Italy; you Britain; and you Germany – all of you, all nations of the Continent will merge tightly, without losing your remarkable identity... A day will come when markets, open to trade, and minds, open to ideas, will become the sole battlefields.”¹⁸⁰

This was a point that was made with respect to the industrial competition between *Boeing* and *Airbus* in the previous chapter – it is beyond corporate competition, it is a national trade war. We will explore in the next section how enterprise physics is used to understand even national “military competitions”.

4.3 The Dynamics of National Enterprises

When you are trained to see and you begin to look, the laws of enterprise physics are everywhere. In recent television interview¹⁸¹, US Secretary of Defense, Donald Rumsfeld answered questions as to why the Spring 2003 War in Iraq went so well:

“...It’s the *law of physics*... *speed* is more important than *mass*”

Even in the public sector, national leaders understand and invoke the power of the laws of physics. Donald Rumsfeld was extolling the need for speed. Although he did not specifically define all the elements of a pendulum, he did cover the important parts explicitly.

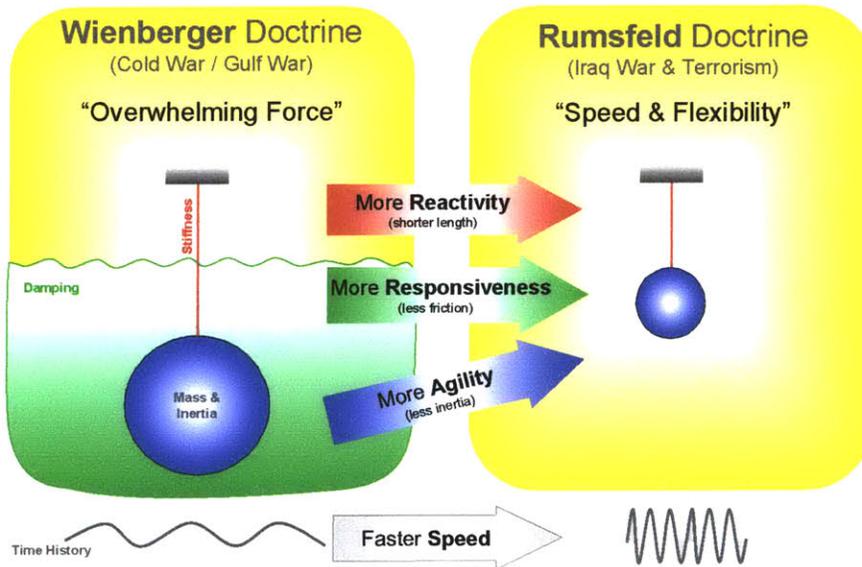
¹⁸⁰ *Birds of Prey - Boeing vs. Airbus: a Battle for the Skies*, Matthew Lynn, 1997.

¹⁸¹ *Meet the Press*, April 13, 2003.

As shown in figure 4.8 below, in the Cold War, with a massive, monolithic threat, from the Soviet Union, the “gravitational field” (competitive pull) was strong. The US clockspeed was slow, meaning the defense’s pendulum was massive, with long chains of command (long pendulum string length), and its policies were full of bureaucratic friction (damping). This strategy of “overwhelming force” was necessary to match the USSR in the “higher, faster, farther” world.

With the subsequent break-up of the Soviet Union, with no single, clear massive threats, the US military complex is now faced with a new type of dynamic environment. Now the enterprise needed to be more reactive (i.e. shorter pendulum length), it had to be more responsive (i.e. reduce the viscosity), and it needed to be more responsive or more agile (i.e. have less inertial mass). All of these things together resulted in a faster clockspeed.

Figure 4.8: Evolution of War Strategies

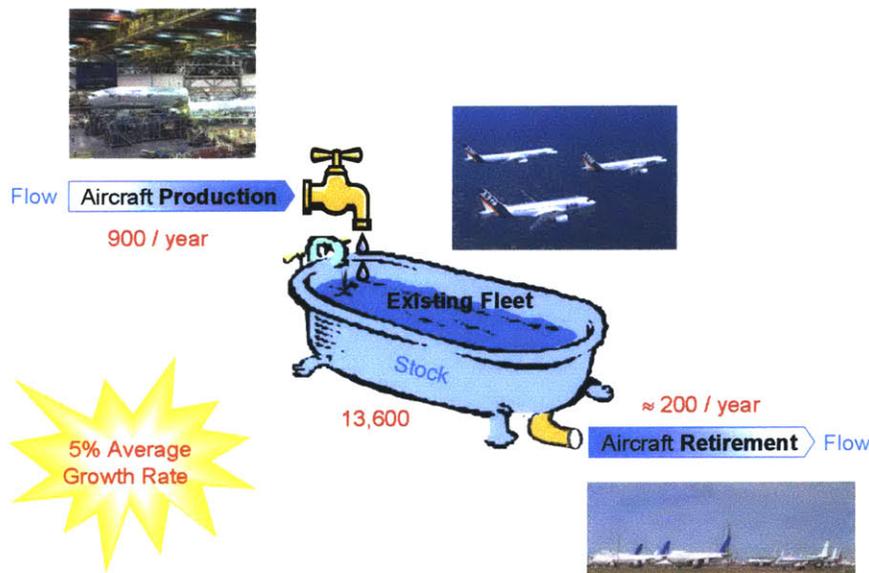


4.4 Macroeconomic “Bullwhip”

As was discussed in sections 2.2 and 3.3, the bullwhip represents demand amplification up a value chain. Fine describes that it is due to information and delivery delays that cause over- and under-ordering.¹⁸²

Micro-economists describe the causes slightly differently¹⁸³. They argue that the bullwhip is much more prevalent for durable goods (like commercial aircraft) than for non-durables. By definition, the stock of durables is large compared with annual demand (see figure 4.9 below for commercial aircraft). The current stock of around 14,000 aircraft is much greater than the annual demand of around 1,000 aircraft¹⁸⁴. With annual retirements of around 300 aircraft, the net inflow of 700 aircraft represents around 5% growth on the 14,000 base. Note that this 5% growth matches the long-term demand for aircraft travel. Aircraft are such long-lived assets that the entire fleet will renew itself on average every 20 years.

Figure 4.9: Stock and Flow of Commercial Aircraft



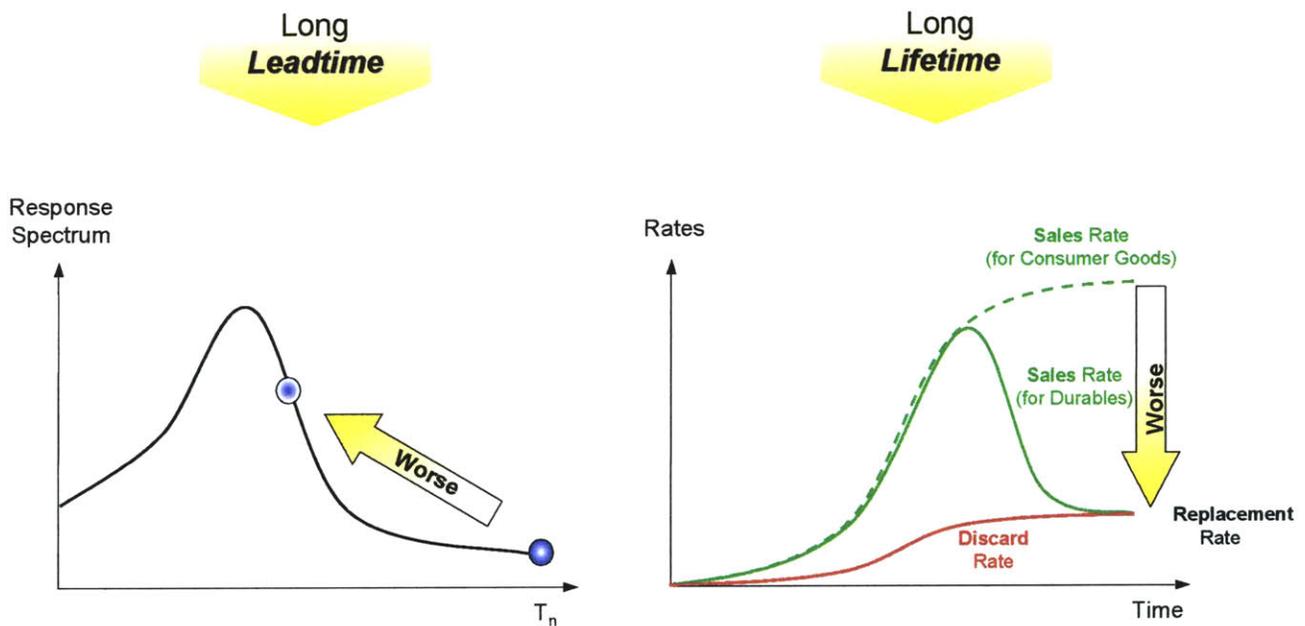
¹⁸² Charles H. Fine, *Clockspeed*, 1998, pg. 90-93.

¹⁸³ *Microeconomics*, Pindyck and Rubinfeld, pg. 37-38.

¹⁸⁴ “Airbus A3XX: Developing the World’s Largest Commercial Jet (A)”, Benjamin Esty, *Harvard Business School* Case 9-201-028, June 20, 2002.

To summarize therefore, durable goods exhibit a high degree of dynamic complexity (and are more affected by the bullwhip) due to their longer *leadtimes* and *lifetimes* as shown in figure. As was discussed previously in Chapter 4, long *leadtime* industries like aerospace tend to be out-of-phase (i.e. “hyper-dynamic”) with the 3-5 year business cycle, making conventional stiffening or speeding-up tactics produce adverse effects as one begins to climb up the response spectrum. In addition as just discussed above, the fact that durable goods by definition have long *lifetimes* can cause overbuilding of capacity and precipitous drops in price and profitability as competitors often follow in this profitability death spiral.¹⁸⁵

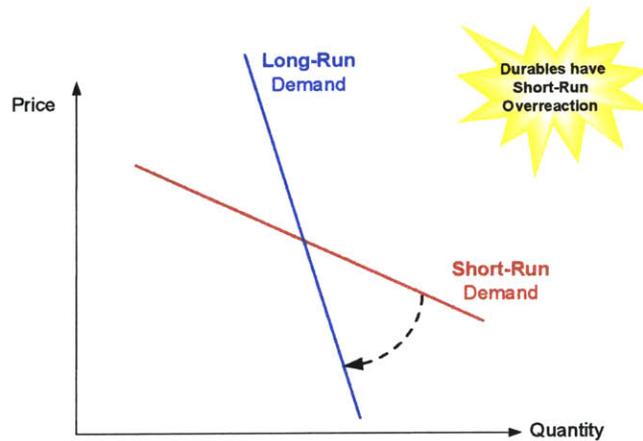
Figure 4.10: Effects of *Leadtimes* and *Lifetimes* on Dynamic Complexity



The durability of goods causes short-run elasticities to be larger than long-run elasticities, i.e. the demand for durable goods fluctuates sharply in response to short-run changes in income and less so in the long run as replacement of durables is necessary (see figure 4.11 below).

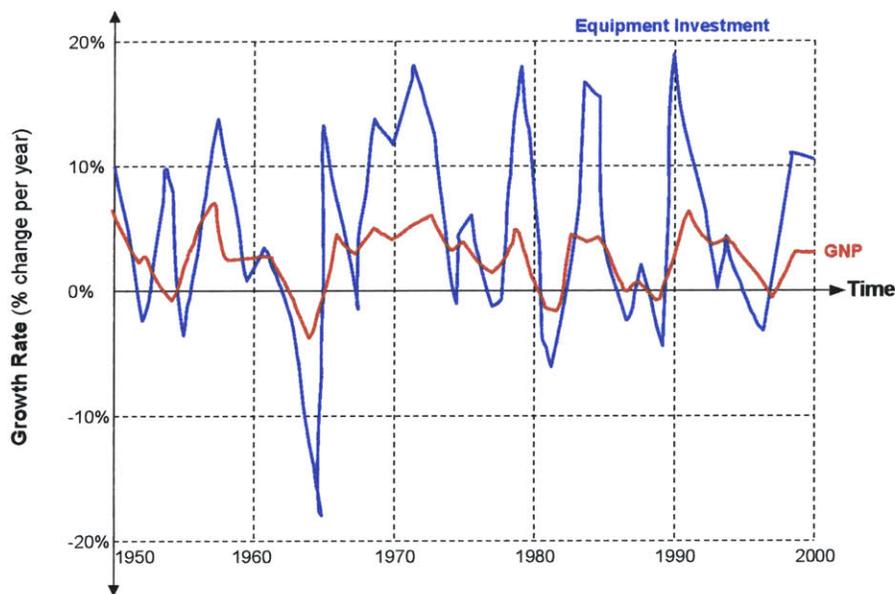
¹⁸⁵ See Sterman & Paich for a more detailed description of “Boom & Bust”.

Figure 4.11: Elasticities of Durable Goods



Durable industries therefore are quite vulnerable to changing macroeconomic conditions like the business cycle where they magnify changes in macro-variables like GNP. Short-run GNP elasticity of demand is larger than the long-run elasticity for long-lived capital equipment, thus changes in investment in equipment magnify changes in GNP. It is for this reason that capital goods industries are considered “cyclical” (see figure 4.12 below).

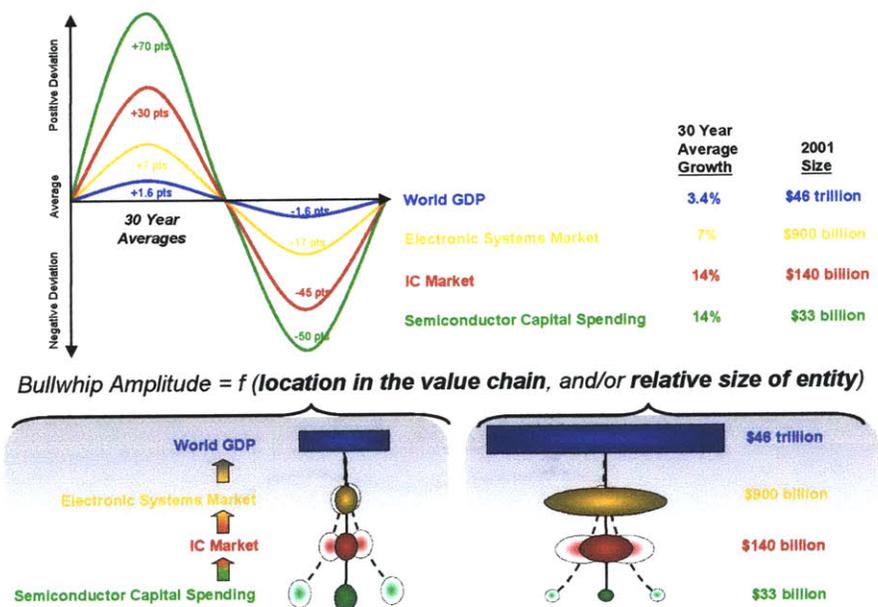
Figure 4.12: GNP and Investment in Durable Equipment¹⁸⁶



¹⁸⁶ *Microeconomics*, Pindyck and Rubinfeld, pg. 37.

In looking at multiple stages in an industry value chain, there is greater amplification the farther upstream you are. This can be explained either as there is more propagation of phantom orders due to information and delivery lags or it can be explained as the enterprise participant with the greatest mass and inertia moves the least. From figure 4.13 below, it is clear that the massive “world GDP” moves the least (at +/- 1.6%) while the least massive semiconductor capital market moves the most (at +/- 60%)¹⁸⁷.

Figure 4.13: Bullwhip in the Semi-Conductor Industry



There is one curious observation in the bullwhip for macro-economies. We saw in chapter 3 that not only is there demand amplification up the supply chain, but there are subtle delays causing phase shifts among the players in the supply chain. In the above figure, we can see the demand amplification, however there is no phase shift i.e. all the sine waves cross the zero axis at approximately the same times. This curious synchronized vibration is known as “entrainment”¹⁸⁸.

Forrester notes that entrainment is a notion that in all dynamic systems, similar modes of behavior lock together with even the slightest coupling between systems. Very small signals will entrain or synchronize such systems, especially in highly damped systems. Forrester notes that when the National

¹⁸⁷ Data taken from Lou Rassey’s 2003 LFM thesis and internship at Intel.

¹⁸⁸ See John Sterman (2001) and Alan Graham (1977).

Bureau of Standards used pendulum clocks for the basic time standard that entrainment was enough of a concern that two clocks had separate concrete foundations and were also turned at right angles to one another to keep synchronizing forces from being transmitted between them.¹⁸⁹

4.5 The “Governing Dynamics” of Economic Ideologies

I end this chapter on the dynamics of macroeconomic trends with a brief discussion about fundamental economic ideologies which distinguish between the most basic notions of competition and cooperation. This theme has already come up within the context of “stakeholder cooperation” vs. “shareholder competition” in sections 6.1 and 6.4, “public” vs. “private goods” in section 6.6, as well as the in the context of “enterprise integration” vs. “functional competition” of section 3.7.

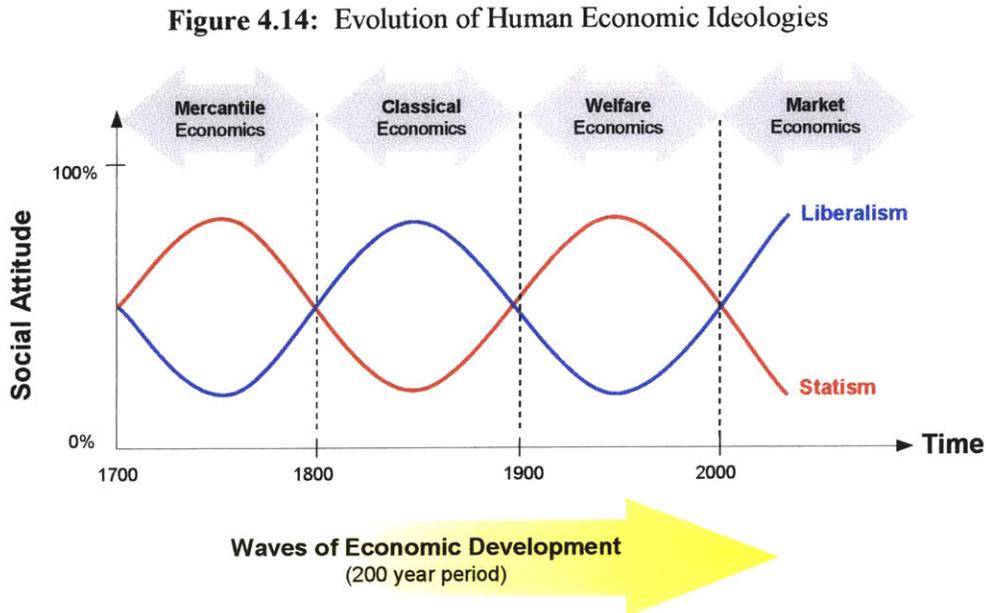
Adam Smith’s notion of an “invisible hand” that will guide the common good, via the collective (but disconnected) selfish interactions of individuals was challenged (or extended) over 200 years later by John Nash in his search for the “governing dynamics”. Nash’s “equilibrium” is a sort of win-win state where the best possible outcome occurs when everyone does what is best for themselves *and* the group. Under the invisible hand, each player’s individually rational choice leads to a sub-optimum collective outcome, as expressed in the “Prisoner’s Dilemma” for oligopoly producers (which we will discuss again in the next chapter). But Olsen and others suggest that there is a way out of Adam Smith’s competitive sub-optimum via co-operation enforced by institutions¹⁹⁰.

This Adam Smith vs. John Nash competition vs. cooperation dynamic can be understood by using the generic structure of the pendulum that we have seen thus far throughout. Again, the notion of a balancing loop with delays which causes so much of the oscillatory behavior in social and technical systems can be extended to look at very high-level trans-national, trans-era issues, like the dynamics of

¹⁸⁹ Keough, Mark and Doman, Andrew, “The CEO as Organization Designer: An Interview with Prof. Jay W. Forrester”, *The McKinsey Quarterly*, 1992 Number 2, pp. 3-30.

¹⁹⁰ Olson, Mancur, “The Logic of Collective Action: Public Goods and the Theory of Groups”, *Harvard Economic Studies*, Vol. CXXIV, 1971.

economic ideologies as shown in figure 4.14 below¹⁹¹. Note the 200-year period of oscillation. It is interesting to note that the two ideologies broadly capture the competing dynamic philosophies of *Boeing* and *Airbus*.



4.6 Chapter Summary

This chapter raised the discussion of enterprise design from the microeconomic level of firms and value chains, to the macroeconomic level of three different macro-enterprises: nations, multi-national trading blocks and global economic ideologies.

We applied the pendulum physics introduced in Part I, to the US, Japan and EU economies in order to understand the [dynamic structure of nations](#) (e.g. clockspeed). We then illustrated how the methodology of pendulum physics could be applied to designing [national defense strategies](#).

And finally, we briefly explored how the generic structure of the pendulum could be used to understand the dynamics of global [economic ideologies](#).

¹⁹¹ From Eric White's LFM Thesis, "Lean Enterprise Distribution Tactics with Customer Supply Chain Integration", June 2003.

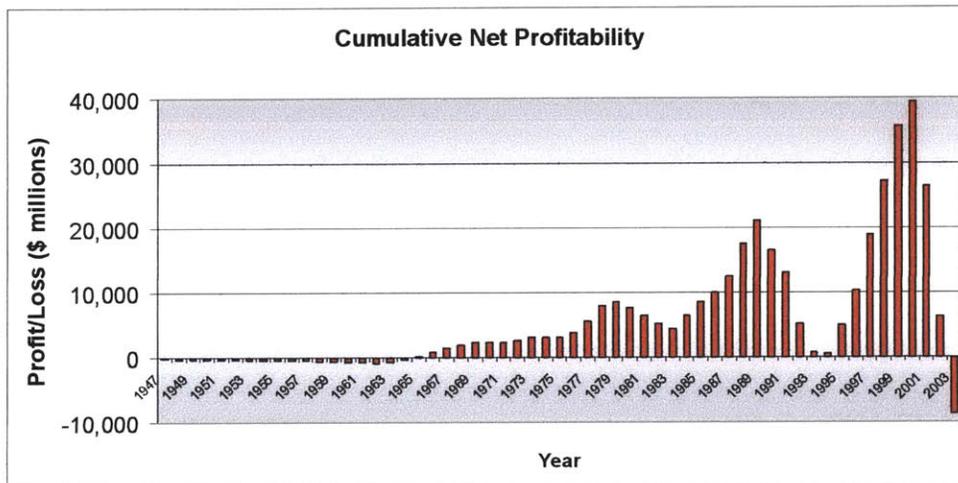
Chapter 5: The Dynamics of the Airline Industry

5.1 “The World’s Worst Industry”

“There is no worse business of size that I can think of than the airline business. Since it began in 1903, the industry has had an overall net loss. If there had been a capitalist at Kitty Hawk, the guy should have shot down Wilbur! I mean... one small step for mankind, and one huge step backwards for capitalism.”¹⁹²

So spoke Warren Buffet, widely regarded as the world’s most successful investor, and *Fortune* magazine’s “Most Powerful Man in Business” in 2003¹⁹³. In fact, as shown in figure 5.1 below, the cumulative net profit of the global airline industry is negative.

Figure 5.1: Cumulative Net Profit of the Global Airline Industry

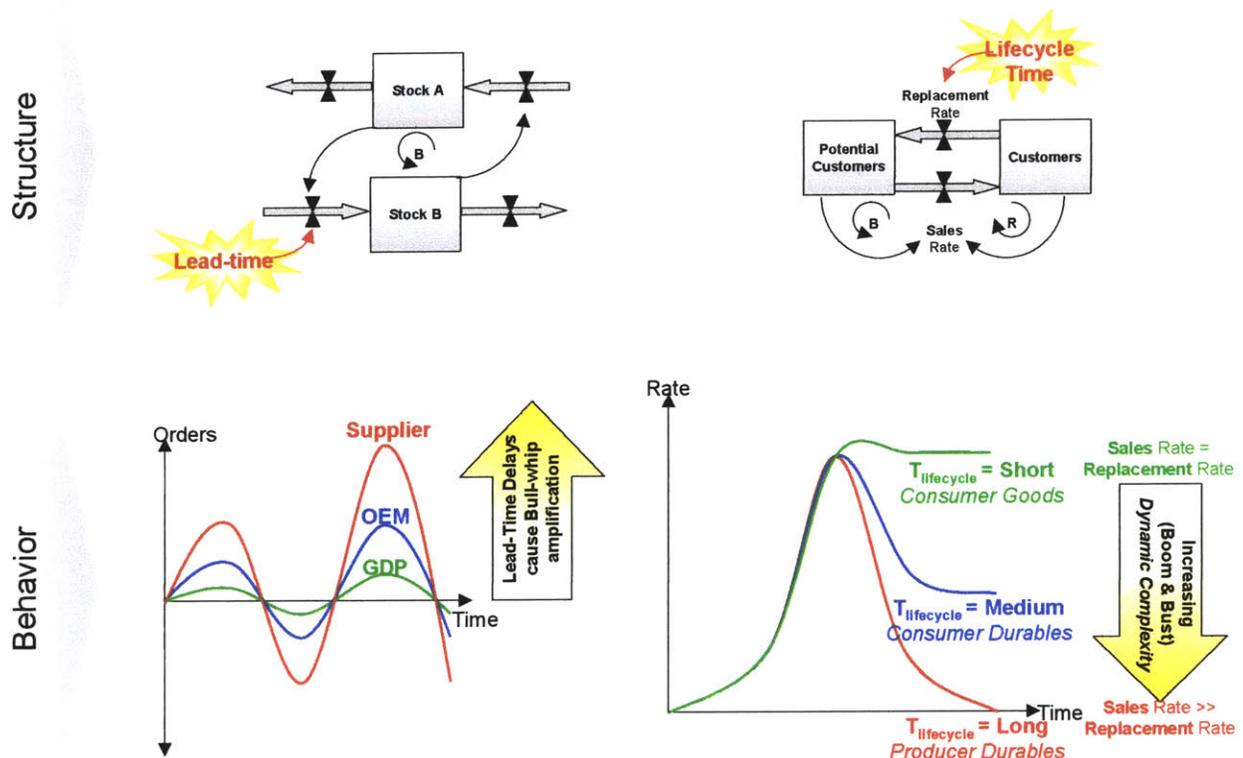


This work contends that an understanding of the dynamics of the industry lies in an understanding of the structure of the dynamic complexity of the industry. I contend that (among other strategic issues to be discussed later in this chapter) the airline industry is extraordinarily dynamically complex with cause and effect being very distant in time and space, and that two such structural sources of this dynamic complexity can be seen below in figure 5.2 as being long *leadtimes* and long *lifetimes* of the capital equipment (i.e. the aircraft) as was introduced in chapter 4.

¹⁹² “Warren Buffet Talks Business”, discussion at the *Kenan-Flagler Business School at the University of North Carolina at Chapel Hill*, PBS Home Video, 1995.

¹⁹³ *Fortune* magazine, “The 25 Most Powerful People in Business”, July 21, 2003.

Figure 5.2: Sources of Dynamic Complexity in the Airline Industry: long capital *Leadtimes* & *Lifetimes*

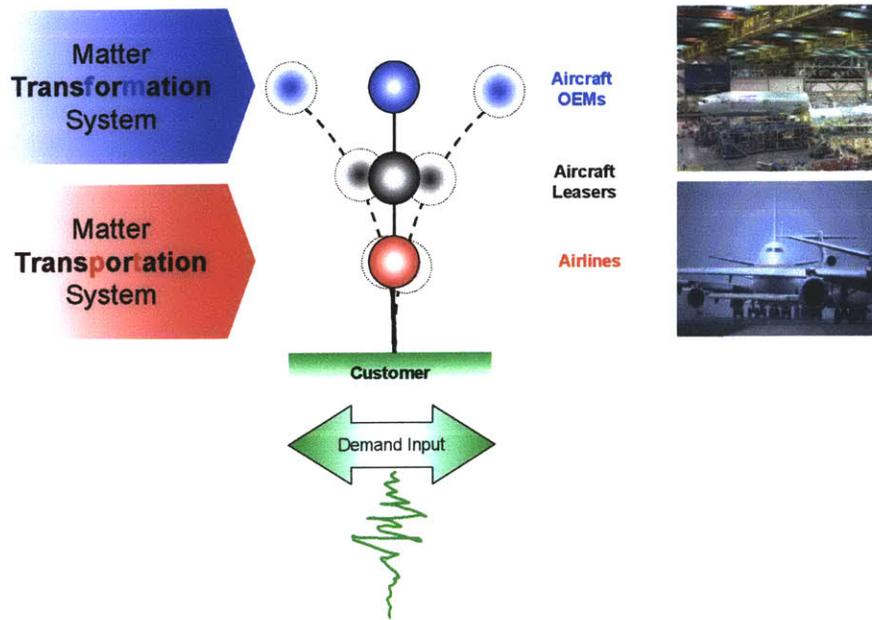


As has been discussed in Chapter 2, long leadtimes in the order-delivery cycle give rise to delays which can result in oscillation throughout the supply chain, resulting in excess costs and inefficiencies (as is seen in the two figures on the left). Also, long product lifetimes can lead to overcapacity in the airlines due to imperfect forecasting and delays in capacity expansion and contraction.

In order to understand the effect of fixed capital costs (e.g. airplanes) on the airline industry as well as the effect of the airline industry on its suppliers of fixed capital (i.e. airplane manufacturers), this work proposes to examine the coupling of two types of engineering systems: matter transformation and matter transportation systems as a production-distribution system shown in figure 5.3 below.¹⁹⁴

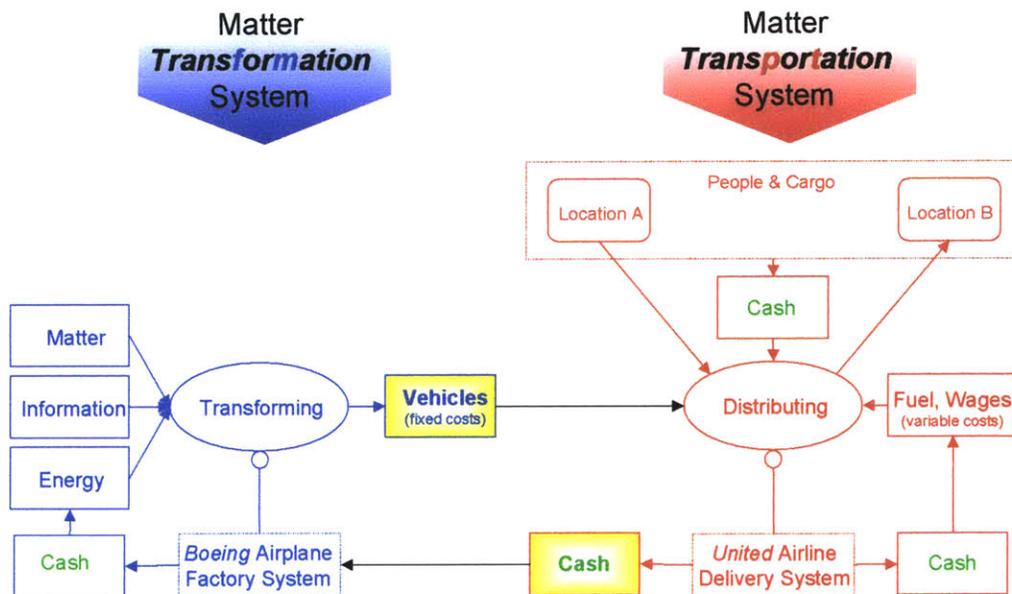
¹⁹⁴ Magee, C.L. and de Weck, O.L., "An Attempt at Complex Systems Classification", *Proceedings of the ESD Internal Symposium*, May 29-30, 2002, Massachusetts Institute of Technology, Engineering Systems Division, Cambridge, Massachusetts, pp. 217-250.

Figure 5.3: The Airline Industry & its Suppliers as a Production-Distribution System



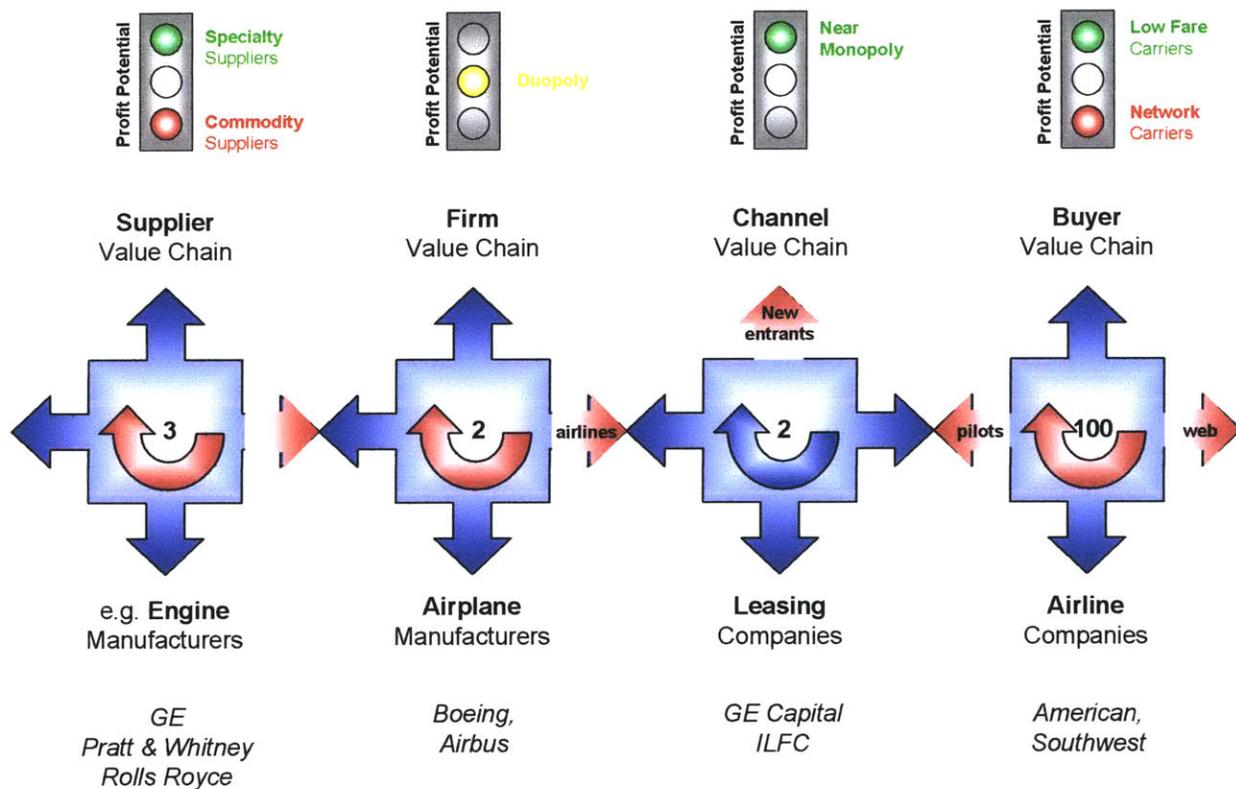
The two engineering systems can be represented using object-process diagrams as shown in figure 5.4 below. Note that the primary exchanges between the two systems are manufactured product (i.e. airplanes) in exchange for cash.

Figure 5.4: Object-Process Diagrams of the Airline Industry & its Suppliers



As shown in figure 5.5 below, a simple five forces¹⁹⁵ industry analysis would reveal that low profitability (especially for network carriers) is due to supplier power (e.g. pilot labor costs), buyer power (due to web-based fare visibility) and overcapacity driven by high barriers to exit. This lack of profitability at the end of the value chain *can* act to constrain profitability in the suppliers to the airline industry – like the equipment (airplane) manufacturers. Although the number of competitors of airplane manufacturers is small (effectively only *Boeing* and *Airbus*), the rivalry is unexpectedly intense as the competition is not purely on corporation-based market forces, but on broader national strategic interests.

Figure 5.5: Five Forces Analysis of the Airline Industry

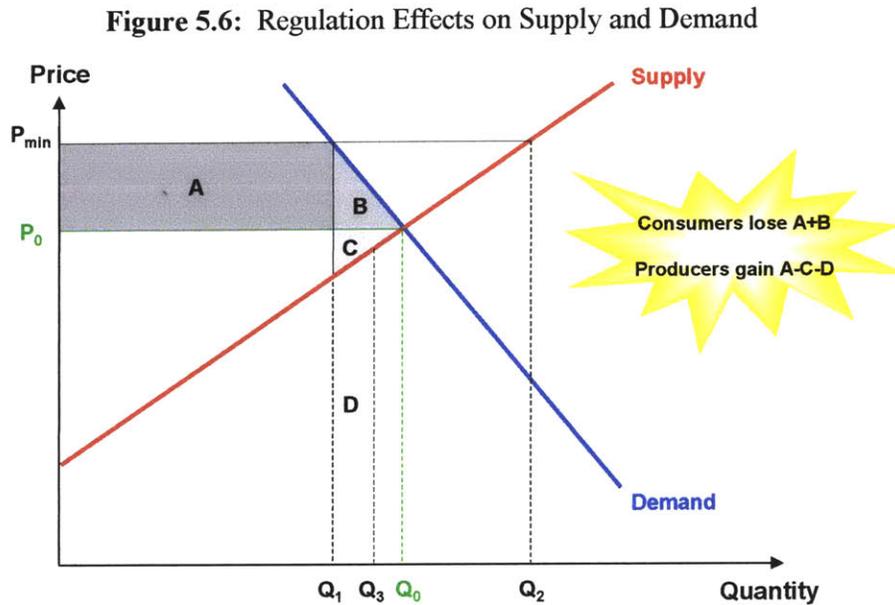


5.2 Deregulation, Instability and Oscillation

Due to the strategic importance of the airline industry, national governments around the world regulated its performance in order to provide stability to this vital strategic asset. Governments protected

¹⁹⁵ Michael Porter, *Competitive Strategy*, 1980.

this industry by setting fares (i.e. P_{\min}) well above that which would have cleared in a free market (i.e. P_0), as shown in the supply and demand curves of figure 5.6 below¹⁹⁶.



This price minimum, P_{\min} , acts to create a loss to consumers (i.e. the traveling public) represented by the areas $A+B$. The producers (i.e. the airlines) receive a transfer of money from consumers represented by rectangle A . It is clear therefore that regulation favors the producers over the consumers by redistributing wealth.

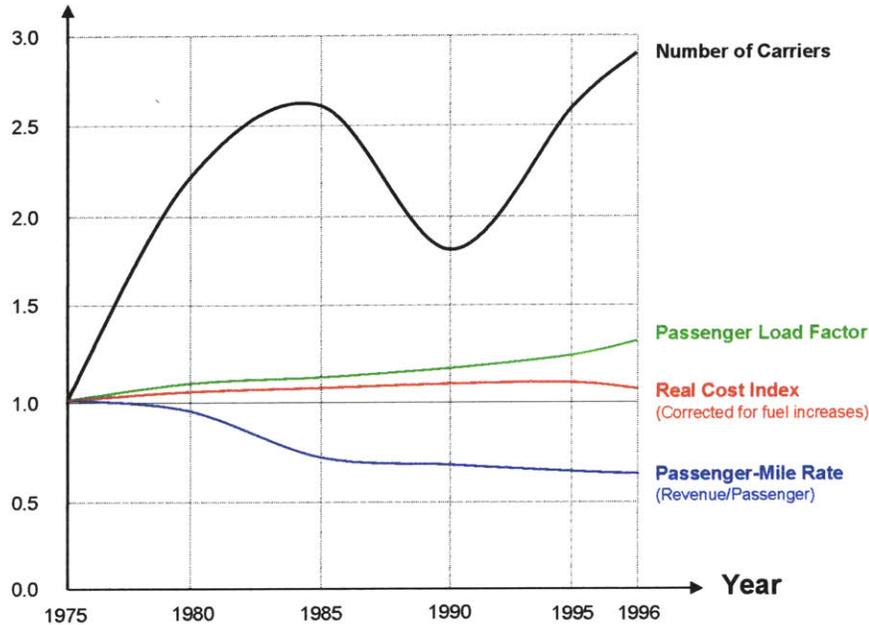
If the producers were to respond to unsold output by cutting production (i.e. limiting production to Q_1), then the loss to producers is $A-C$. Note, however, that at a price of P_{\min} , the producers would like to supply Q_2 , which is much more than the consumers are willing to buy. Even if they have some restraint in production, they will still produce up to Q_3 , hoping to sell this quantity at the expense of competitors. This trapezoid D measures the cost of unsold output. The total loss to producers in this case is actually $A-C-D$. Therefore, although a regulated market should help producers profitability, it is clear that overproduction by the airlines will limit their profitability.

Overproduction notwithstanding, as long as price was propped above its market-clearing value, average profits would be higher than in a free market. Conversely, in a deregulated world, prices drop

¹⁹⁶ *Microeconomics*, Robert S. Pindyck and Daniel L. Rubinfeld, 2001, pg. 301.

considerably (as predicted in figure 5.3 above) and costs remain largely the same, reducing profitability for airlines as shown in figure 5.7 below¹⁹⁷. Deregulation therefore largely favors the consumers and squeezes the producers.

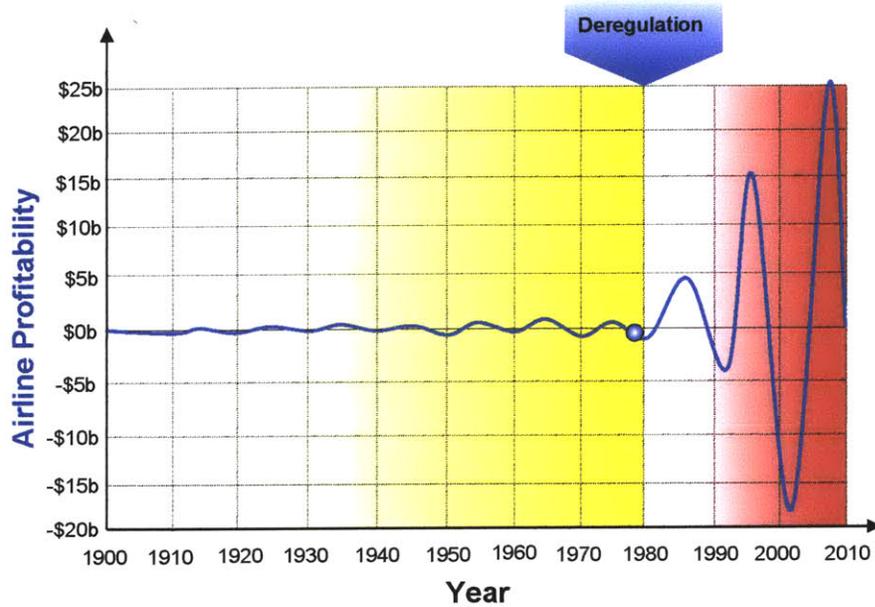
Figure 5.7: Overall Effects of Deregulation



After deregulation around 1980, the airline industry exhibited clear dynamic instability and oscillation as shown in figure 5.8 below. The airline industry began to behave as a dynamic system (with a characteristic natural period of vibration to be discussed further in Chapter 7) undergoing forced vibration defined by the sudden rush of capital and construction of new capacity. The relative ease of inducing capital inflows in economic upswings and difficulty in flushing out excess capacity in economic downswings (i.e. low barriers to entry and high barriers to exit) have resulted in chronic instability and low average profitability.

¹⁹⁷ Department of Commerce, *U.S. Statistical Abstract*, 1986, 1989, 1992, 1995, 1998.

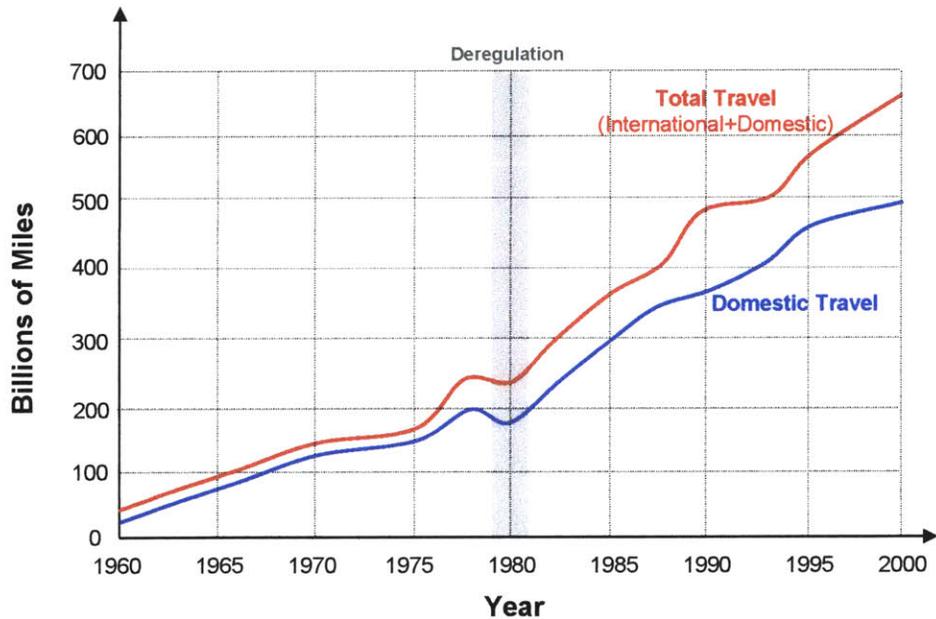
Figure 5.8: Deregulation Effects on Airline Profitability



Source: Murman et al.

Regulation had the effect of constraining growth below free-market levels. Deregulation, on the other hand had the effect of expanding growth to levels twice as high as in a regulated environment (see the slope of the growth curve before and after 1980 in figure 5.9 below).

Figure 5.9: Deregulation-Induced Demand Growth



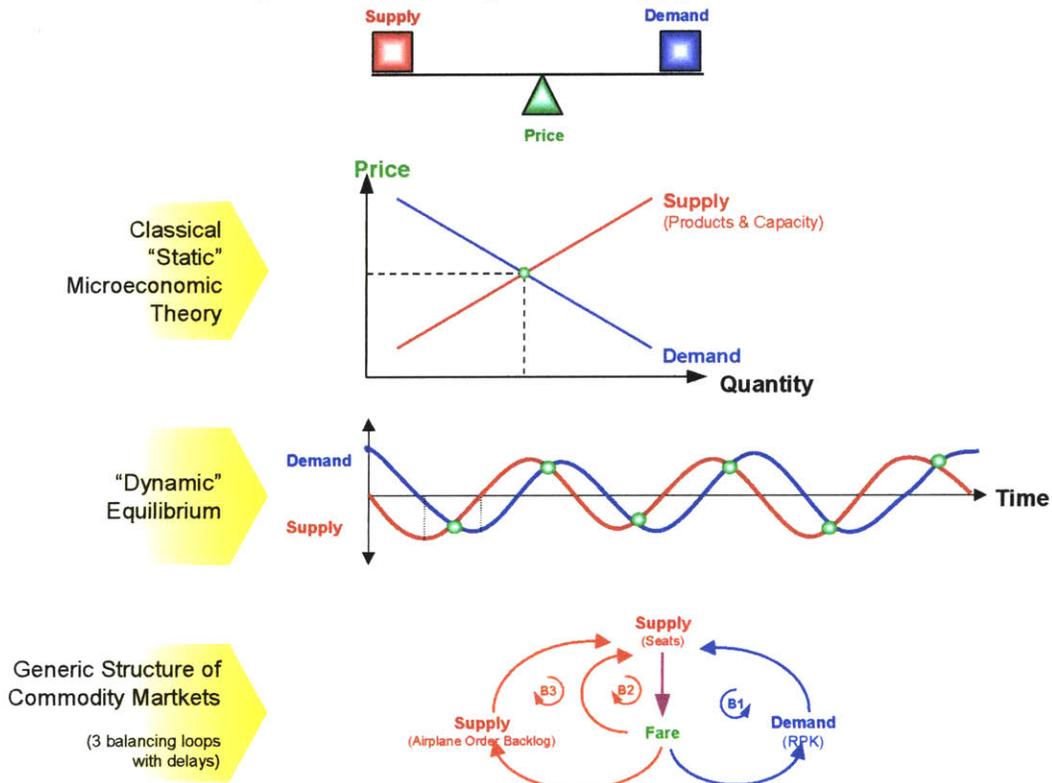
Source: Murman et al.

5.3 The Dynamics of Capacity (Supply) & Demand

We are taught in classical microeconomics that supply and demand are equilibrated by price. This static equilibrium assumes that there are no delays in the achievement of this goal-seeking, balancing feedback loop.

Figure 5.10 below shows how price equilibrates supply and demand in the classic (static) microeconomic model. However due to the delays embedded in the three balancing loops shown below, there is dynamic oscillation in the generic structure of a commodity market. This “commoditization” manifests itself as recurring cycles in investment, capacity utilization, prices, margins and return on capital.

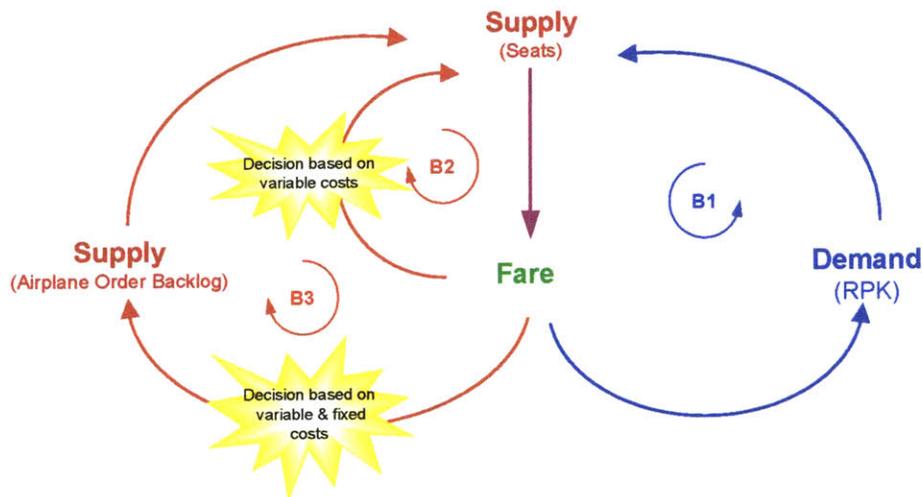
Figure 5.10: Price Equilibrates Supply and Demand



In fact, it is this simplified generic structure model of commodity markets, that is used by *Airbus* to understand and drive the strategy of designing and delivering airplanes.^{198,199} As can be seen in figure 5.11 below, there are is one primary balancing loop in which price balances supply with demand. Again, because of delays, there are significant oscillations to this loop, just like in any commodity market.

In addition to this primary balancing loop, there are three lesser positive reinforcing loops (which are not shown on figure 5.11) that include: increasing orders due to the “lead time/supply line effect” and enjoyable travel begets more travel.

Figure 5.11: Basic Dynamics of Airline Industry



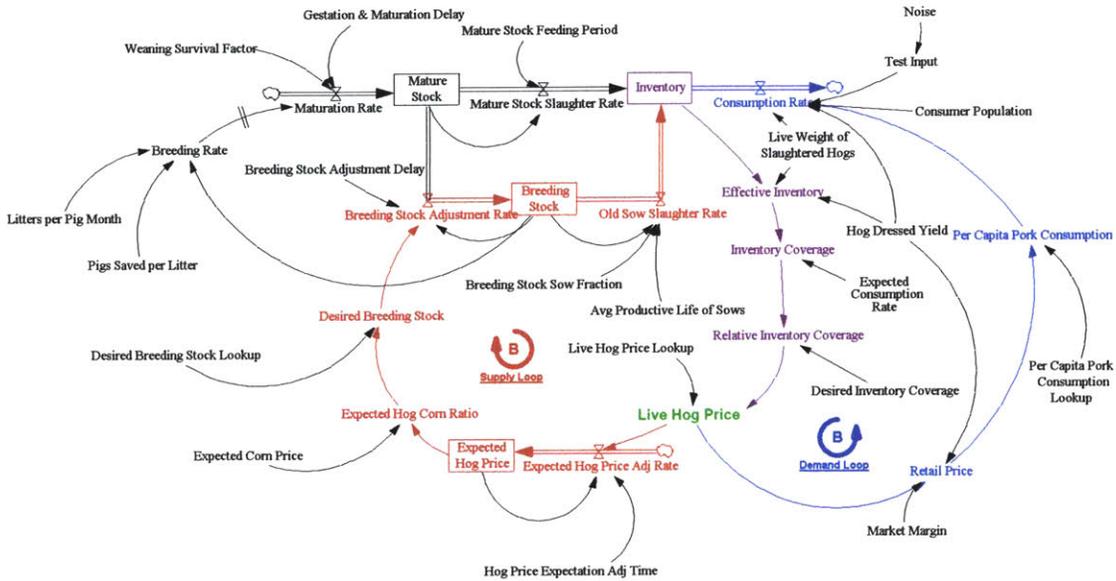
Again, it is interesting to note that the dynamics of any commodity, whether it is high-technology airplane production, or low-tech pork-belly production, figure 5.12 below shows that the underlying dynamic structure is the same²⁰⁰. Note that as price (in green) attempts to equilibrate demand (in blue), with supply (in red). As supply contains significant delays, the result is instability, just like in the airline industry.

¹⁹⁸ “System Dynamics for Market Forecasting and Structural Analysis”, Jim Lyneis, System Dynamics Review, Volume 16, Number 1, Spring 2000.

¹⁹⁹ “Commoditization of Technology-Based Products and Services: A Generic Model of Market Dynamics”, Henry Birdseye Weil, MIT, 11 March 1996.

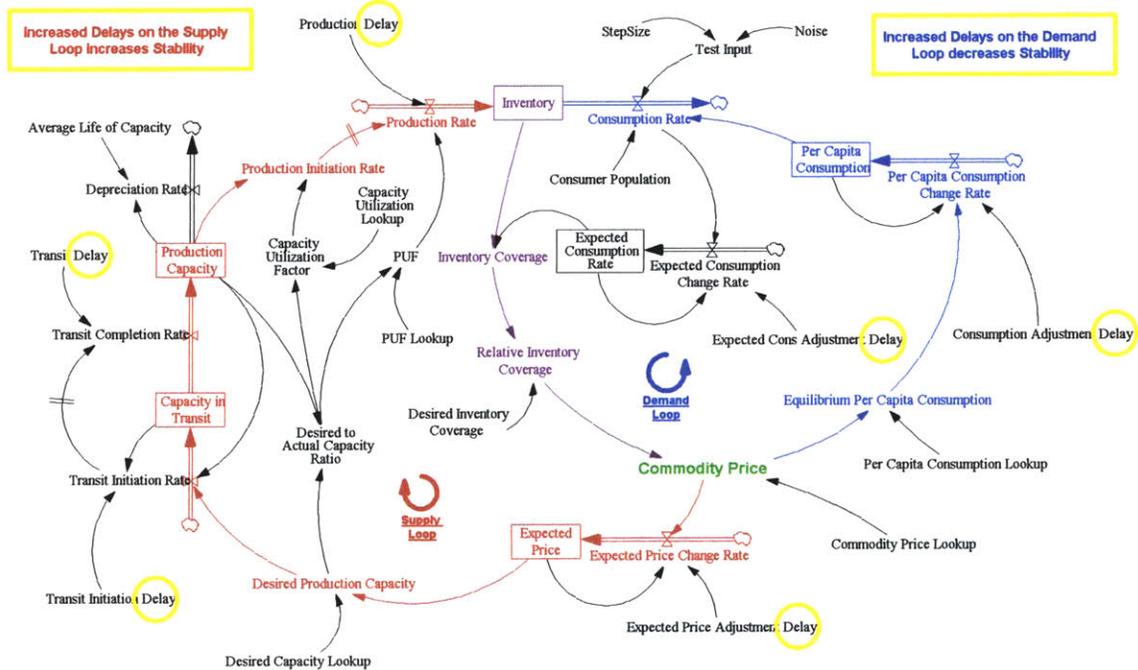
²⁰⁰ *Dynamics of Commodity Production Cycles*, Meadows, D.L., Pegasus Communications, 1970.

Figure 5.12: Basic Commodity Dynamics of Hog Production (source: Meadows)



Finally, the generic structure can be seen in figure 5.13 below²⁰¹. Price (in green) is balancing the demand loop (in blue) with the supply loop (in red). Again, the supply loop contains significant delays, (which are illustrated by the yellow circles) resulting in instability. The equations for the *Vensim* model are reproduced in Appendix G.

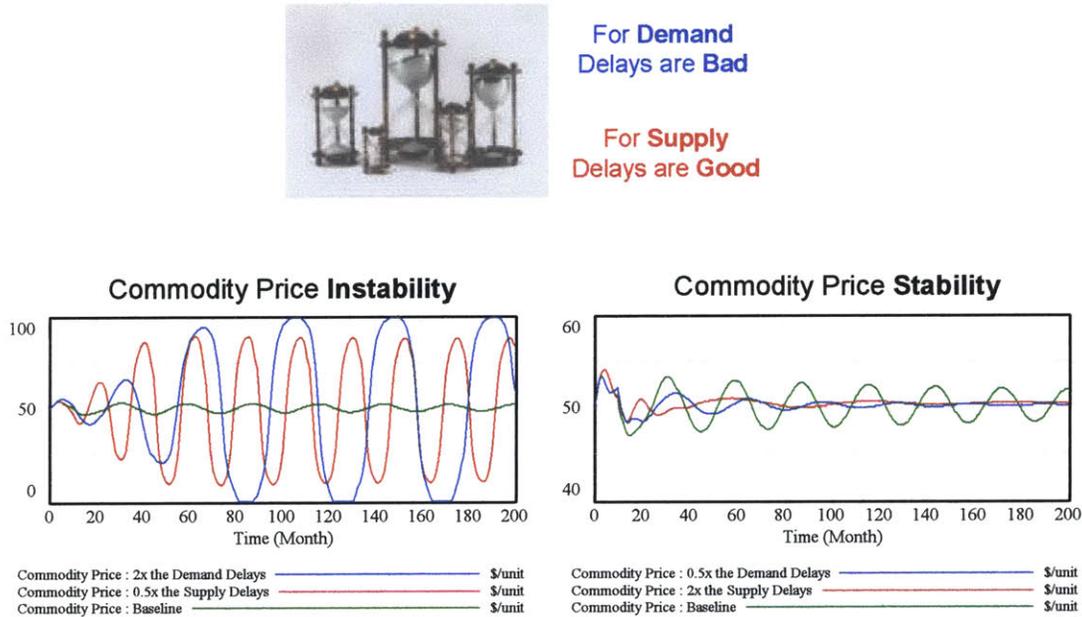
Figure 5.13: Basic Commodity Dynamics (source: Meadows/Fiddaman)



²⁰¹ *Dynamics of Commodity Production Cycles*, Meadows, D.L., Pegasus Communications, 1970.

As Forrester pointed out, delays can be both helpful and harmful with respect to causing instabilities, depending on where they are in the system.²⁰² In parametric studies conducted by this author on the above commodity dynamics model, I observe that there is a trend of increasing the stability of the system by increasing the delays in the supply loop, while decreasing the delays in the demand loop (as shown in figure 5.14 below).

Figure 5.14: Effect of Delays in the Supply and Demand of Basic Commodities Dynamics



5.4 The Dynamics of Supply & Demand in the Airline Industry

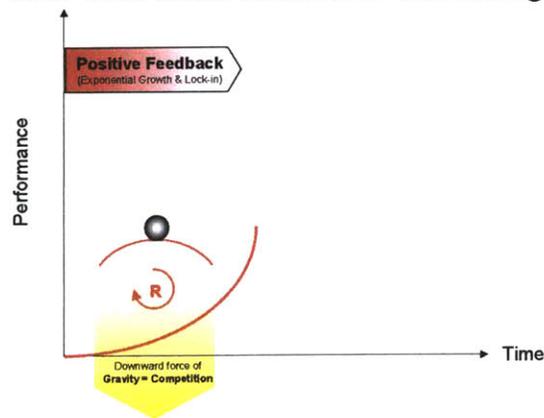
Having looked at the general dynamics of supply and demand (with reference to the classic commodity cycles), I now apply this generic model to the specific case of the airline industry. From Weil²⁰³, the basic system dynamics model of the airline industry can be seen in figure 5.15 below.

In this figure, fares and other cash items like revenues and profitability are shown in the outer loop in green. Costs are shown in red in the interior and are broken down into fixed and variable. Demand and its associated variables are shown in blue. Capital expenditure on fixed cost infrastructure is shown in the yellow loop in the upper right of the figure.

²⁰² *Industrial Dynamics*, Jay W. Forrester, 1961, pg. 62.

²⁰³ "Commoditization of Technology-Based Products and Services: A Generic Model of Market Dynamics", Henry Birdseye Weil, MIT, 11 March 1996.

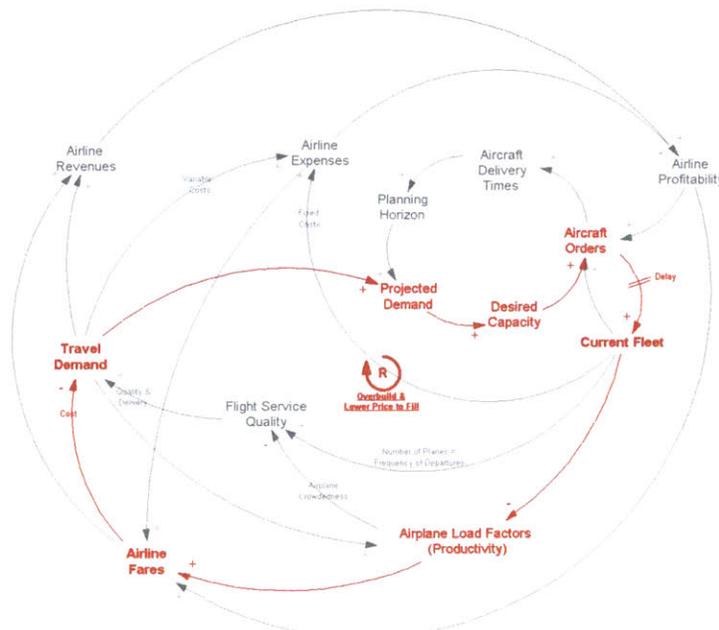
Figure 5.16: The Positive Feedback of “Reinforcing” Loops



These growth dynamics are caused by the commoditization of the three important customer metrics: quality, cost and delivery – none of which are tied explicitly to airline profitability! We will explore each of these in turn.

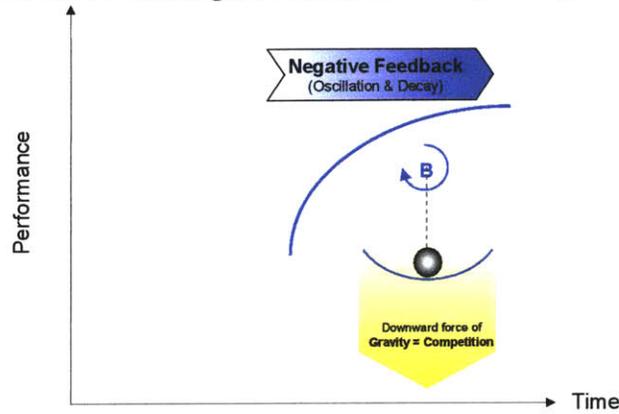
As can be seen in figure 5.17 below, airline capacity expansion (in the form of new aircraft orders), is fueled by the need to lower fares to improve flight productivity (or “load factors”) when new planes are brought on line. This in turn drives up demand that drives up the need for more planes. I call this “*cost-based commoditization*” because the airline passengers are attracted to fly by the lower fares, which translate into lower transportation costs for them. This behavior of overbuilding and then lowering price to fill capacity drives further overbuilding.

Figure 5.17: Cost-based Commoditization



Having considered the dynamics that cause growth, we can now briefly explore those embedded dynamics that drive “balancing” behavior. Balancing behavior, (otherwise known as “negative feedback”) by definition drives a system towards a stable equilibrium like a marble in a bowl as shown in figure 5.20 below.

Figure 5.20: The Negative Feedback of “Balancing” Loops



In the aforementioned dynamics of capacity expansion of commodities, there are two fundamental balancing dynamics that bring a system to a stable equilibrium. The first is that demand growth drives prices up, which in turn stabilize demand growth, as shown in figure 5.21 below.

Figure 5.21: Demand Balances Price (or Cost to Customers)

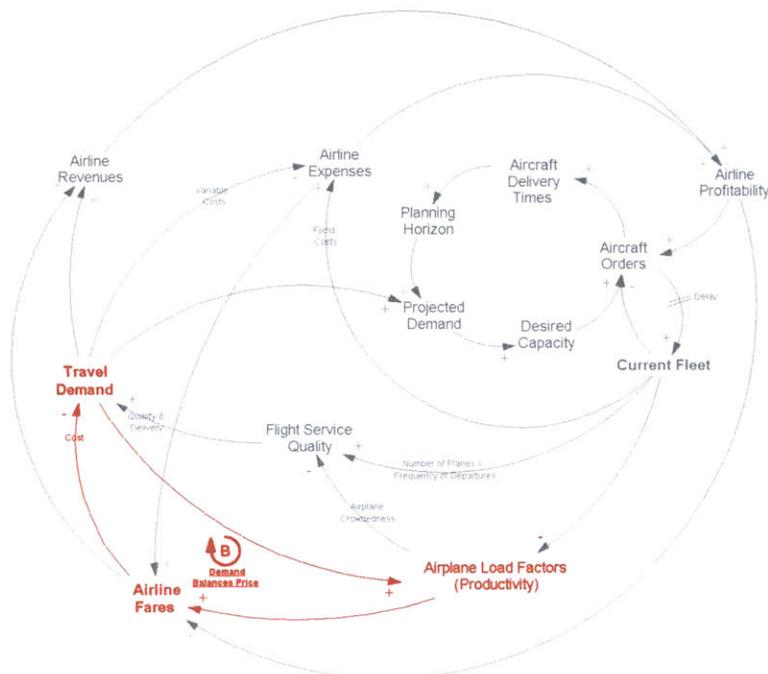
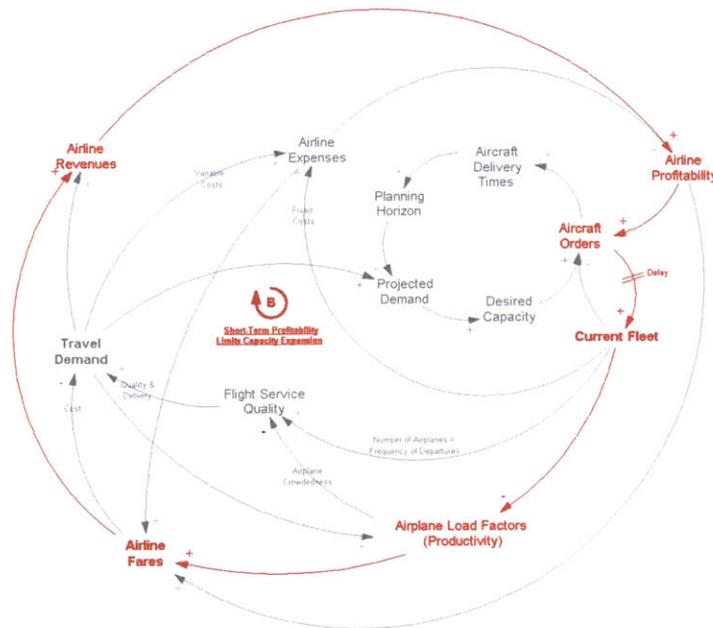


Figure 5.23: Low Short-Term Profitability Limits Capacity Expansion (due to lower revenues)



In addition, fleet capacity expansion can be limited by short-term hits on profitability due to rising variable costs associated with increased travel demand. Again, this is attributed either to lower costs, higher departure frequency or better quality as shown in figures 5.24, 5.25 and 5.26 respectively below.

Figure 5.24: Low Short-Term Profitability Limits Capacity Expansion (due to higher variable costs related to lower fares)

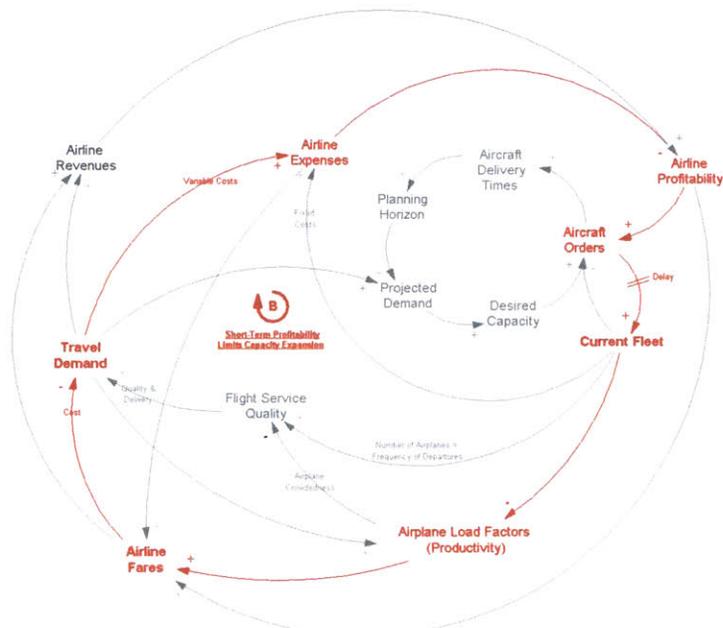


Figure 5.25: Low Short-Term Profitability Limits Capacity Expansion
 (due to higher variable costs related to more frequent departures)

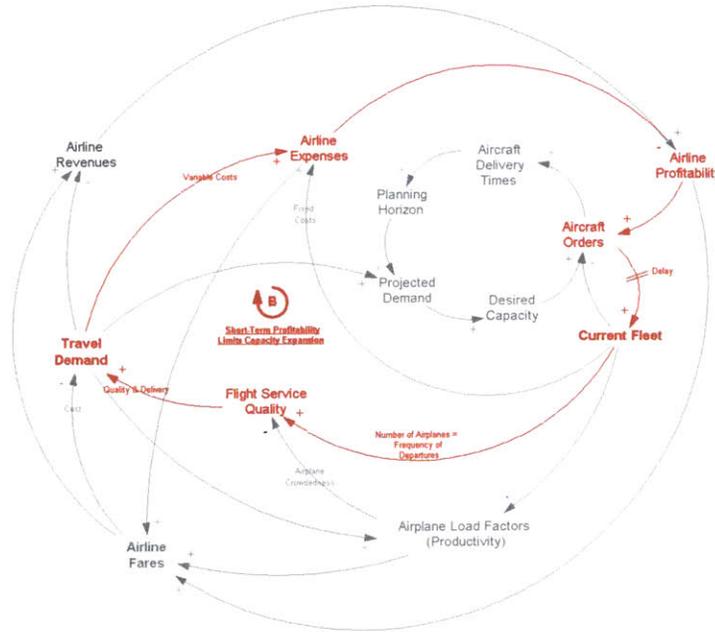
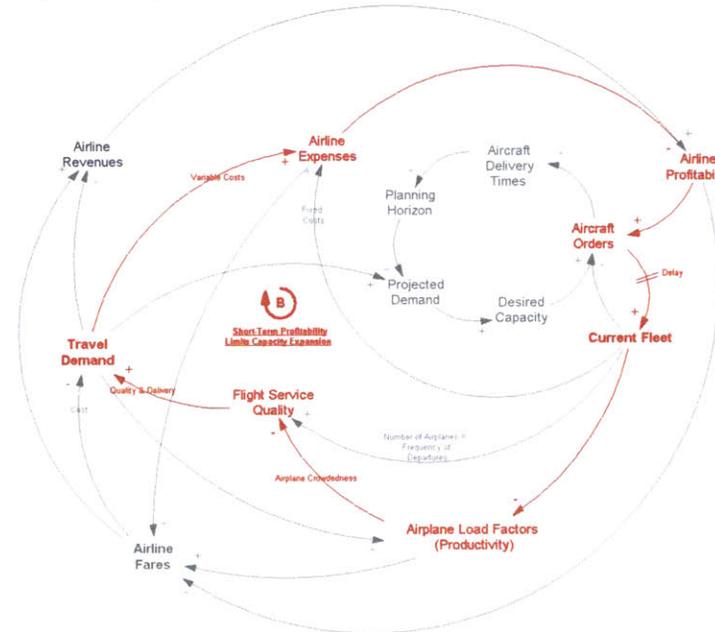
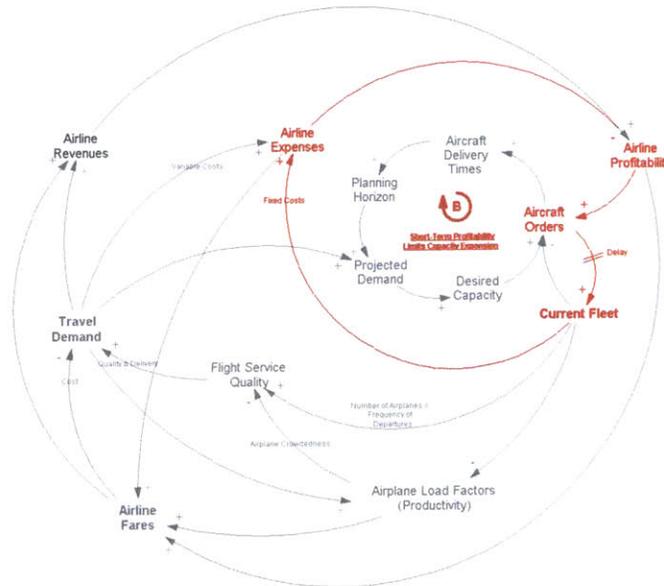


Figure 5.26: Low Short-Term Profitability Limits Capacity Expansion
 (due to higher variable costs related to higher quality flights)



Finally, fleet capacity expansion can be limited by short-term hits on profitability due to rising *fixed* costs associated with investment in the fleet as shown in figure 5.27 below.

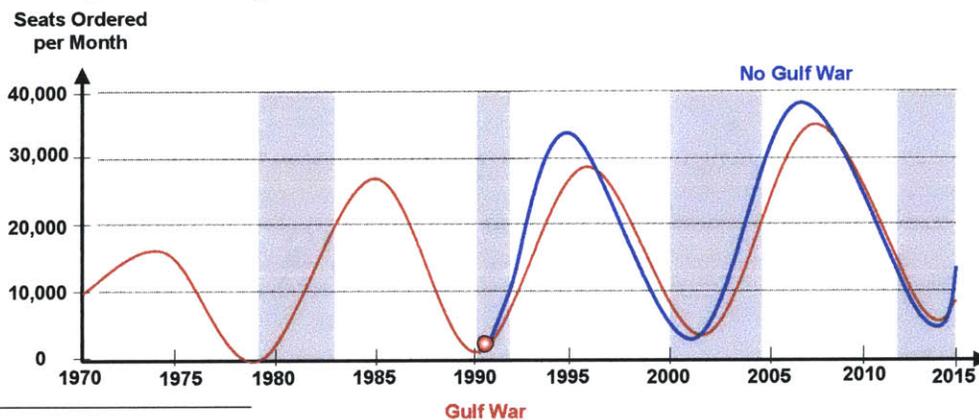
Figure 5.27: Low Long-Term Profitability Limits Capacity Expansion (due to higher fixed costs)



5.7 The Dynamics of Exogenous Shocks to the Airline Industry

Using a system dynamics model (not unlike the one we have been discussing), one can begin to explore the effects of exogenous shocks to the airline industry. This is important today, as exogenous shocks like September 11th bombings, the Iraq war and the SARS outbreak have all been cited as causing the significant downturn in airline profitability. Researchers have examined the impact of such shocks like the Gulf War in 1991 on the airline industry as shown in figure 5.28 below²⁰⁶.

Figure 5.28: Impact of the Gulf War on the Airline Industry (source: Liehr et al.)



²⁰⁶ Liehr, Martin; Grossler, Andreas; Klein, Martin; Milling, Peter M.; “Cycles in the Sky: Understanding and Managing Business Cycles in the Airline Market”, *System Dynamics Review*, Volume 17, Number 4, Winter 2001, pg. 311-332.

It is interesting to note that in the presence of an exogenous shock, the inherent dynamic structure of the industry remains intact. That is, the ten-year period of vibration remains largely unchanged, indicating that the industrial inertia and reactivity (the quantities that make-up the industrial clockspeed) have not been modified. The primary difference in the scenario with and without the Gulf War is the amplitude of demand, which returns to its dynamic equilibrium within a few cycles, i.e. within a few decades.

5.8 Positive Feedback and The Dynamics of Cost

Finally, I end this chapter on an exploration of the dynamics of the airline industry by considering the important dynamics of cost.

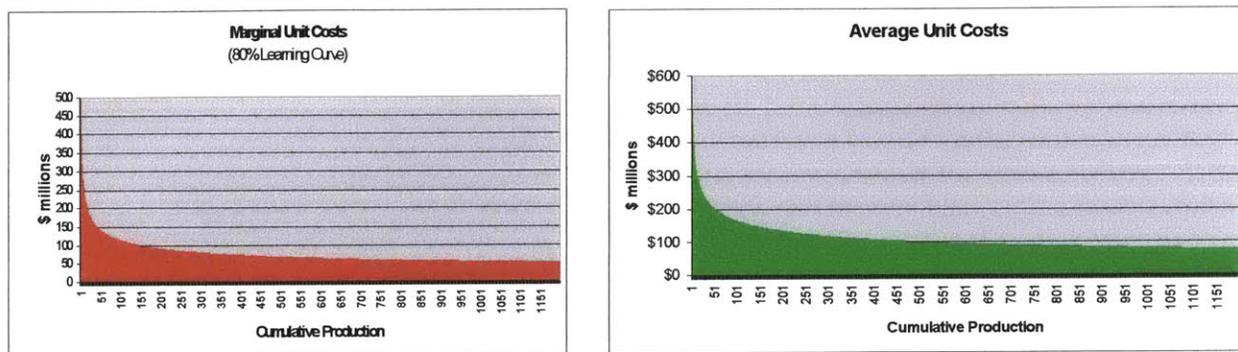
Modern economic theory rests on the century-old notions of equilibrium and decreasing returns associated with negative feedback which leads to a predictable equilibrium for prices and market shares. However, as Arthur points out, knowledge-based parts of the economy like aircraft manufacture are largely subject to the positive feedback of increasing returns as such products are complicated to design and manufacture.²⁰⁷ As aircraft require large initial investments in research, development, testing and tooling (i.e. non-recurring costs), once sales begin, incremental production is relatively inexpensive. As more aircraft are built, unit costs continue to fall and profits continue to increase. If there are increasing returns to scale, then it is economically advantageous (from a public policy perspective) to have one or two large firms producing (at relatively low cost) rather than to have many smaller firms producing (at relatively high cost). In fact, the greater the returns to scale, the larger the firms tend to be. It is for this reason that the manufacture of large aircraft has evolved to a global duopoly. This public policy approach of encouraging a few, large firms in industries of increasing returns is often followed by closer regulation as is seen for example in power companies.

Industries with increasing returns have production costs fall as market share increases, however this increased production has the additional benefit of gaining more experience in manufacturing, known

²⁰⁷ Arthur, W. Brian, "Positive Feedbacks in the Economy", *The McKinsey Quarterly* 1994 Number 1, page 83-84.

as the “learning curve”. The learning curve describes a phenomenon in which the cumulative average recurring production cost per aircraft tends to decline by a more or less constant percentage between doubled quantities of production. Research has indicated that, for complex modern aircraft, learning coefficients between 75% and 80% are typical²⁰⁸. This means that for every doubling in cumulative aircraft production, the associated marginal production costs would reduce by 20%-25%, as shown in figure 5.29 below.

Figure 5.29: The Learning Curve for Aircraft Manufacture



It is important to note that airplane costs (and therefore profits) are a function of the total number of airplanes built. There are strong reinforcing incentives to price initially at the expected future cost rates, in order to bring forward sales ahead of competitors which increases cumulative production, which in turn drives down costs – a sort of self-fulfilling prophesy. If one does not estimate demand accurately and take learning into account the cost calculations, the calculation of airplane program value may be incorrect. In fact, if the selling price remains approximately constant over the life of the program, then the first production runs will actually lose money, and profit-making production will be in the distant future, where it is discounted. It is well known that firms in industries that exhibit strong learning curve effects have typically based their pricing strategies on anticipated market development rates²⁰⁹.

²⁰⁸ Reinhardt, U.E.. “Break-even Analysis for Lockheed’s Tri-Star: An Application of Financial Theory,” *The Journal of Finance*, 1971.

²⁰⁹ Kim Warren, *Competitive Strategy Dynamics*, John Wiley & Sons, 2002, pg. 284-286.

5.9 Chapter Summary

This chapter extended the use of system dynamics from exploring a generic enterprise (i.e. a value chain) to exploring an entire industry (i.e. the [airline industry](#)). We began by exploring the causes of the industry [oscillation](#), before using a [commodity](#)-based system dynamics model to understand the dynamics structure underlying industry [profitability](#).

Finally, we discussed the dynamics of the nature of the primary capital expenditures in the airline industry: the airplanes. We noted that durable goods have their own worse-before-better equilibrium, and we noted that the costs for the production of aircraft decline over time as a manufacturer descends the “learning curve”.

In Part I of this thesis, we have laid out the principles of “enterprise engineering” which were based on the “laws of enterprise physics”. The first step in mastering “dynamic complexity” has been established – namely the quantification of the *dynamic* behavior of enterprises or the exploration of the *temporal* distance or disconnection of cause and effect.

In the Part II, we will focus on the principles of “enterprise architecting” which are rooted in the “heuristics of enterprise design”. This is the second part of mastering dynamic complexity, namely the quantification of the *complexity* embedded in the enterprise or the exploration of the *spatial* distance or disconnection of cause and effect. In the next chapter, we will first consider the proper “extent” of the boundaries of the enterprise and the nature of the relationship amongst the different actors in comprising this extended enterprise.

Part II: Enterprise *Architecting*

“We are called to be the architects of the future, not its victims.”

Buckminster Fuller
Engineer, Architect, Philosopher

“Architectural insights are worth far more than ill-structured engineering analyses.”

Eberhardt Rechtin
Professor, Systems Architect

Chapter 6: Architecting Enterprise Relationships

In this chapter, I will attempt to define three important activities in architecting enterprise relationships: defining the appropriate extent of the enterprise (i.e. the boundary), defining the interfaces at the boundaries (i.e. the governance profile), and finally how to grow the capabilities of the enterprise through managing the dynamic resources.

One of the most important activities in systems thinking is what John Sterman calls, “challenging the clouds”²¹⁰. The highest leverage policies often occur beyond the boundaries of the enterprise for which corporate policy makers are accustomed to operating within. In the following, I will define both the “quantity” of relationships with potential stakeholders followed by a discussion of the “quality” of relationships with stakeholders.

6.1 Quantity of Relationships: Stakeholders vs. Shareholders

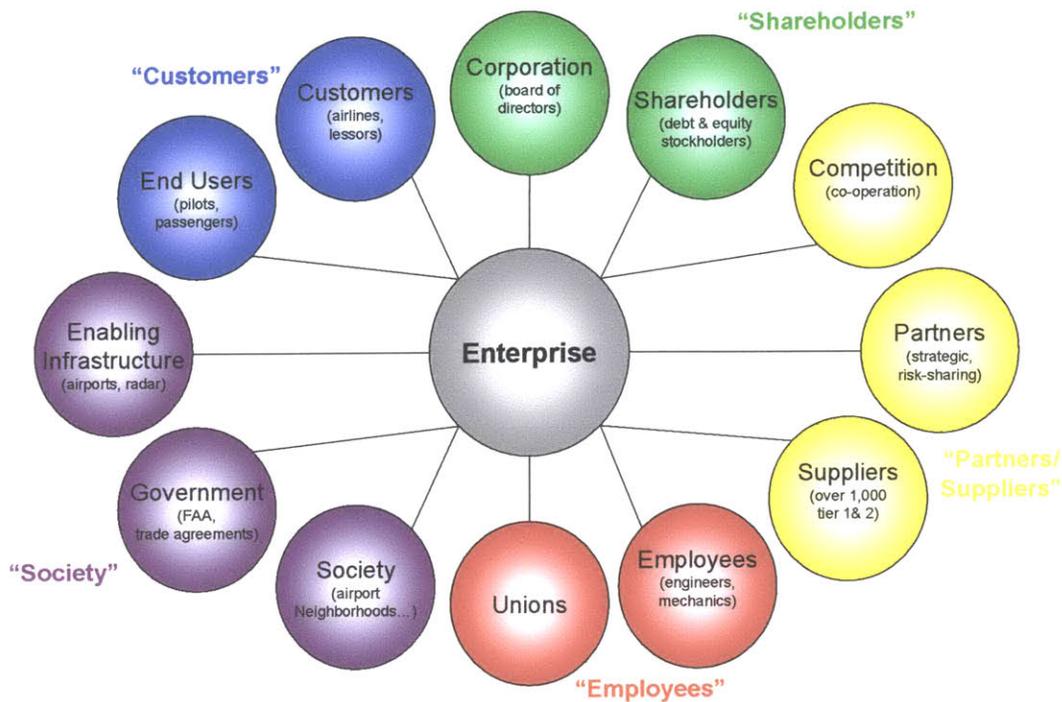
One of the most important strategic decisions that a corporation can make, is to define the extent of the “governance profile”, that is which stakeholders to explicitly include in the firm’s value web. A stakeholder analysis²¹¹ begins with the identification of the possible range of stakeholders which can be broken down into the five general types: Shareholders, Customers, Employees, Partners/Suppliers, and Society, as shown in figure 6.1 below.

Other than the recognition of the existence of these stakeholders, the obvious challenge is to prioritize the importance of each stakeholder and to define the level of economic rent-sharing with each. To this end, there are two well-known “objective functions” which can be optimized: Economic Value Model (Economic Rate of Return) and the Stakeholder Surplus Model (Financial Rate Return).

²¹⁰ *Business Dynamics*, John Sterman, 2000, pg. 222.

²¹¹ *Lean Enterprise Value*, Earl Murman et al., 2002.

Figure 6.1: Stakeholder Analysis



The *Economic Value Model* is typified in the US market-based capitalist economy. It tends to focus almost exclusively on maximizing wealth for the shareholders. This rather limited stakeholder scope has the benefits of clear objectives and relatively transparent, well-defined methods to achieve this objective. Companies operating under such economic objectives tend to answer to the faster clockspeed, frictionless demands of the capital markets which results in a focus on the shorter-term. From our previously-developed concepts of *enterprise physics*, one could conjecture that in general, shareholder-focused US firms tend to have higher Value Chain Reactivity and Customer Responsiveness along with lower Organizational Inertia.

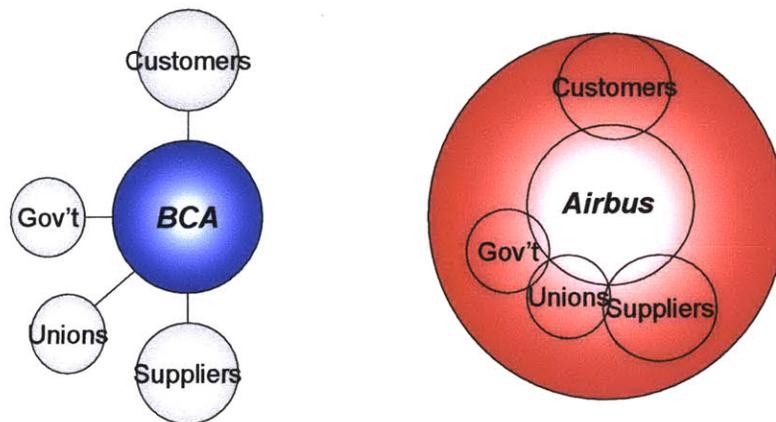
The *Stakeholder Surplus Model* on the other hand is typified in the European and Japanese social-based economies. These tend to focus on a broader, more complex range of stakeholders, which include employees/unions, suppliers as well as shareholders. The objective function to maximize is wealth for the whole group. Companies operating under such economic objectives tend to have slower clockspeeds and they focus on the longer-term. Again, from *enterprise physics*, one could conjecture that in general,

stakeholder-focused firms tend to have lower Value Chain Reactivity and Customer Responsiveness along with higher Organizational Inertia.

6.2 World-Class Company vs. World-Class Enterprise

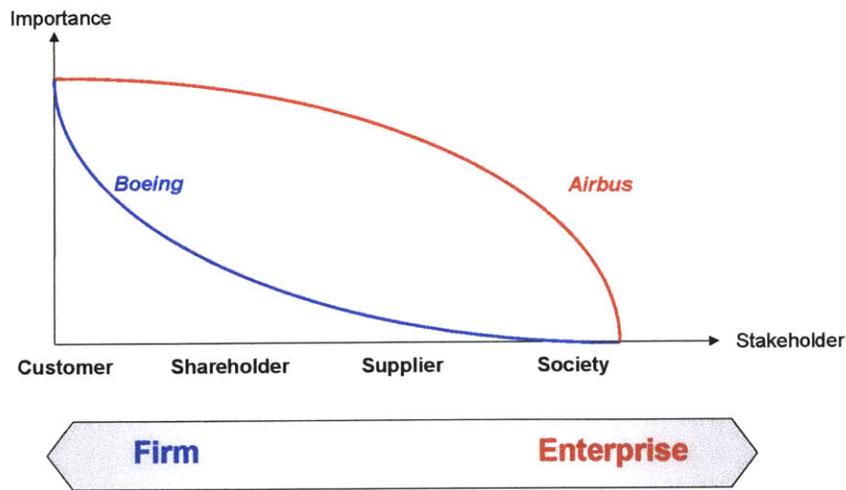
Having looked at the two generic economic models, we can now begin to see how *Boeing* and *Airbus* view themselves within the context of their business environment. Figure 6.2 below illustrates conceptually the architecture of the stakeholder network for each company. As can be seen, *The Boeing Company* defines and operates itself as a well-defined corporate identity with clear, distinct relationships with other non-explicit stakeholders, for example: suppliers, labor unions and government. In contrast, *Airbus* defines its enterprise architecture more broadly with more stakeholders with more explicit responsibilities and a more complex objective function.

Figure 6.2: Boeing vs. Airbus Enterprise Architectures



As shown on the conceptual “firm-enterprise spectrum” in figure 6.3 below, *Airbus* gives more explicit importance to the needs of multiple stakeholders. This is a much more complex endeavor, often with much less transparency than does *Boeing’s* more traditionally-limited stakeholder scope in which delivering customer value (based on quality, cost and delivery metrics) and delivering shareholder value (based on earnings per share) is a relatively well-known optimization function in US business research.

Figure 6.3: Firm-Enterprise Spectrum

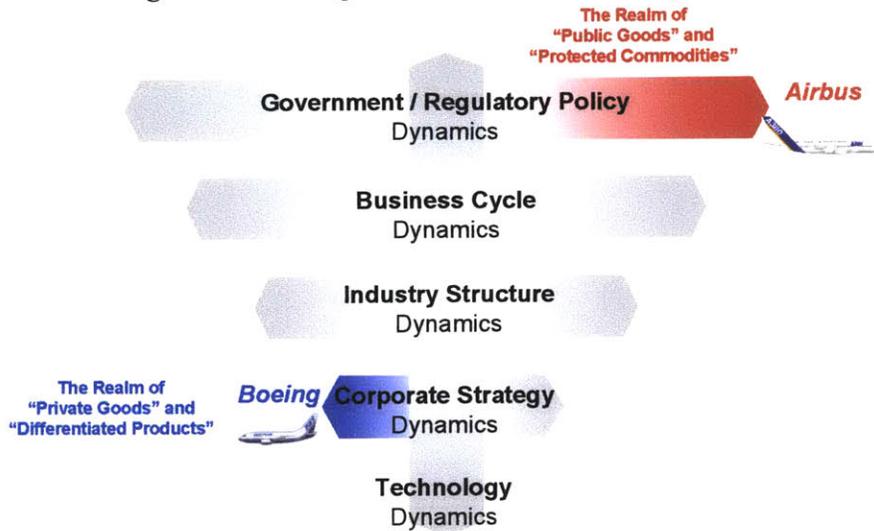


In fact, when we begin to examine how *Boeing* and *Airbus* engage the respective interconnected dynamic forces²¹² of: government policy dynamics, business cycle dynamics, industry structure dynamics, corporate strategy dynamics, and technology dynamics, we can see that *Boeing's* decidedly corporate view of its business means that it views its products as “private goods” in which product differentiation is the strategy.

However as shown in figure 6.4 below, *Airbus'* enterprise architecture engages these five dynamics at a decidedly higher level of government and public policy. This means that it views its products as “public goods” in which commodity production and protection is the strategy. It is interesting to note that in the inverted pendulum structure of figure 6.4 below, *Airbus* operates from the large, massive, slow clockspeed level of government, while *Boeing* operates from the less massive, faster clockspeed level of the corporation – a position metaphorically not unlike the tail being wagged by the dog. The question therefore arises, “are these two different enterprise architectures a function of each company simply reflecting the economic environmental model within which it arises”, or is there some deeper logic to the “architectural fit” between the products & services of the commercial aviation industry.

²¹² From MIT Professor Charles Fine's Fall 2002 class “Technology Roadmapping”.

Figure 6.4: Boeing vs. Airbus Stakeholder Emphasis

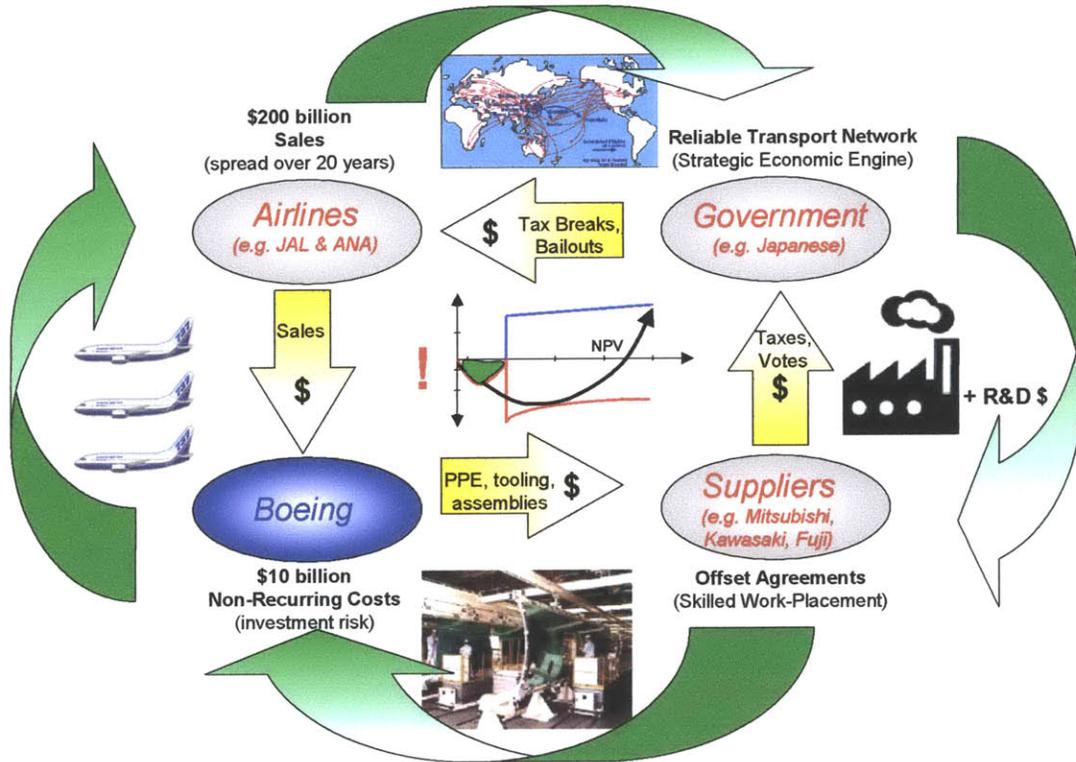


5.3 Dynamic Complexity of Enterprises

The nature of commercial airplane financing, design and delivery is a very complex system with significant feedbacks and time delays resulting in severe cycles of over- and under-investment and low aggregate industry profitability, as shown in figure 6.5 below.

In the upper left of the figure, we see the customer (i.e. the Japanese airlines) who would demand new airplanes to fuel capacity expansion of their networks. They therefore give *Boeing* money (flow of capital is shown in yellow arrows) in return for products (flow shown in green arrows). The problem is that the launch of a new commercial airplane program can cost as much as \$10 billion and take as much as 10 years to realize. A question for *Boeing* is simply “can you close the business case on a new airplane program when demand is so cyclical and uncertain and fixed costs are so large and so high?” In effect, every \$10 billion launch of a new airplane program for a \$40 billion revenue company is like betting the ranch every decade. So where does the investment money come from? (The NPV diagram which is at the center of the diagram is also at the center of the problem for *Boeing* and *Airbus*).

Figure 6.5: Enterprise “Dynamic Complexity” and Feedback



In the past, *Boeing* would share the costs and risks with the “launch customer” airlines, but the business model of the large network carriers is making it difficult for them to underwrite new airplane development. Therefore airplane manufacturers have begun to turn to their supply base (see lower right of figure) for risk-sharing agreements. It is interesting to note the power of the customers and suppliers in this relationship. The Japanese airlines will only buy airplanes from *Boeing*, if *Boeing* agrees to provide work to Japanese suppliers – a situation called “offset agreements”. *Boeing* therefore agrees, provided that the suppliers agree to cover their own non-recurring production costs. But where do these suppliers get such investment money?

The Japanese suppliers in turn provide tax revenues and votes to the Japanese political parties which divert national tax revenues towards supporting the technology and production infrastructure costs of bringing *Boeing’s* production to Japan. But why would the Japanese government agree to indirectly underwrite *Boeing’s* development costs? One reason is that the Japanese economy gets skilled high-technology jobs which they can build into an industry of their own in the future.

The other reason comes from closing the “causal loop” diagram. The government agrees to subsidize the supply base because it also wants a reliable and efficient national transportation network, which it views as a strategic economic engine. Because the government does not want to outsource such an important activity to foreign operators, they are willing to subsidize the Japanese air carriers via tax breaks, soft-loans, etc.²¹³

So as can be seen, this is a complex enterprise, involving multiple international stakeholders, whose destinies are all tied together. It illustrates the blurring of the definition of “government subsidies” as for example one could construct an argument that the Japanese government is subsidizing its participation in the offset arrangement. Importantly, we note that the decisions of these diverse stakeholders may be distant in space and time, resulting in significant system dynamic complexity.

The size and complexity of such a stakeholder interest group, coupled with a focus on the long-term explains why firms operating under such an environment tend to use tools and methodologies which reveal that business cause and effect are not tightly-coupled in time and space, that is they have high “dynamic complexity”. Companies like *Toyota* and *Southwest Airlines*, therefore have begun to design strategies which leverage the complexity of the shareholder-focused firm, and companies like *Airbus* have begun to use methodologies like system dynamics to analyze the effects of such designs.^{214,215}

The enterprise architectures of the two rivals (*Boeing* and *Airbus*) in the global airframe duopoly are very different. *Boeing's* shorter-term shareholder-focus and *Airbus's* longer-term stakeholder focus lead to very different strategies. The results of these two architectures are a likely reason for *Airbus's* erosion of *Boeing's* market share as shown in figure 1.27.

Finally, before we leave the topic of dynamic complexity of enterprises, I would like to make the observation that if cause and effect are distant in space and time, then one would expect the same to be true in how costs and revenues are accounted for in such dynamically complex enterprises. *Business*

²¹³ In the US, government “bailout” of struggling airline carriers is done to preserve a functioning national air transportation network, however, in the long-run such policies lead to high barriers-to-exit, ensuring continued overcapacity in the market and lower profits for all airlines.

²¹⁴ “Towards Better Government”, *PA Consulting Group* paper.

²¹⁵ Henry Birdseye Weil, MIT Spring 2002 course notes “Competitive Strategy”.

Week magazine recently ran an article on the commercial aerospace's industry's accounting practices²¹⁶. It is interesting to note the popular business press' disdain for the relatively obscure methods of "program accounting", which allows aircraft manufacturers to offset steep upfront costs with distant payoffs. One brokerage analyst remarked, "you can drive a truck through what's GAAP (Generally Accepted Accounting Practices) in aircraft manufacturing", which is precisely my point – cause and effect are more distant in space and time in this industry than the more traditional industries for which GAAP unquestionably applies.

6.4 Enlarging the Stakeholder "Pie"

As shown in figure 6.6 below, the Shareholder-focused objective function is to maximize value to shareholders, which can sometimes come at the expense of other stakeholders like employees and suppliers in the form of mass layoffs which result in large swings in capacity. The economic valuation principle is "financial (or internal) rate of return"²¹⁷. This is known as the "zero-sum game" in which some stakeholders must lose in order for others to win.

The Stakeholder-focused objective function is to maximize value for all (or more) stakeholders, which is equivalent to enlarging the pie for all. Although the economic interaction of all stakeholders is more indirect, it is not less valid – it only requires more sophisticated ways for evaluating the enterprise success. The economic valuation principle is the economic rate of return²¹⁸. This is known as the famous "win-win" situation. As noted by *PA Consulting*, "stakeholder management creates 'virtuous circles' among multiple stakeholders which perpetuates long-term success, while short-termist 'value-grabbing' strategies on the other hand create 'vicious spirals' which encourage negative outcomes for all, including shareholders."²¹⁹

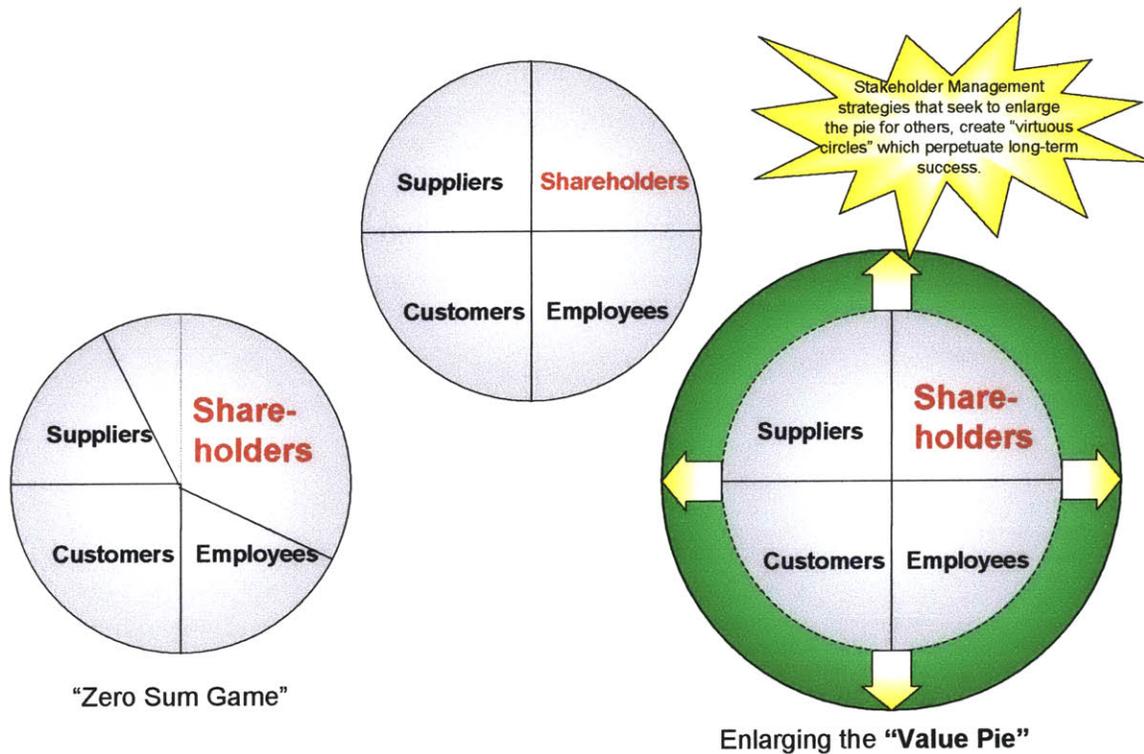
²¹⁶ *BusinessWeek*, "Boeing's Secret", May 20, 2002, pg. 110-120.

²¹⁷ Prof. Benjamin Esty, "Boeing vs. Airbus: a Case of Failed Pre-emption"?

²¹⁸ *Ibid*, Esty.

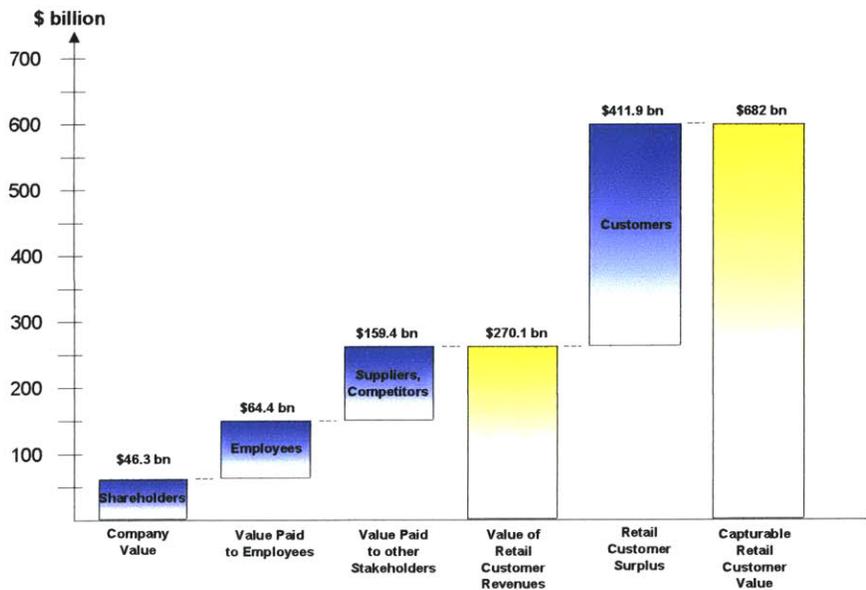
²¹⁹ "Dynamic Strategy: Creating Shareholder Value Through Stakeholder Management", *PA Consulting Group*.

Figure 6.6: Enlarging the Value Pie



I will attempt to demonstrate in chapter 8 that world-class companies are expert in managing the apparently counterintuitive discipline of simultaneously managing to the long- and short-term via taking the care of all relevant stakeholders. As shown in figure 6.7 below, such companies recognize that there is immense un-captured value embedded in aligning multiple stakeholders.

Figure 6.7: Un-captured Stakeholder Value (source: PA Consulting)



6.5 Commodity Strategies

Airbus's multiple stakeholder point of view, allows (in fact, encourages) them to take a long-term view. I will briefly investigate two objectives of the multiple-stakeholder view that leads to very different strategies than *Boeing* employs.

First, the provision of a strong and efficient transportation network is seen as imperative to a well-functioning common market. Therefore they view the air transport network as an integrated system with both infrastructure fixed costs and variable costs. They observe that airline customers are “myopic” (i.e. are short-sighted) and are unwilling to pay for expensive new airplane fleet. To avoid this non-productive anti-investment cycle, the government employs the same strategy as the savvy commercial products manufacturers/marketers: namely cross-subsidization of loss-leader complementary goods in order to make profits back on the complementary service with lower variable costs.

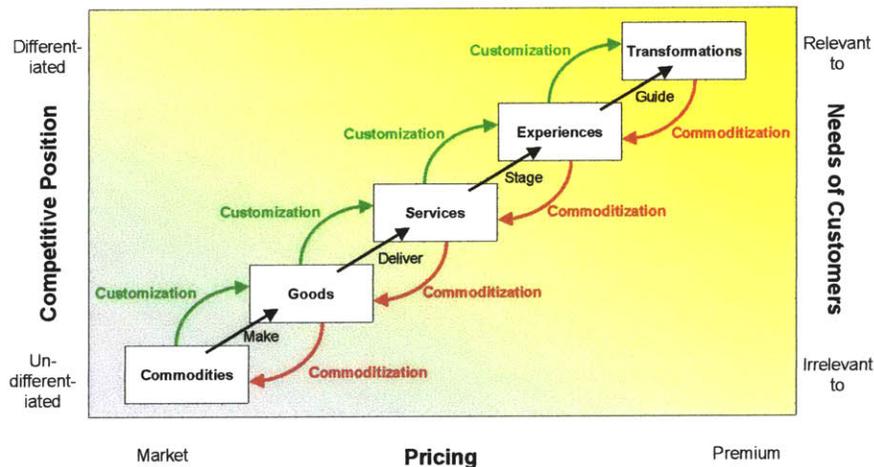
As seen in figure 6.8 below, *Gillette's* strategy for giving away the relatively expensive razor handle (infrastructure), in order to lock the customer into the *Gillette* shaving system, whereby profits are made in the repeat business of low variable cost disposable razor blades. Likewise, the “corporation” of the French, German, Spanish and British governments, effectively “give away” the relatively expensive airplanes (infrastructure), in order to lock the passenger into the European air transport system, whereby profits (in principle) are made in the repeat business of low variable cost business seat passengers. It is important to note that even though these products (whether razors or jumbo jets) can be marketed and sold as differentiated high-value products, they are sold and distributed as commodities.

Figure 6.8: Strategy of Subsidizing *Loss-Leaders*



Second, the provision of a stable employment environment is high on the stakeholder priority list and, leads them to slow but steady growth and counter-cyclical production. This drives them to see their output as commodities²²⁰ that are protected by government. As figure 6.9 shows, there is an economic progression of eventual government protection from traditional “extraction” industries like agriculture, towards low-technology goods like steel and finally, towards high-technology goods like aircraft²²¹. In fact, it is interesting to note that *Airbus* was originally founded as a *groupement d’interet economique* (GIE) which is a form of commercial partnership established by French law in the mid-1960’s which was intended to help wine growers.²²²

Figure 6.9: The Progression of Economic Value (source: Pine)



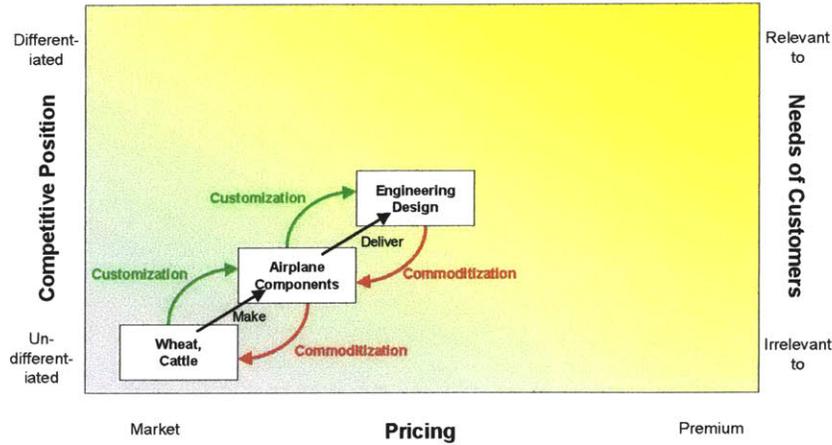
An example of this in the US is the Midwest, which for over 100 years served as the US powerhouse for agricultural production (e.g. wheat and cattle). It became so efficient however that farm subsidies became the norm until displaced workers could excel as manufacturers of airplane products, e.g. the city of Wichita acquired the status of “the air capital of the world”. It is interesting to note that the next step in the expansion from manufacture of technology-based goods towards services is already beginning to take place in the US heartland, as *Airbus* recently opened up an office in Wichita which specializes in the design of wings for the A380 super jumbo – see figure 5.10 below.

²²⁰ “Commoditization of Technology-Based Products and Services: A Generic Model of Market Dynamics,” Henry Birdseye Weil, MIT International Center for Research on the Management of Technology.

²²¹ Joe Pine, class presentation, Jim Utterback’s Spring 2002, *Managing Change in Product and Process Innovation*.

²²² *Birds of Prey: Boeing vs. Airbus – A Battle for the Skies*, Matthew Lynn, 1995, pg. 113.

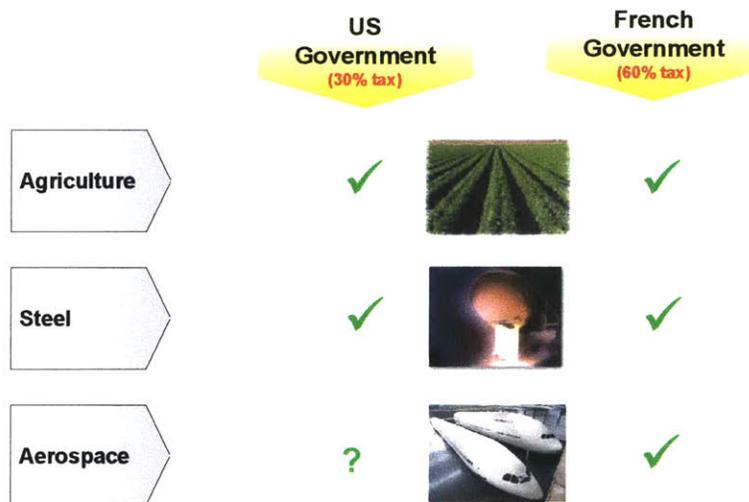
Figure 6.10: The Progression of Economic Value in the US Midwest



Finally, it is also interesting to note that in its quest to produce the A380, *Airbus* recognizes the informal “offset” agreements required to build and sell abroad. As a result, it states that approximately 50% of the suppliers and vendors for the A380 are located in the US which translates into approximately 120,000 American jobs – therefore every order for an *Airbus* aircraft is a boost for the US economy.²²³

Note that although the EU leads in this subsidization process, the US eventually follows as shown in figure 6.11 below. *The Economist* recently noted that in the past two years, the US federal government has come to the rescue of farming, steel and the airlines²²⁴.

Figure 6.11: Subsidization of Commodities

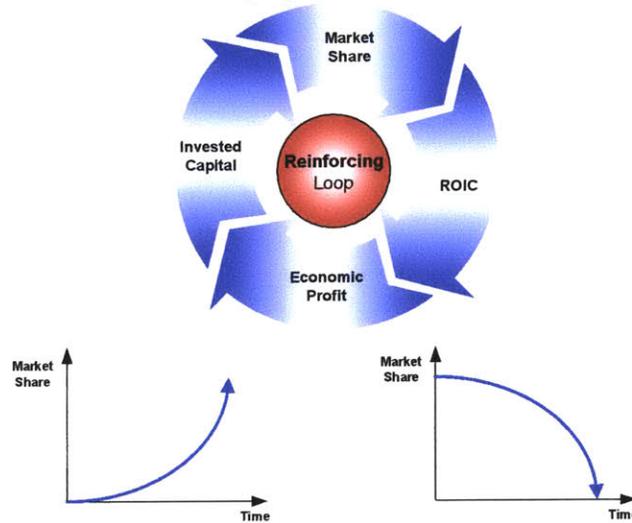


²²³ “Transport on the Rebound?” *Aviation Week & Space Technology*, June 23, 2003, pg. 24.

²²⁴ “Extinction of the Car Giants”, *The Economist*, June 14th 2003, pg. 11.

Airbus can therefore afford to buy market share at the expense of profitability as seen in figure 1.27. And it is this growing market share that allows them to offer a family or platform of products, which in turn grows their market share as shown in figure 6.12 below.

Figure 6.12: Reinforcing Dynamics of Attacking Market Share



Henderson notes that such deliberate investments to buy market share in order to reduce future costs (a.k.a. “dumping” or the sale of temporary excess capacity at marginal costs) should be encouraged and is in fact a realistic and superior business strategy.²²⁵ Under such a strategy, the consumer is always the beneficiary, while the principal victims are competitors seeking price stability.

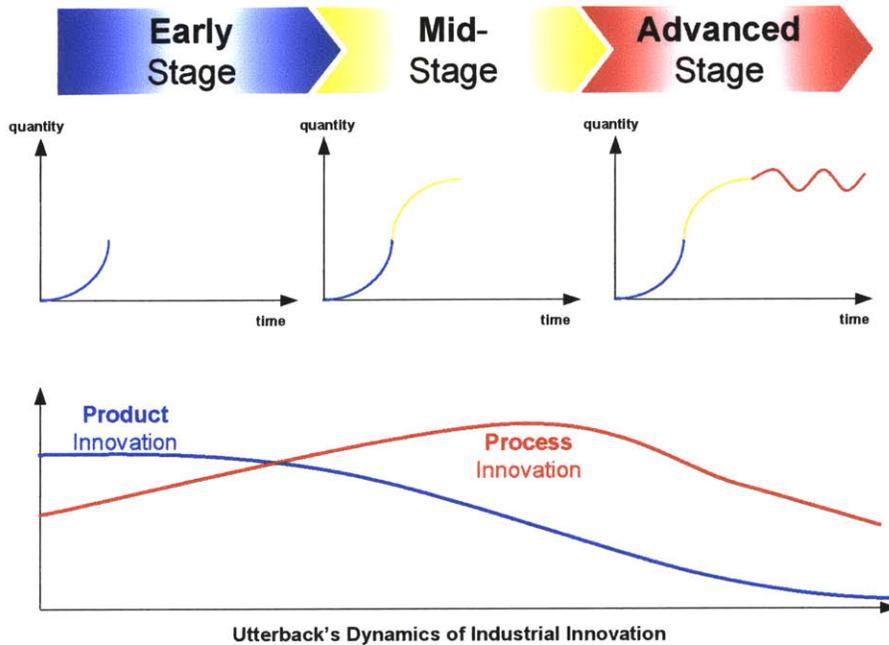
Weil defines the stage of ‘advanced commoditization’ as “a competitive environment in which product differentiation is difficult, customer loyalty and brand values are low, and sustainable advantage comes primarily from cost (and often quality) leadership.”²²⁶ In this light, it is clear that the commercial airplane industry can be thought of as entering an advanced stage of commoditization. As shown in figure 6.13 below, the three stages of commoditization have generic dynamic behaviors associated with

²²⁵ Stern, Carl W., and Stalk, George Jr., *Perspectives on Strategy* from the Boston Consulting Group, 1998, pg. 291.

²²⁶ “Commoditization of Technology-Based Products and Services: A Generic Model of Market Dynamics,” Henry Birdseye Weil, MIT International Center for Research on the Management of Technology.

them. In fact, the advanced stage of commoditization is frequently met with severe cyclic behavior. It is also interesting to note that such stages can be mapped to the dynamics of industrial innovation.²²⁷

Figure 6.13: Stages of Commoditization



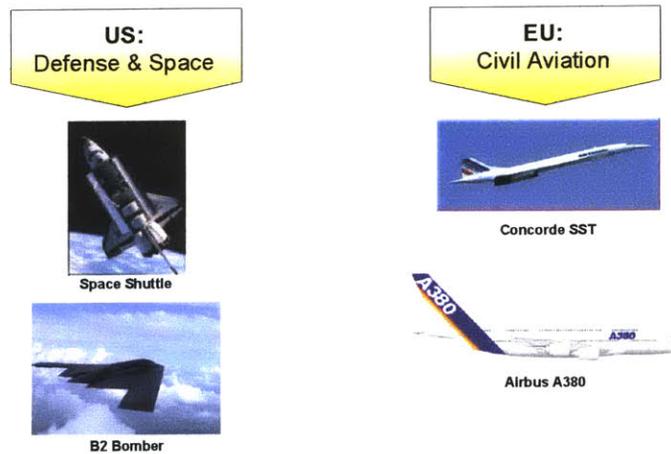
5.6 Public vs. Private Goods

The nature of the aerospace industry is further complicated by the interaction between the defense sector and the civil sector. Due to the highly competitive nature of the civil aviation industry, there is not a lot of capital to spend on basic R&D in launching new products. The opposite is true however for civil aviation's sister sector, the defense sector, where demand for high-performance products can be so inelastic that significant government-led R&D investment provides significant developments.

The US has the world's largest military and space spending programs, which provides such aerospace "public goods" as the B2 bomber and the Space Shuttle, as shown in figure 6.14 below. Europe chooses to make its own big investments in aerospace development, but due to its history, elects to fund its own "public" goods in the form of the *Concorde SST* and the new *Airbus A380*.

²²⁷ James Utterback, *Mastering the Dynamics of Innovation*, 1994.

Figure 6.14: Public Goods Delivering high *Economic* (not Financial) Rates of Return



In both cases, government funds are used to support “public goods” in supported industries, ranging from military and space to the national transportation of people and goods – all strategically important industries.

A “public good” has two characteristics, it is “nonrival” (meaning that the marginal cost of its provision to an additional consumer is zero) and it is “nonexclusive” (meaning that people can not be excluded from using it).²²⁸ A major \$10 billion tunnel or a \$5 billion suspension bridge is therefore a public good, in that once built the marginal cost of another driver going over it is effectively zero, and it is difficult to collect revenue from it to pay for it during the lifetime of the public good – i.e. charging tolls is both time consuming, expensive and if tolls leading to a reasonable return on investment were charged, it would make travel on the bridge cost prohibitive. Although one might conclude that building such a bridge would not be economically viable, this public good is provided as a means to stimulate economic growth into an entire region, the social benefits of which can be shown to outweigh the costs with a rate of return and payback period that is acceptable to an entire society. As case in point is the \$14 billion Boston Central Artery/Tunnel project, a bridge-tunnel asset for which 90% is being paid for by US federal taxes, that is by taxpayers in 49 other states who are unlikely to ever use or directly benefit from the project.

²²⁸ *Microeconomics*, Robert S. Pindyck and Daniel L. Rubinfeld, 2001, pg. 593 and 644.

As markets tend to undersupply public goods, governments can resolve the problem by either supplying the good itself, or by altering incentives for private firms to produce it. The provision of public transportation infrastructure asset like a major bridge or fleet of aircraft allows for an effective network of “private” goods and services to be employed e.g. cars on the bridges or airlines on the aircraft, as shown in figure 6.15 below. Taxpayers do not think twice about paying for roads and highways (the infrastructure of transport), why not subsidize the air transport infrastructure (i.e. airplanes)?

Figure 6.15: Transportation Infrastructure Assets as Public Goods



Neither the US nor Europe’s government-sponsored aerospace programs are judged on “financial rate of return” grounds, but on “economic rate of return” grounds, as they provide skilled jobs, advanced technology development, and strong strategic networks. The question for both *Boeing* and *Airbus* is how efficient is the technology transferred from the commercial and military sides of each company’s operations.

To summarize the enterprise architectures of *Boeing* and *Airbus* using the enterprise physics methodology developed herein, it appears that *Boeing* has higher value chain reactivity and customer responsiveness than *Airbus*. But the interesting piece of the physics lies in the inertia or apparent inertia. There is something clearly deflecting *Boeing’s* profit trajectory downward. Could it be the pull of *Airbus’* larger explicitly-defined stakeholder enterprise?

6.7 Macro- vs. Microeconomics

From the above discussions on public vs. private goods, it is clear that each engages a different economic sector, namely the macro- and micro-economies respectively. The policy

decisions in the realm of macroeconomics surround the topics of GDP output, unemployment and inflation²²⁹. The corporate decisions in the realm of microeconomics surround the topics of price, quantity and cost structure.

“More than any other sphere of activity, aerospace is a test of strength between states, in which each participant deploys his technical and political forces.”

These words, from a report to the French Parliament in 1977²³⁰ illustrate the nature of competition and the scope of the relevant stakeholders that *Airbus* sees itself. It is conjectured that *Airbus* explicitly engages the high-level topics of macroeconomics while *Boeing* engages the lower-level topics of micro-economics.

The products of the commercial aircraft industry have long been the US’ largest export²³¹. This has a significant effect on the balance of trade (or U.S. balance of payments) and the currency exchange rate.²³²

6.8 Quality of Relationships: *Governance Profile*

Having defined the *quantity* or extent of the enterprise stakeholders of *Boeing* and *Airbus*, I will now attempt to discuss the *quality* of the relationships among the stakeholders. Both the quantity and the quality are essential in defining the actual dynamic properties of the enterprises.

Jeffery Dyer describes the notion of a firm’s relationships with its supply network as its “Governance Profile.”²³³ A firm’s relationship with its supply network can have three general forms: internal “vertical integration”, external “arm’s length contracts” and external (or internal) “virtual integration. The pressures that define the basic need to outsource are shown in figure 6.16 below. In general, if there are complex tasks to be managed or coordinated, firms are best placed to do this via

²²⁹ *Macroeconomics*, Olivier Blanchard, 2000, pg. 19.

²³⁰ *Birds of Prey - Boeing vs. Airbus: a Battle for the Skies*, Matthew Lynn, 1997.

²³¹ *Made In America: Regaining the Productive Edge*, Michael L. Dertouzos, Richard K. Lester, Robert M. Solow, pg. 201, 1989.

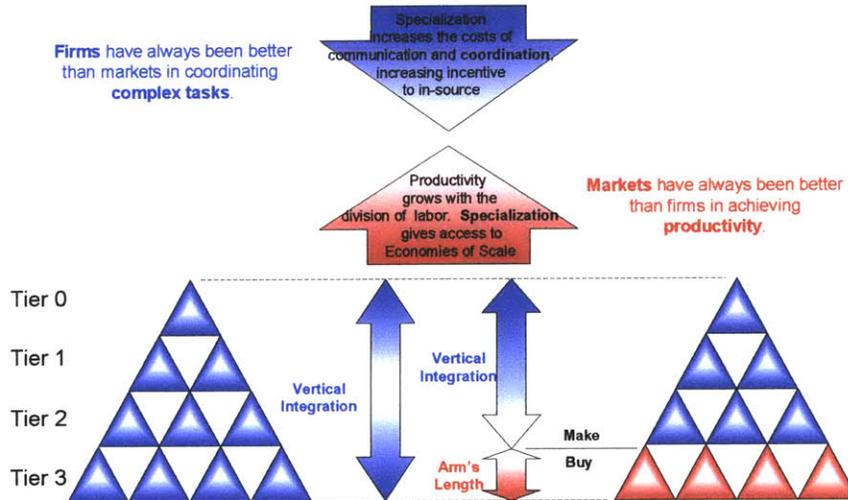
²³² *Macroeconomics*, Olivier Blanchard, 2000, pg. 372.

²³³ *Collaborative Advantage: Winning Through Extended Enterprise Supplier Networks*, Jeffery Dyer, 2000.

internal hierarchy. However, if increased productivity is the goal, markets rather than firms are best-suited for this.

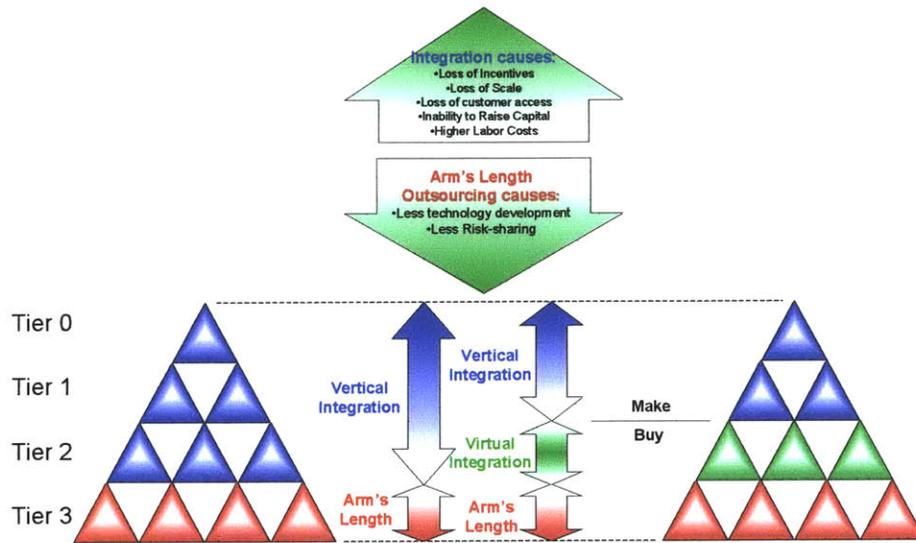
Dyer notes the limits to arm's length relationships include less technology development taking place as well as less risk-sharing throughout the supply base. The limits to vertical integration however include loss of incentives to compete, loss of access to potential economies of scale, inability to raise capital and generally higher labor costs. As will be discussed in Chapter 7, there is a clear industry dynamic which describes the evolutionary swing from internal hierarchy to external specialization and market efficiencies.

Figure 6.16: Integration-Disintegration Pressures (source: Dyer)



As industries continue to evolve, there are further pressures to refine the relationships within the governance profile towards more outsourcing, but less arm's length relationships. This interesting middle ground, Dyer calls, "Virtual Integration" as shown in figure 6.17 below. The primary ingredients for virtual integration are: Investments in dedicated assets, inter-organizational knowledge-sharing and inter-organizational trust.

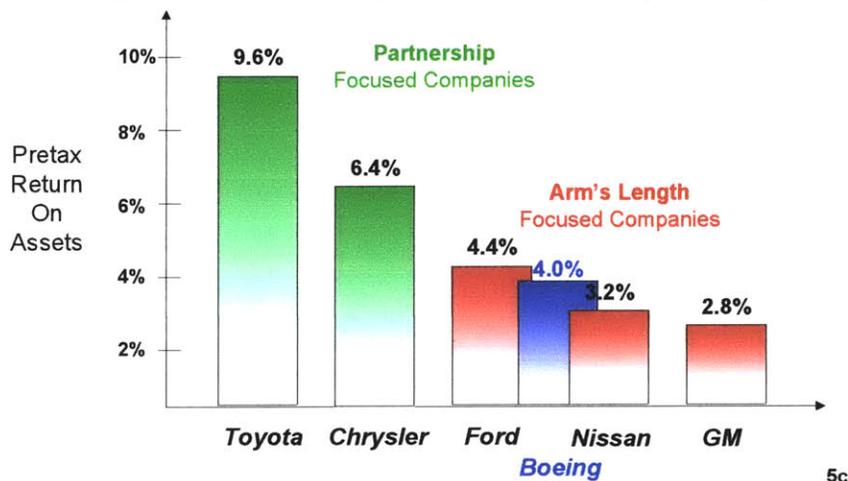
Figure 6.17: Collaboration Pressures (source: Dyer)



It is interesting to observe the profitability metrics (e.g. pretax return on assets) of companies having different governance profiles. As can be seen from figure 6.18 below, those companies focused on Partnership-based governance profiles exhibit from 2%-7% greater ROA than those companies whose governance profiles are dominated by the traditional arm's length contracts.

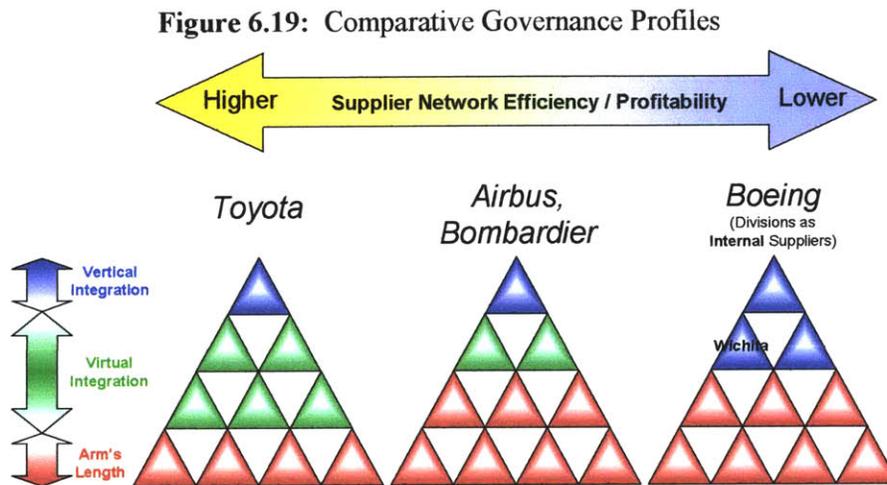
As an aside, it is also interesting to note within the US automotive industry, that although *Ford* is known as the lean *manufacturing* company, *Chrysler* (with 50% higher ROA) is known as the lean *enterprise* company. We shall return to this topic again in chapter 7.

Figure 6.18: Profitability of Lean Enterprises (source: Dyer)



5c

Boeing, although in a different manufacturing sector than the other companies in the figure, exhibits the traditional sub-5% ROA results that its fellow arm’s length firms do. In fact, when we compare the governance profiles of *Boeing* and *Toyota* as shown in figure 6.19 below, we see that there is clearly an opportunity for *Boeing* to evolve its internal suppliers to become partner suppliers, who could then become teaching centers to disseminate knowledge out to the supply base, converting “arm’s length companies to partner/suppliers.



As a final anecdote on the importance of the quality of enterprise relationships, it is interesting to observe the behavior of *Toyota*, a commanding value chain leader. As shown in figure 6.20 below, a recent article of *BusinessWeek* magazine ran an editorial admonishing *Toyota* for foolishly subsidizing one of its suppliers, implying that such behavior must certainly not be a characteristic of a leading company.²³⁴ Yet ironically 10 pages later, *Toyota's* president Fujio Cho was cited in *BusinessWeek's* annual list of the top international managers for *Toyota's* outstanding performance. Apparently US business culture finds long-term, trust-based learning partnerships counterintuitive to sound financial performance.

²³⁴ “Stop Feeding the Losers, Toyota”, and “Managers to Watch”, *BusinessWeek*, January 13, 2003 pp. 48 and 61.

Figure 6.20: Toyota's Counterintuitive Enterprise Relationships

BusinessWeek

pg. 48

COMMENTARY
By Chester Dawson

STOP FEEDING THE LOSERS, TOYOTA

Why would the world's third-largest auto maker act like the Salvation Army? That's a question Toyota Motor Corp. investors should be asking after the Toyota group agreed on Dec. 27 to inject \$85 million into Tomen Corp., a money-losing Japanese trading house in search of a new lease on life. Tomen hit Toyota up for dough because both belong to the same extended corporate group, or *keiretsu*. Winners subsidizing losers: It's a time-honored Japanese tradition. What's amazing is that the practice persists in Japan's stressed-out economy. This is the second big bailout since 2000 for Tomen, which has been trying to right its ship for years. So even though the aid to Tomen is pigeon feed for Toyota, with its \$125 billion in worldwide revenue, there's a risk that other

spending heavily on cutting-edge technologies such as hydrogen-fueled cars to keep a step ahead of rivals in the U.S. and Europe. It needs to keep pumping money into programs to upgrade its existing lineup. And it could boost its paltry 2% annual dividend. So far, Toyota investors seem oddly unfazed by the Tomen news. Standard & Poor's says the Tomen aid is too small to affect Toyota's creditworthiness. But *S&P* warns of a slippery slope. Toyota risks being asked to shore up other ailing companies, according to an *S&P* report. If it opens its purse wider, the report says, "going forward, the rating on Toyota Motor could come under pressure." There's no doubt Tomen is in trouble. The company reported on Dec. 27 that it expects a loss of

ern Europe, and making a huge bet on China, where Toyota opened its first factory last October. All told, Toyota wants 15% of the world's market—up from a current 10%. To get there, Cho needs to nurture the Toyota culture of cost containment and quality. That's why he set up the Toyota Institute, an in-house executive-education program. Cho even moonlights as a lecturer. A fitting post for a master of international relations. □

Manager of the Year - 2003

FUJIO CHO
Toyota Motor

Fujio Cho, president of Toyota Motor Corp., is known for his easygoing personality. But don't let his style fool you. Cho has set an ambitious course for his company—and is delivering. Despite a shrinking home market and worries about a slowdown in the U.S. in 2003, Cho, 65, has steered Toyota to record profits. The world's third-largest auto maker (after General Motors Corp. and Ford Motor Co.) posted a 90% jump in net profits, to \$4.6 billion, during the half-year through September. Sales rose 15.4% to \$65.7 billion. Cho's greatest legacy may be his commitment to making Toyota a truly global carmaker. He's expanding production in the U.S., moving into East-

KEY ACCOMPLISHMENTS

- >> Boasts stock market capitalization of \$94 billion, more than DaimlerChrysler, Ford, and GM combined
- >> Cinched deals for new factories in China, the Czech Republic, and Poland

In summary, the two notions of “enterprise boundaries” and “governance profile” work to define the clockspeed and therefore the dynamics of the enterprise. They combine to define both the competitive pull, where mass is beneficial, as well as organizational inertia where mass can be limiting. In this way, stakeholder focus can add competitive pull, while virtual integration can streamline organizational mass while maintaining value chain reactivity.

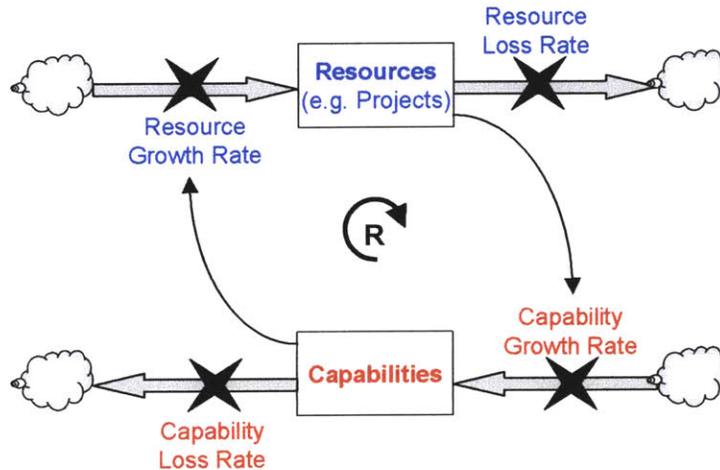
6.9 Growing Relationships: Dynamic Resources

Having defined the appropriate extent of the enterprise (i.e. the boundary), and then the interfaces at the boundaries (i.e. the governance profile), I will now turn to how to grow the capabilities of the enterprise through managing the dynamic resources. Charlie Fine²³⁵ captured the simple richness of the feedback dynamics of projects (or resources) which along with making money, can create new

²³⁵ *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*, Charles Fine, 1998, pg. 164-165. Referenced from Dorothy Leonard-Barton, *Wellsprings of Knowledge*.

capabilities which again in turn create new projects as shown in figure 6.21 below. Such reinforcing behavior can either drive the company exponentially upwards if the core capabilities are positive, or downwards if they become core rigidities.

Figure 6.21: The Dynamics of Resources and Capabilities (source: Fine, Leonard-Barton)

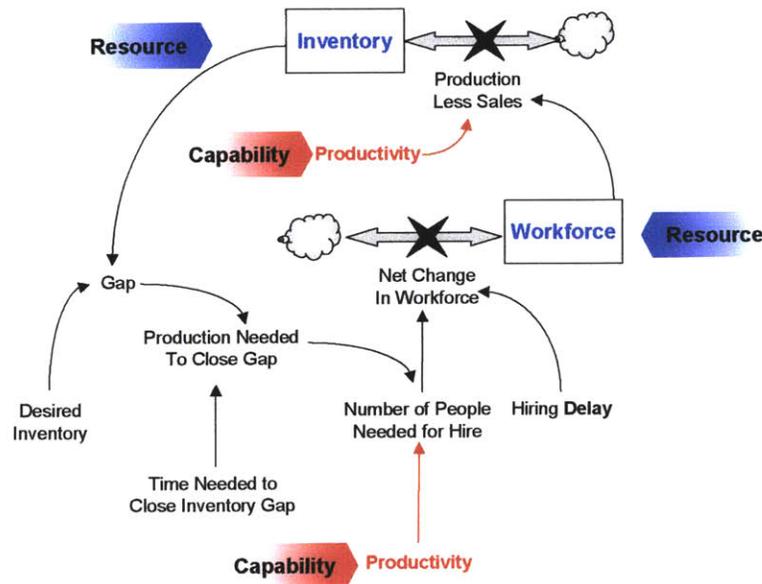


Kim Warren notes that a firm’s performance is a function of its ability to accumulate and retain stocks of resources, which in turn is a function of its ability to manage its resource flows²³⁶. The interdependence between resources (stocks) and capabilities (flows) is implicit in the architecture of the enterprise. Such a system dynamics view of the dynamics of resources (and therefore competitive advantage) has become known as the “Dynamic Resource-Based View”, DRBV.

In the simple generic structure of our industrial enterprise, shown in figure 6.22 below, we can see that the strategic resources of workforce and inventory are driven by capabilities like productivity. But an interesting question is, what drives capability?

²³⁶ “Strategic Performance Dynamics”, Kim Warren, *British Academy of Management Conference*, 2002.

Figure 6.22: Industrial Example of the Dynamics of Resources and Capabilities



Warren notes that firms do not exhibit a uniform tendency to accumulate capability in any resource-building task unless they have high learning effectiveness.²³⁷ Other researchers²³⁸ note that highly successful companies like *Toyota* have at the core of their corporate DNA, a highly effective learning organization. This is a topic we shall return to in chapter 7, when we discuss what policies or architecture enables such an environment.

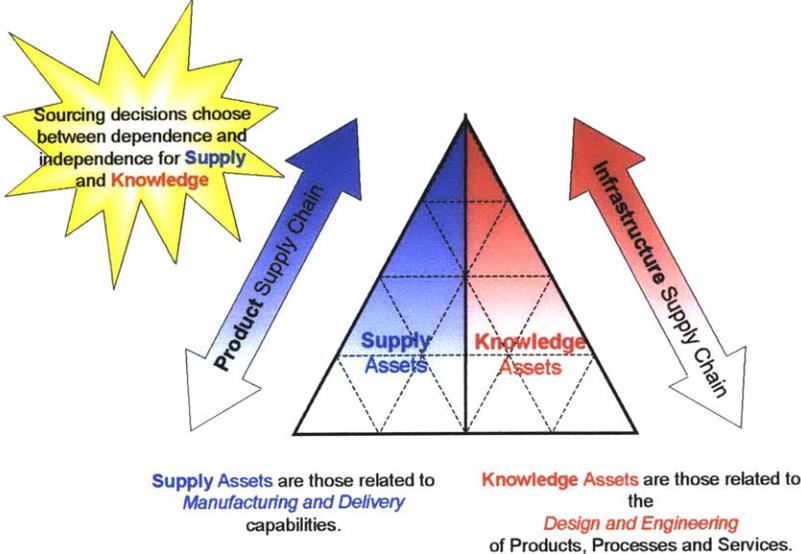
Fine and Whitney²³⁹ discovered some of the ‘secrets’ to *Toyota*’s success in learning comes from their dynamic assessment of the capabilities that they want to possess. In the classic make vs. buy decision, most companies do not distinguish from the dynamics of this decision, that is, the stocks of supply assets and the flows of knowledge capabilities as shown in figure 6.23 below.

²³⁷ “Strategic Performance Dynamics”, Kim Warren, *British Academy of Management Conference*, 2002, pg. 11.

²³⁸ “Decoding the DNA of the Toyota Production System”, Steven Spear and Kent Bowen, *Harvard Business Review*, September-October 1999.

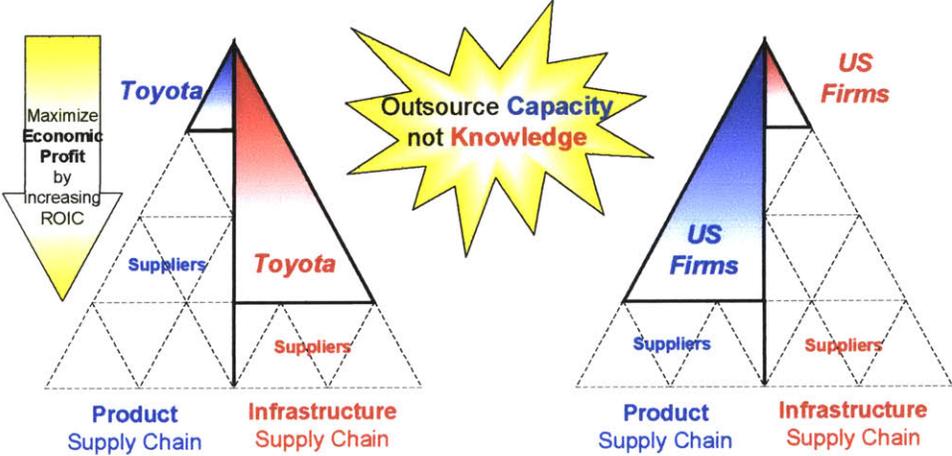
²³⁹ “Is the Make-vs.-Buy Decision Process a Core Competence?”, Charles H. Fine and Daniel Whitney.

Figure 6.23: Supply vs. Knowledge Assets (source: Fine & Whitney)



Toyota, on the other hand clearly distinguishes between *product* (or resource) supply and *infrastructure* (or capability) supply. As shown in figure 6.24 below, Toyota takes the opposite view than do most US competitors about what to outsource. Toyota holds onto to infrastructure or knowledge assets, in order for them to learn how to build. They then build enough product to learn further, then outsource capacity not knowledge. This allows them to further teach (and learn from) the enterprise.

Figure 6.24: Learn to Build, Build to Learn, Teach the Enterprise (source: Fine & Whitney)



Note Toyota's large knowledge-based infrastructure triangle, serves the small internal capacity-based product triangle.

6.10 Chapter Summary

To summarize what we have discussed in chapter 6, we have examined the spectrum of characteristics of a business endeavor ranging from the corporation to the enterprise. As shown in figure 6.25 below, we can begin to understand the philosophical differences between *Boeing* and *Airbus*.

Figure 6.25: *Boeing vs. Airbus: The Rules of Engagement*

World-class Corporation	World-class Enterprise
Shareholder focus	Stakeholder focus
Financial Rate of Return	Economic Rate of Return
Economic Value Model	Stakeholder Surplus Model
Equity Markets	Debt Markets
Rapid Growth Expectations	Slow Growth Expectations
Short-Term Planning	Long-Term Planning
Production of Private Goods	Production of Public Goods
Realm of Microeconomics	Realm of Macroeconomics

Due to the embedded public-sector and private-sector nature of this business, it would be a mistake to view the industry as in fact, a business. It is more accurately viewed as meta-business, or “big business”, in which national interests are at stake, whether these include an effective international transportation network, an effective high-technology national workforce, or a satisfied stock market. In order to win in this game, the successful enterprise will have to be as good on “the hill” (i.e. Capitol Hill) as it is on “the street” (i.e. Wall Street).

This chapter discussed the importance of defining the quantity and quality of the relationships that make up the **extended enterprise**. Using the commercial airplane industry as an example, I introduced the notion of shareholders as an important but limited subset of an enterprise’s **stakeholders**.

In addition to the enterprise composition, we then discussed the nature of the airline/aerospace industry as operating within the realm of both private goods and **public goods**, which lead us to explore strategies of typical **protected commodities** associated with public goods.

Finally, we ended with an introduction to the **three-dimensional concurrent engineering** capabilities required for the concurrent design of the enterprise’s products, production systems and supply chain, expressed as dependencies on knowledge, capacity and governance profile, respectively.

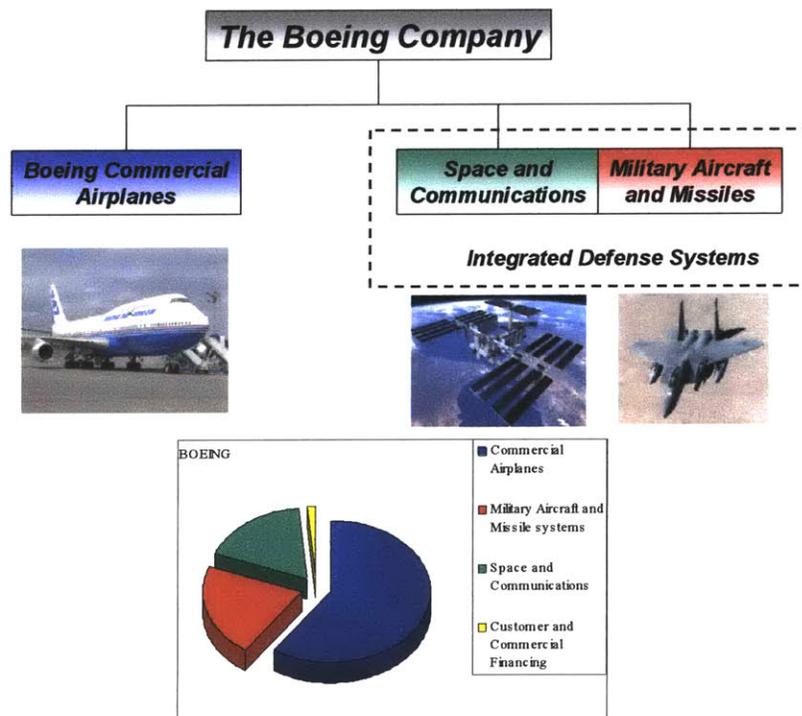
Chapter 7: Architecting Corporate & Product Strategies

From the microeconomic multi-firm enterprise, to the macroeconomic enterprise, I now turn back to the dynamics of an individual firm, to use Enterprise Physics to help understand the dynamics of the corporate architecture and its product selection and launch timing strategies.

7.1 Corporate Strategy: Market Dynamics

The Boeing Company is organized around two different market sectors in the commercial aerospace industry: Commercial Airplanes and Integrated Defense Systems (which includes military aircraft and missiles as well as space and communications), as shown in figure 7.1 below.

Figure 7.1: Primary Market Sectors of *The Boeing Company*



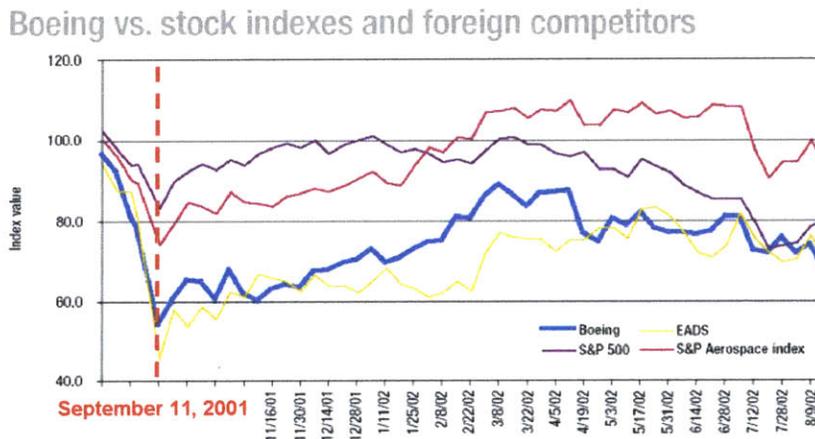
The market for BCA's products lies in the hands of airline companies, whether privately-owned, publicly-held, or state-run as well as airplane leasing companies. BCA's primary competitor in this space is *Airbus Industrie* (80% owned by EADS – the European Aeronautic Defense and Space company). As can be seen from above, BCA accounts for over 50% of *Boeing's* revenues. The market

for IDS' products lies largely in the hands of government military and space programs. IDS' primary competitor in this space is *Lockheed Martin*.

Boeing's clear bipolar market composition can be exposed by examining the response of its stock market valuation with respect to its competitors in the different market segments when the market is subject to an exogenous shock like the September 11th attacks. Figure 7.2 below illustrates the effect of this dynamic on the commercial airplane side of *Boeing's* business.

As both *Boeing* and *EADS (Airbus)* earn the majority of their revenues from commercial airplane manufacture, their stock price valuation took a severe hit (relative to both the *Standard & Poor's 500* index as well as the *S&P Aerospace Index*) as the market recognized the impact of the terrorist attacks on air transportation demand.

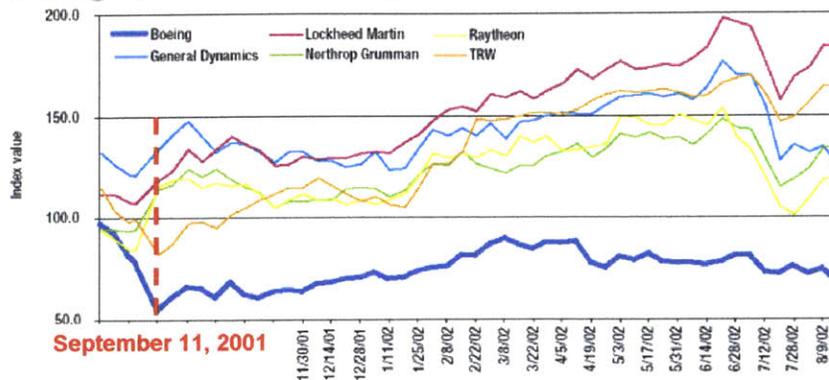
Figure 7.2: Effect of September 11th on *Boeing Commercial Airplanes* (source: *Boeing*)



Conversely, the September 11th shock had the opposite effect on defense-related business, as investors recognized the future growth in demand for defense assets in a new terrorist environment. As can be seen in figure 7.3 below, *Boeing's* competitors in the defense markets had increased share prices post-September 11th, while *Boeing*, with the majority of its revenues coming from the commercial airplane market, languished.

Figure 7.3: Effect of September 11th on *Boeing Integrated Defense Systems* (source: Boeing)

Boeing vs. U.S.-based competitors



7.2 Product Strategy: When to Launch?

The launch of a new commercial airplane program represents an upfront investment cost of approximately \$10 billion and a development time on the order of 10 years. When considering which new type of airplane to launch (see figure 7.4 below), and when to launch it, firms can use enterprise physics to help understand market and industry dynamics.

Figure 7.4: Product Type and Launch Timing (source: *The Boeing Company*)



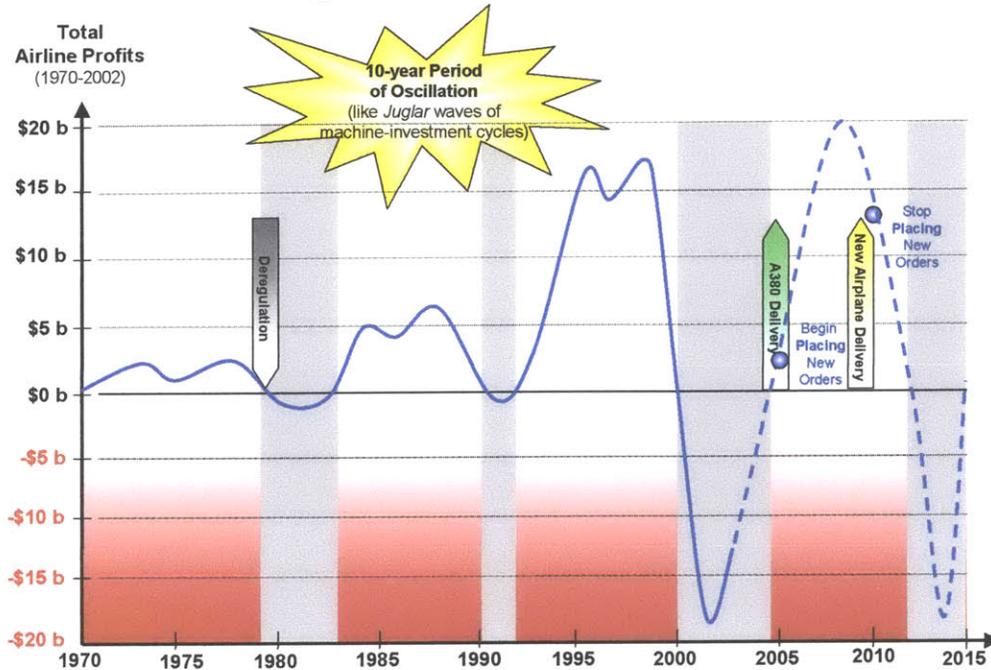
Sonic Cruiser
(Higher, Faster, Farther)



7E7
(Better, Faster, Cheaper)

To answer the difficult question of when to launch the next product, there are obviously a myriad of complex considerations centered on the customer's needs, the competitor's strategies, etc. However there is also an interesting dynamic that is embedded in the system that envelops both the customers and the competitors: the profitability cycle as shown in figure 7.5 below.

Figure 7.5: Airline Profitability



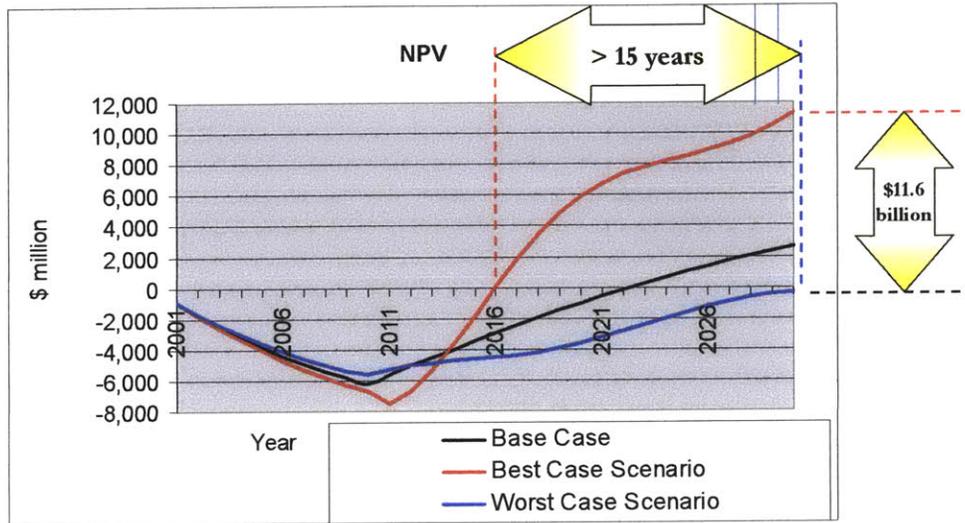
The figure shows the profitability of the global airline industry over the last 30 years. The first thing to note is that prior to 1978, the industry was under a stable, damped oscillation, reporting negligible profits and losses since the beginning over 70 years ago. After 1978, however the enterprise began oscillating wildly, and has done so ever since. What was going on in the dynamics of the enterprise?

Prior to 1978, the industry had significant damping in the form of smoothing, leveling and averaging, otherwise known as “regulation”. After 1978, de-regulation made the system become oscillate like a lightly damped pendulum. In fact, post 1978, I notice another interesting observation: there appears to be a 10-year periodicity inherent in the dynamic enterprise. This may be related to the 10-year Juglar machine investment cycles that I referred to in Chapter 2 (figure 2.7). In addition, the amplitude of oscillation appears to be increasing with time.

When closing the business case on a \$10 billion dollar gamble which could bring in \$200 billion in revenues over the next 20 years, launch timing is important, because receiving 5-10 years of increasing sales will pull forward the NPV result more than launching in an environment where there will be 5-10 years of decreasing sales, thereby pushing future free cash flows out into the future where the time value

of money works against you. This can be seen in figure 7.6 below, where the difference between hitting and missing launch timing can mean as much as \$12 billion in Net Present Value and can more than 15 years in break-even²⁴⁰.

Figure 7.6: Project NPV



7.3 Product Strategy: What to Launch?

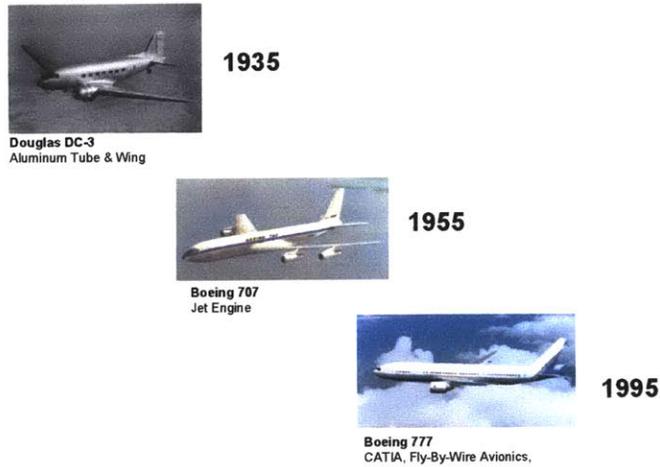
An equally complex question surrounds marketing, and what product should you launch. What attributes should it have? This is particularly difficult when the voice of the customer in today's economic environment may not reflect what the customer wants when the product arrives in their fleet 10 years from now. This is a very complex systemic problem in which cause and effect are significantly distant in space and time.

Most of the time, marketing decisions are bottom-up analyses made by assessing customer fleet planning requirements and considering the competitor's long-term product strategy. Rarely does the product strategy involve a long-term top-down assessment of the dynamics of the industry structure. But as we will see, enterprise physics may shed some light on the problem.

²⁴⁰ Source: Marchini, Masashi, Piepenbrock, Taguchi, and Wright, MIT course 1.45 Construction Finance, Fall 2002.

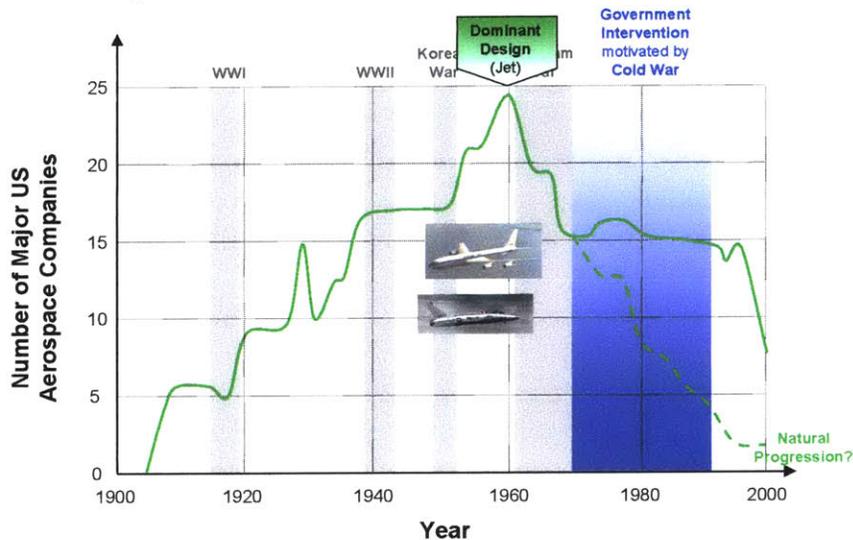
Figure 7.7 below shows the development of products in commercial aircraft over the past 70 years. We can see that the “dominant design”²⁴¹ of aluminum tube and wing with wing-mounted jet engines arrived in 1955²⁴², with marginal technological improvement in the 40 years since.

Figure 7.7: Dominant Design – Technology



I couple this piece of knowledge with the observation that the occurrence of the dominant design in the mid-1950’s also coincided with the maximum number of firms in the industry as shown below in figure 7.8.

Figure 7.8: Dominant Design – Firm Concentration



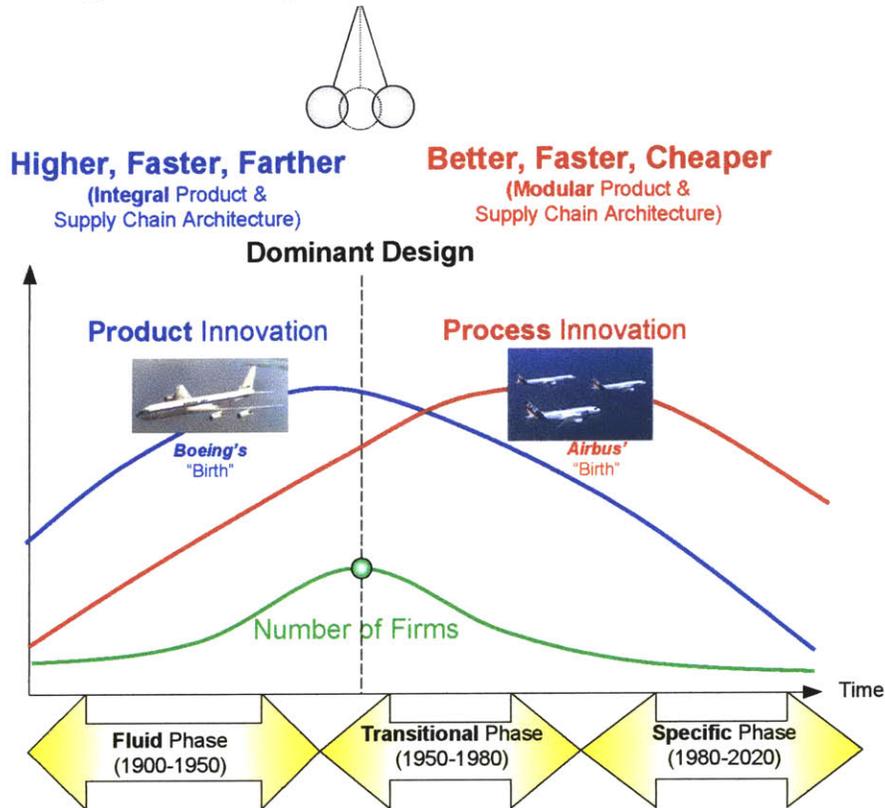
Source: Murman et al.

²⁴¹ *Mastering the Dynamics of Innovation*, Harvard Business Press, James Utterback, 1996.

²⁴² *Lean Enterprise Value*, Murman et al., Palgrave Press, 2002.

James Utterback²⁴³ noted that the emergence of a dominant design was approximately coincident with the maximum number of firms in an industry. Before this time product innovation was the prime competitive advantage and after this time, process innovation is the prime competitive advantage (see figure 7.9 below).

Figure 7.9: Aerospace “Industrial Evolution” (source: Utterback)



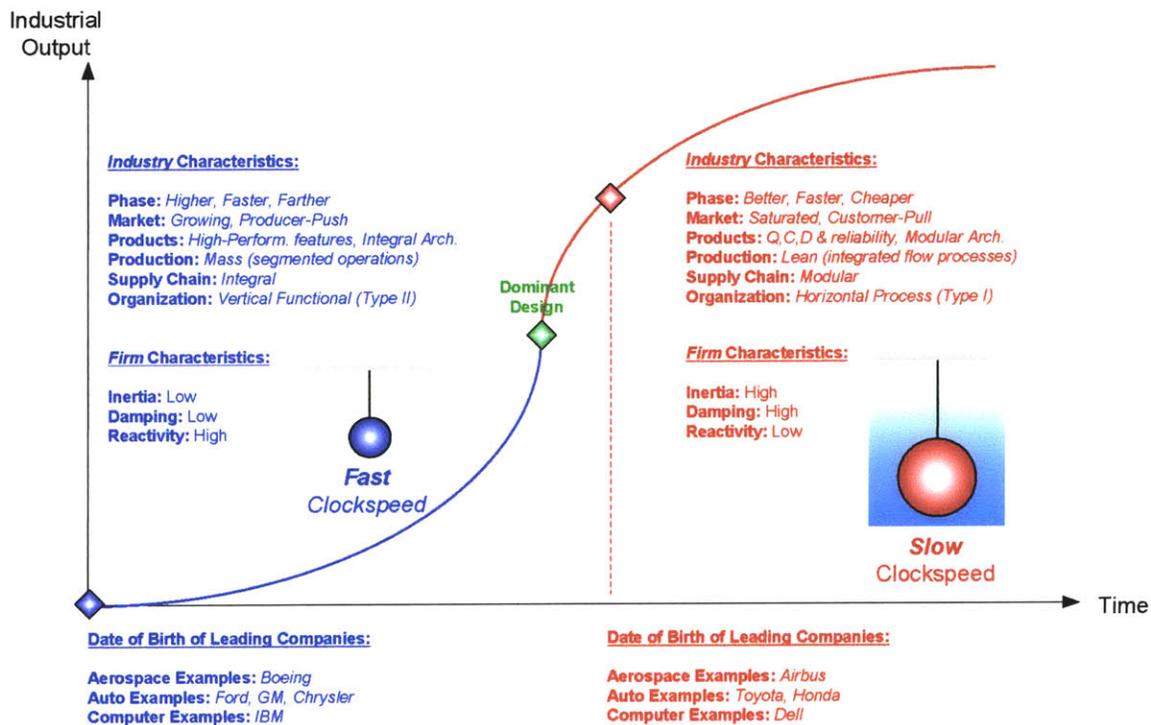
In fact in the evolution of any industry, Utterback notes that there are three distinct phases. The first or “fluid” phase is characterized by *craft* production, in which products have high performance – indicating the onset of the higher, faster, farther world. In the second or “transitional” phase, which is characterized by segmented operations in *mass* production, products are characterized by their features, around which a dominant design emerges. Finally, the third phase is characterized by integrated flow

²⁴³ *Mastering the Dynamics of Innovation*, James Utterback, 1996.

process in *lean* production, where quality, cost, delivery and reliability are the primary product characteristics – indicating the onset of the better, faster, cheaper world.

In general, the evolution of an industry can be characterized by a classic technology or product or firm S-curve. The above evolution is shown in figure 7.10 below with the fluid and transitional phases combined for simplicity.

Figure 7.10: S-curve of Industrial Evolution

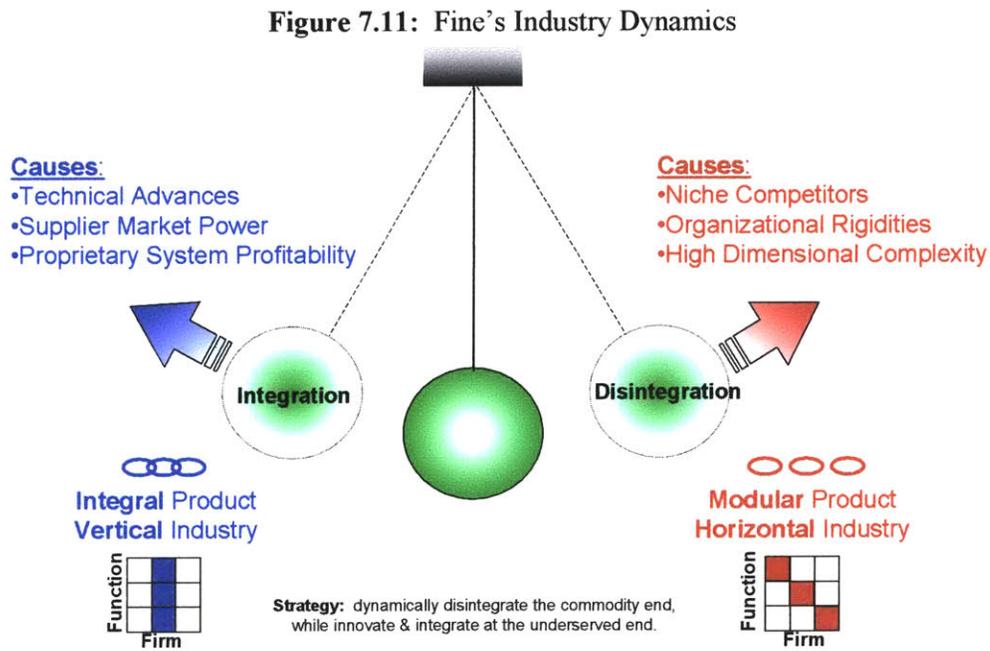


Note that the examples shown above do not claim that *Boeing*, *GM* and *IBM* are not today “lean” companies, but merely that they grew-up in a “mass” world and therefore have their DNA hardwired to thrive in that environment. For them transition into the better, faster, cheaper world requires a reprogramming or re-architecture. For companies that grew up in the better, faster, cheaper worlds in their respective industries (like *Airbus*, *Toyota* and *Dell*) their DNA is hardwired to thrive in the post-dominant design world

Recalling the enterprise physics from chapter 2, successful firms or value chains have different dynamic characteristics in each phase of the S-Curve. In the rapid growth phase, successful firms will be

configured to be fast clockspeed, that is their inertia will be relatively low, their damping will be relatively low, and their stiffness or reactivity will be relatively high. In the mature phase, successful firms will be configured to be slower clockspeed, that is their inertia will be relatively high, their damping will be relatively high, and their stiffness or reactivity will be relatively low. There is an important distinction however which will be discussed in detail in chapter 9 regarding the substructure and superstructures of firms and value chains particularly in the mature phase of the industrial S-Curve²⁴⁴.

As seen in figure 7.10 above, the enterprise physics model can be applied both to understanding the dynamics of firms as well as to the dynamics of the industry (within which the firm operates). Charlie Fine explores the dynamics of industrial evolution further, by looking beyond the empirical notion of a dominant design as a leading indicator or industrial evolution towards the forces that cause industrial evolution via the “Double Helix”.²⁴⁵ The pendulum in figure 7.11 below summarizes the forces which cause firms and industries to swing from integral product and supply chain architectures to modular product and supply chain architectures. The displacement trajectory of such an industrial pendulum can be considered to be a double helix.

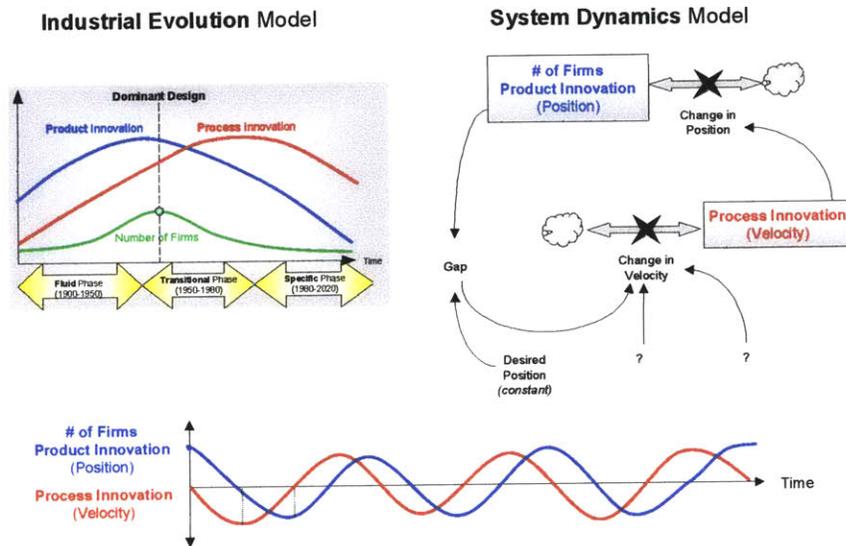


²⁴⁴ I draw this distinction, because in the mature phase the clockspeed appears to be faster. I argue that this is the case for the clockspeed of the *superstructure*, not the *substructure* and thus not the entire system.

²⁴⁵ Fine, Charles; *Clockspeed: Winning Industry Control in an Age of Temporary Advantage*, Perseus, 1998.

Once again, this phase-shifted sinusoidal dynamic looks like a familiar application of the generic structure of the second order-balancing loop with delays that was described in its general form in chapter 2. Therefore I can postulate another simplified pendulum model (as shown in figure 7.12 below) in which product and process innovation are in oscillation just like displacement-velocity and inventory-workforce.

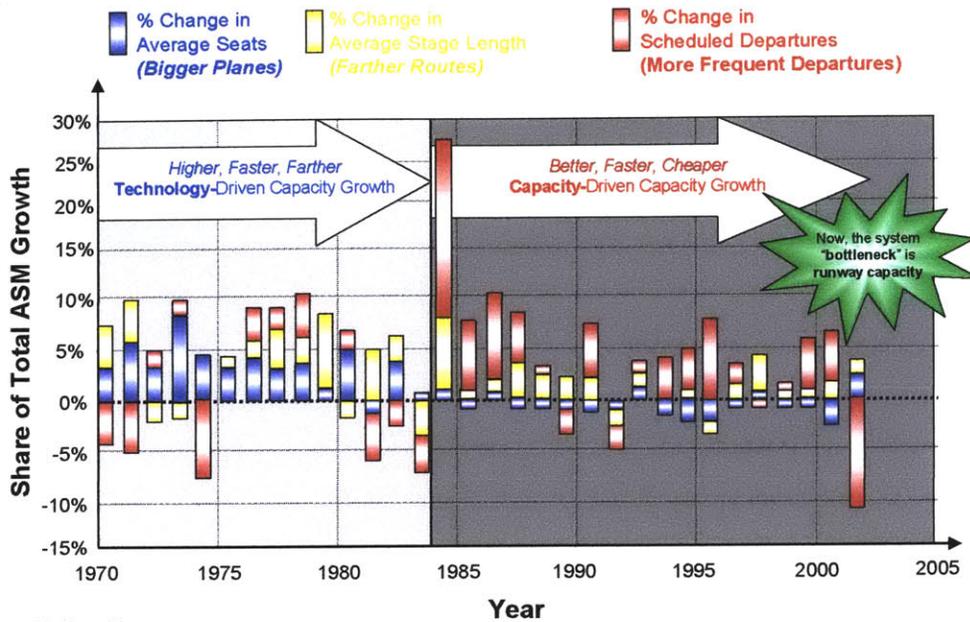
Figure 7.12: Generic Structure: Industry Dynamics



From this industry dynamic, it appears that the industry is consolidating after the dominant design, and is favoring the network process improvements associated with the 7E7. This observation is borne out in research done by *Eclat Consulting*²⁴⁶, which demonstrates that prior to deregulation of the airline industry, airline travel capacity expansion was achieved via advancements in product technologies: either larger planes or planes flying further. In contrast, after deregulation as the industry continued to evolve from “higher, faster, farther” products, towards “better, faster cheaper” products and production networks, travel capacity expansion was achieved via more frequent departures, as shown in figure 7.13 below.

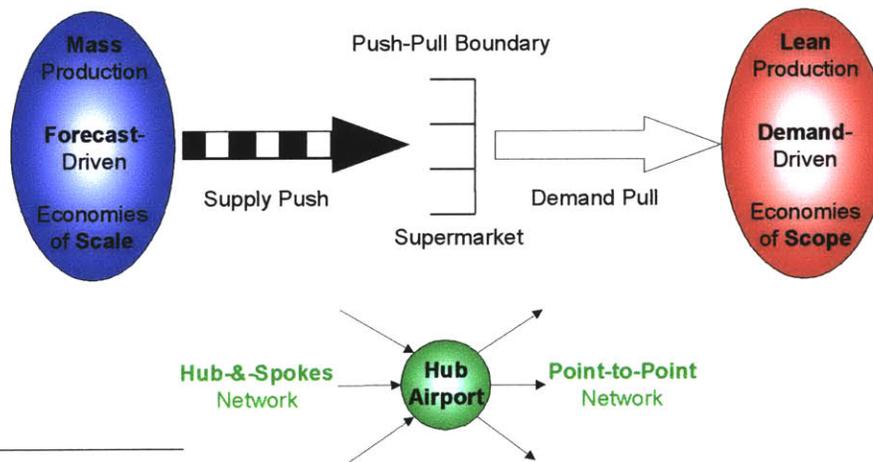
²⁴⁶ From guest lecture by *Eclat Consulting* in MIT Fall 2002 course, The Airline Industry.

Figure 7.13: Evolution of Airline Travel Growth Sources (source: Eclat Consulting)



The question of which product to launch could be thought of within the system of which product would best support the network within which it operates, given the abovementioned industry evolution towards, “better, faster, cheaper”. As figure 7.14 below shows, the lean network is one in which passengers flow directly from point-to-point without having to be batched, while the mass network is one in which passengers are batched into “sorting centers”²⁴⁷ which is driven by network economies of scale. The question of whether speed or efficiency of airplane fits best with the point-to-point lean network model.

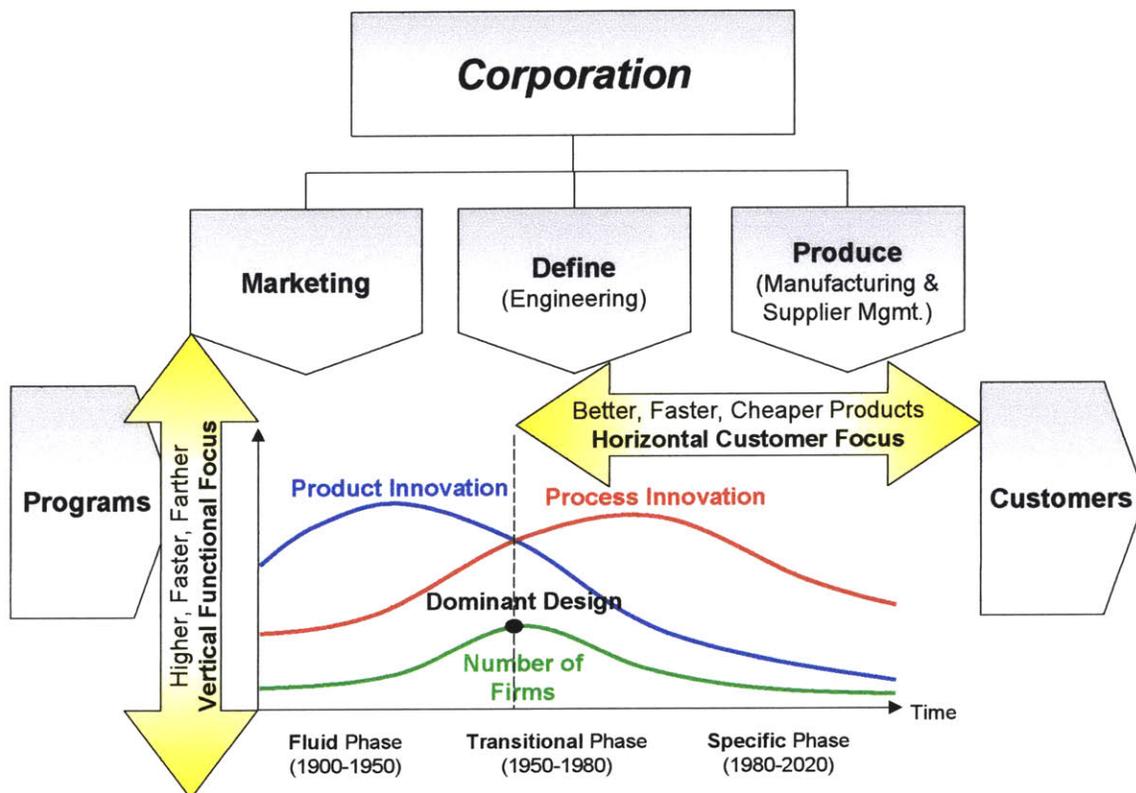
Figure 7.14: Better, Faster, Cheaper Networks



²⁴⁷ *Lean Thinking*, James Womack and Dan Jones, 1996.

Finally, just as there are clear product and process evolutions, there is also an associated post-dominant design organizational evolution. The “higher, faster, farther” world is characterized by vertical functional organizations, while the “better, faster cheaper” world is characterized by horizontal process organizations as shown in Figure 7.15 below.

Figure 7.15: Organizational Evolution

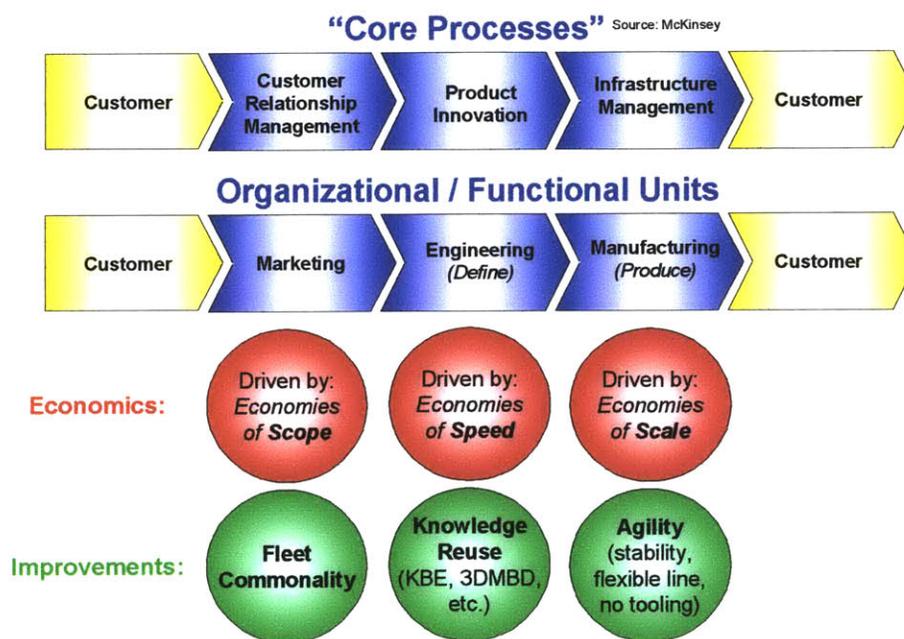


There are different strategies that are appropriate as an organization emerges into the “better, faster, cheaper” world, based on the economies of Scope, Speed and Scale²⁴⁸ (see figure 7.16 below). The customer relationship management organization (a.k.a. marketing) is now driven by economies of scope, that is, by the need to offer diverse, customized products and services. In the commercial aviation industry, this might mean offering a broad product platform that leverages commonality. The product innovation organization (a.k.a. engineering) is now driven by economies of speed, that is, by the need to deliver product innovation faster to serve the rapidly changing needs of the customers. In the commercial

²⁴⁸ Hagel III, John and Singer Marc, “Unbundling the Corporation”, *Harvard Business Review*, August 2000.

aviation industry, this might mean reusing technical knowledge and expertise (e.g. knowledge-based engineering, or three-dimensional model-based definition). The infrastructure management organization (a.k.a. manufacturing) is driven by economies of scale, that is, by the need to improve asset utilization. In the commercial aviation industry, this might mean being able to send multiple products down the same assembly line or maintaining stable volume production to ensure workforce stability and maximize production learning.

Figure 7.16: Organizational Strategies



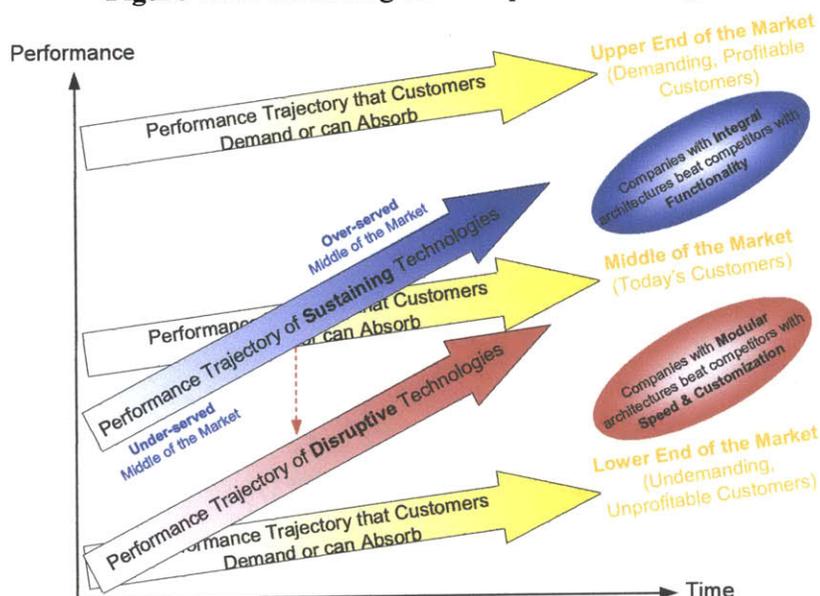
7.4 Product Strategy: the Dynamics of Disruptive Technologies

Clayton Christensen differentiates between a “Sustaining” and a “Disruptive Technology”²⁴⁹. A sustaining technology is typically developed by companies that tend to have integral product and supply chain architectures, who beat competitors with increased functionality (as in the “higher, faster, farther” model). By comparison, a disruptive technology is typically developed by companies that tend to have modular product and supply chain architectures, who beat competitors with speed and customization (as in the “better, faster, cheaper” model).

As shown in figure 7.17 below, the performance trajectories of both supply (i.e. products) and demand (i.e. customer preferences) are upward-sloping with respect to time, with technological advancement typically growing at a faster rate than customers’ ability to absorb the performance increases. When a technology is under-serving the desired market, sustaining technological improvements are made. In fact, such improvements are usually made in the quest for the more profitable customer segment (upper in figure 7.17 below). Once a significant enough of the market becomes over-served by the sustaining technology, a discontinuity called a “disruptive technology” often arises in which a low-performance product targets undemanding customers. Often, the disruptive technology is competing against non-consumption - that is against customers who simply weren’t in the market. Therefore a poor-performing product is often good enough to beat non-consumption. In response to this movement, the incumbent product provider is more than happy to let go of the lower end of its market, in the search for the more profitable upper end of the market. Large volumes of low profit customers allow the disruptive technology to improve on its own sustaining technology trajectory, pushing the incumbent out of higher and higher profit market segments. In fact, a disruptive *technology* is actually a misnomer, it is actually a trivial technology using a disruptive *business model*.

²⁴⁹ *The Innovator’s Dilemma: When New Technologies Cause Great Firms to Fail*, Clayton M. Christensen, Harvard Business School Press, 1997.

Figure 7.17: Sustaining vs. Disruptive Technologies



In the realm of commercial aviation, *Boeing* and *Airbus* are both developing new technologies (the 7E7 and A380 respectively) that sustain the current business model, namely the hub-and-spokes airline network. This philosophy tends to lead to the development of an ever more efficient fleet of airplanes which can transport large numbers of passengers large distances between network hubs (i.e. twin aisle, wide-body aircraft) and smaller single aisle, narrow-body aircraft that can transport smaller numbers of passengers shorter distances from hubs to final point destinations.

An emerging business model that is beginning to challenge and dismantle the current hub-and-spoke model of the large network carrier is the point-to-point business model of today's most profitable airlines: *Southwest*, *JetBlue*, *RyanAir* and *ValueJet*. These low-fare airlines are targeting the underserved, undemanding markets of leisure travelers – in fact Southwest was originally founded not to compete with other airlines, but to compete with “non-consumption”, that is with car, bus and train travel. As the incumbent manufacturers retreat into smaller and smaller niche markets for larger airplanes, “disruptors” like the Brazilian manufacturer, *Embraer* and the Canadian manufacturer, *Bombardier* are manufacturing and selling inexpensive small products that are “good enough” for the underserved markets of the low-fare carriers.

As a case in point, *JetBlue* recently announced a large order of *Embraer's* new *190*, a 100+ seat airplane (shown in figure 7.18 below), which is beginning to cut right into *Boeing* and *Airbus's* profitable cash-cow products, the *737/717* (bottom, right) and the *A320* family (bottom, left).

Figure 7.18: The Disruptor (top) and the Disrupted (bottom)



Looking beyond the relatively new business model of the point-to-point, low fare carrier, one can begin to see a more radical departure from the current network carrier model, and that is the distributed ownership model of *fractional ownership*.²⁵⁰ Bringing the traveler closer to the arrival of personal air transportation, fractional aircraft ownership delivers the benefits of the point-to-point travel with the added benefits of more customized departure times and locations. All this is done at a fraction of the cost of owning the whole aircraft. Fractional aircraft ownership gives customers access to a large fleet of private aircraft. It is interesting to note that Warren Buffet, “the world’s most successful investor”, who I introduced in chapter 4 as bemoaning the airline industry as “the world’s worst industry”, has made significant investments in *NetJets*, a rapidly growing fractional aircraft ownership company.

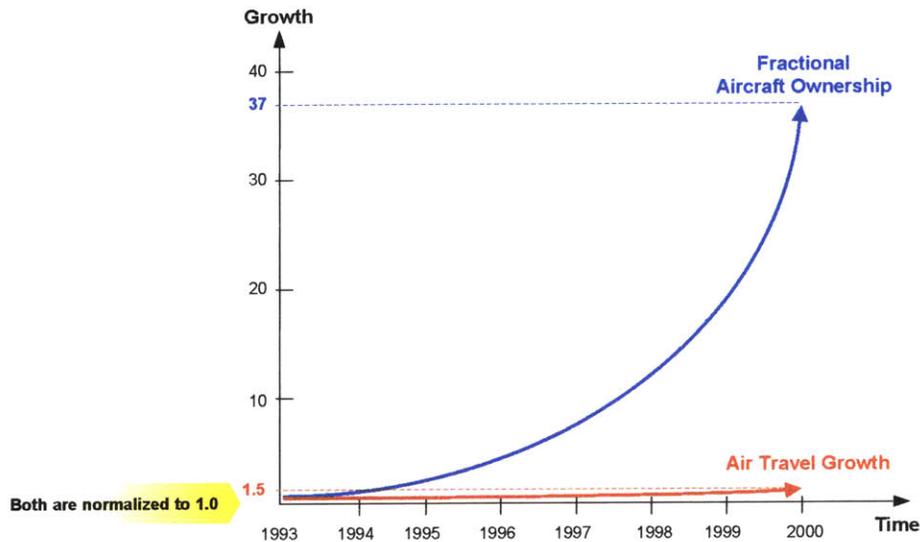
As shown in figure 7.19 below, the number of companies or individuals in the U.S. who owned a share in business aircraft has exploded from 110 in 1993 to 3,694 only seven years later.²⁵¹ In fact, the fractional aircraft ownership business model has been growing at phenomenal 50% annual rates in a 5% annual growth air travel market. Like Moore’s Law of growth in semiconductor speed, this represents a

²⁵⁰ *Driving Airline Business Strategies through Emerging Technology*, Nawal K. Taneja, Ashgate Press, 2002, pg. 123-125.

²⁵¹ *Financial Times*, 6 November 2001, pg. 12.

doubling approximately every 18 months. This expansion exploits the point-to-point network dominance of private aircraft which can fly in and out of approximately 5,400 airports in the U.S. compared to only about 580 airports for the current scheduled airlines.²⁵²

Figure 7.19: Growth of Fractional Aircraft Ownership vs. Growth of Demand for Air Travel



This disruptive technology or business model has its own sustaining technology trajectory, as fractional aircraft ownership companies are looking to offer supersonic business jets to their niche high-margin customers.²⁵³

Casting an eye even further forward, one can use the framework herein to explore the dynamics of future technological and business model evolution. As shown in figure 7.20 below, further advancement of the disruptive point-to-point business model could lead to technologies that allow smaller and smaller planes transporting undemanding, unprofitable customers where they want to go, when they want to go. This trend might extend from the existing smaller 50-seat regional jets (which are flown by much lower labor-cost pilots) down to the new proposed *Eclipse* mini-jet aircraft coupled with *The Nimbus Group's* “air taxi” service in small 5-seat jets²⁵⁴.

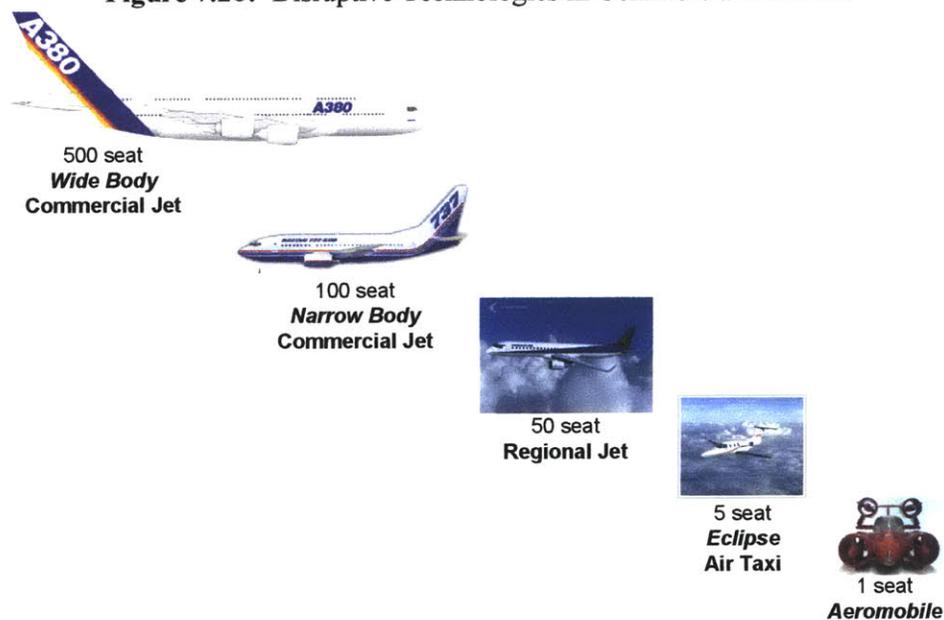
²⁵² *Driving Airline Business Strategies through Emerging Technology*, Nawal K. Taneja, 2002, pg. 125.

²⁵³ *Ibid*, pg 126.

²⁵⁴ *Driving Airline Business Strategies through Emerging Technology*, Nawal K. Taneja, *Ashgate Press*, 2002, pg. 126-127.

Eventually, the dream of the personal air vehicle or *aeromobile* (not-unlike the current automobile) may be realized, but a combination of a large underserved market of undemanding customers will have to meet with a confluence of new technologies. In order to access the global population masses (like automobiles) these technologies might include: UAV (unmanned air vehicle) avionics and flight control systems to allow common (non-expert) users to drive the vehicle, VTOL (vertical take-off and landing) to eliminate the need for conventional runways and airports, and ATM (air traffic management) system to control and safely regulate the congested interactions of millions of *aeromobiles*. As an aside, it is interesting to note that *Boeing* is already developing each of these technologies separately today.

Figure 7.20: Disruptive Technologies in Commercial Aviation



Finally, a distinction must be underlined between the disruptive technologies, which support a disruptive business model, and the sustaining technologies, which while very advanced and sophisticated, only sustain the current business model. In this definition, the *Concorde*, with all of its advanced technologies, flying a smaller number of people point-to-point, was after all a (possibly breakthrough) sustaining technology as it sought to serve today's most profitable customers with a better product, not unprofitable customers with a poor product. It is equally interesting to note that one of the world's most successful enterprises, *Toyota* is quietly developing an air vehicle for an undemanding market with a price under \$100,000 (see figure 7.21 below).

Figure 7.21: Products for “Unprofitable” Customers?

Targeting “**Profitable**” Customers



Concorde

Targeting “**Unprofitable**” Customers



7.5 Product Strategy: the Dynamics of Game Theory

Finally, no product strategy discussion would be complete without an exploration of the economic dynamics embedded in game theory. In a perfectly competitive (or even in monopolistic) market, all firms are doing the best that they can and have no reason to change their price or output. The same is not true, however in an oligopolistic market, where a few firms compete with each other and entry by new firms is impeded. In such an oligopolistic market, each firm will want to do the best it can, *given what its competitors are doing*. This leads to a stable state of equilibrium, known as a “Nash Equilibrium”²⁵⁵ which I will discuss below in the context of the airplane manufacture market.

The market for the manufacture of large (100+ seat) airplanes is a clean example of this oligopolistic market, as it has collapsed down into a duopoly due to barriers to entry and scale economies. As discussed throughout this report, the two players in this duopoly are *Boeing* and *Airbus*. Although each manufacturer would argue for higher degree of product (or product family) quality, aircraft today are largely seen as *homogenous* or identical goods in which consumers consider only price when making their purchasing decisions.

Assuming that it would be uneconomical for both *Boeing* and *Airbus* to develop a new airplane due to the \$10 billion development costs and the limited potential size of the market (say 1,000 planes over 20 years), then the first-mover would have an advantage in capturing the market. For example, assume theoretically that producing a new aircraft could yield a lifetime profit of \$5 billion (after

²⁵⁵ *Microeconomics*, Robert S. Pindyck and Daniel L. Rubinfeld, 5th edition, 2001, pg. 430.

repaying development costs) for either *Boeing* or *Airbus*, while not producing the aircraft would yield a profit of \$0. Conversely, if both companies developed the airplane, they would each lose \$2.5 billion (revenues minus development costs). Figure 7.22 below illustrate the payoffs in this hypothetical example. If *Boeing* had the first mover advantage, it would be logical for them to develop the airplane and take all of the \$5b profits – the game, known as the “prisoner’s dilemma” is solved, with the upper right square representing the Nash Equilibrium.

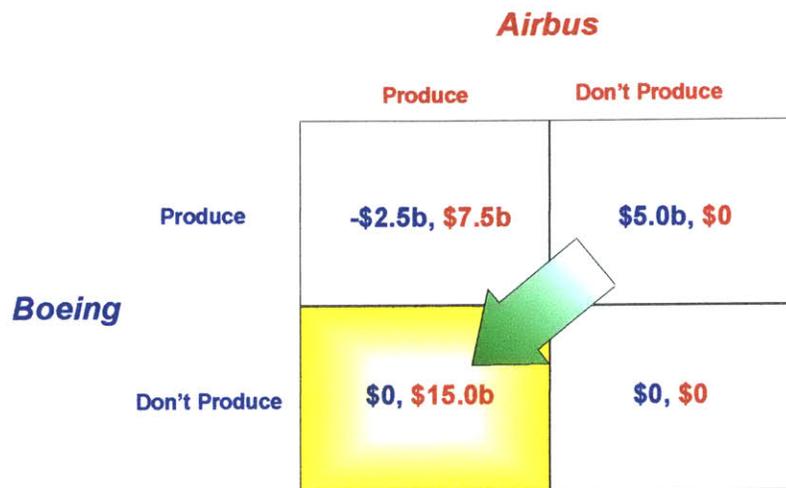
Figure 7.22: “The Aircraft Manufacturers’ Dilemma”

		Airbus	
		Produce	Don't Produce
Boeing	Produce	-\$2.5b, -\$2.5b	\$5.0b, \$0
	Don't Produce	\$0, \$5.0b	\$0, \$0

When contemplating the development of a new aircraft, Krugman²⁵⁶ noted however, that government subsidies can have an important impact on the outcome of defining the Nash equilibrium. If the European government preferred (for various macroeconomic or Economic Rate of Return reasons) for *Airbus* to develop the new aircraft, they might commit to subsidizing the new plane (in accordance with the 1992 GATT bilateral agreements) to the tune of \$10b before *Boeing* has committed to produce the plane. The new payoff matrix would change to that shown in figure 7.23 below.

²⁵⁶ “Is Free Trade Passé?”, Paul R. Krugman, *Journal of Economic Perspectives* 1 (Fall 1987): 131-44.

Figure 7.23: “The Aircraft Manufacturers’ Dilemma” after *Airbus* Subsidy



Now, *Airbus* will make money from a new plane, whether or not *Boeing* produces one. Knowing that *Airbus* will produce either way, *Boeing* will then decide not to produce in order not to lose money, and the Nash Equilibrium has shifted to the lower left corner. The effect of the \$10b subsidy therefore changes the outcome for *Airbus* from one in which they don't produce and earn \$0, to one in which they do produce and they earn \$15 billion. Of this, \$5b is a direct transfer of profit from the US to the EU, making the subsidy a worthwhile investment from a European perspective.

The traditional view that trade restrictions lead to economic deadweight losses to the society carrying them out is therefore challenged in circumstances like the one above. Where there are asymmetric national resources (e.g. Europe's comparative competitive advantage being its willingness to subsidize a domestic industry, while the US is unwilling), there will be benefits transferred by the unsuccessful competitor which outweigh the problems of the sacrificial deadweight losses.

Although this example was fictitious and based on the observations of Krugman²⁵⁷, various researchers²⁵⁸ have recently demonstrated similar benefits of policies which give domestic industries a competitive advantage, in real cases like the *Airbus A380*.

²⁵⁷ “Is Free Trade Passé?”, Paul R. Krugman, *Journal of Economic Perspectives* 1 (Fall 1987): 131-44.

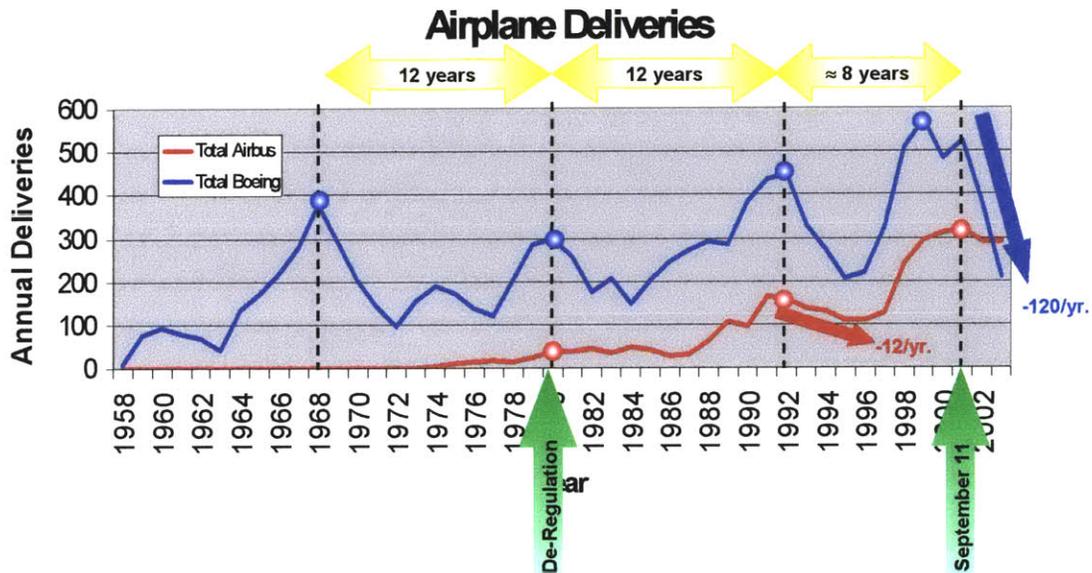
²⁵⁸ “*Airbus* vs. *Boeing*: The Case of Failed Pre-emption”, Benjamin Esty, *Harvard Business School Press*.

7.6 Production Strategy: Velocity

Having decided on what products to launch and when to launch them, it is also important to consider how many to make, or more importantly what is the velocity of which they are made? Underlying this is the complicated question of meeting customer demand and/or taking market share, and/or maintaining capabilities through continuous learning and improvement.

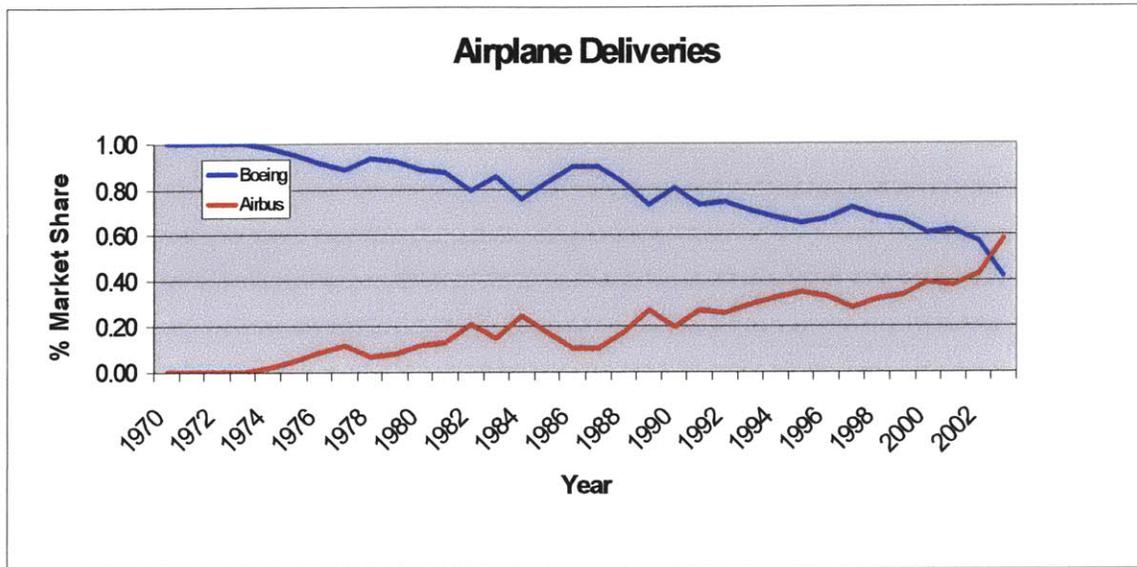
As shown in figure 7.24 below, *Boeing* and *Airbus* have had different philosophies with respect to production velocities (or rates, taken as the slope of the production output curves). In general, *Boeing* appears to have a greater ability (or simply desire) to achieve both higher rates of production as well as higher rates of negative production (i.e. ramping-down speed). Note that *Boeing's* maximum ramping-down rate over the past 30 years is an order of magnitude steeper than *Airbus's*.

Figure 7.24: *Boeing* and *Airbus* Production Output and Production Velocities



One can also express the above data in another way to observe the underlying market shares of each competitor as shown in figure 7.25 below. This leads to the question, is growing market share simply correlated to or caused by stability in output. We will return to this question in chapter 9.

Figure 7.25: Boeing and Airbus' Share of Deliveries



7.7 Corporate Strategic Choices: “The Race to the Bottom” vs. “The March to the Top”

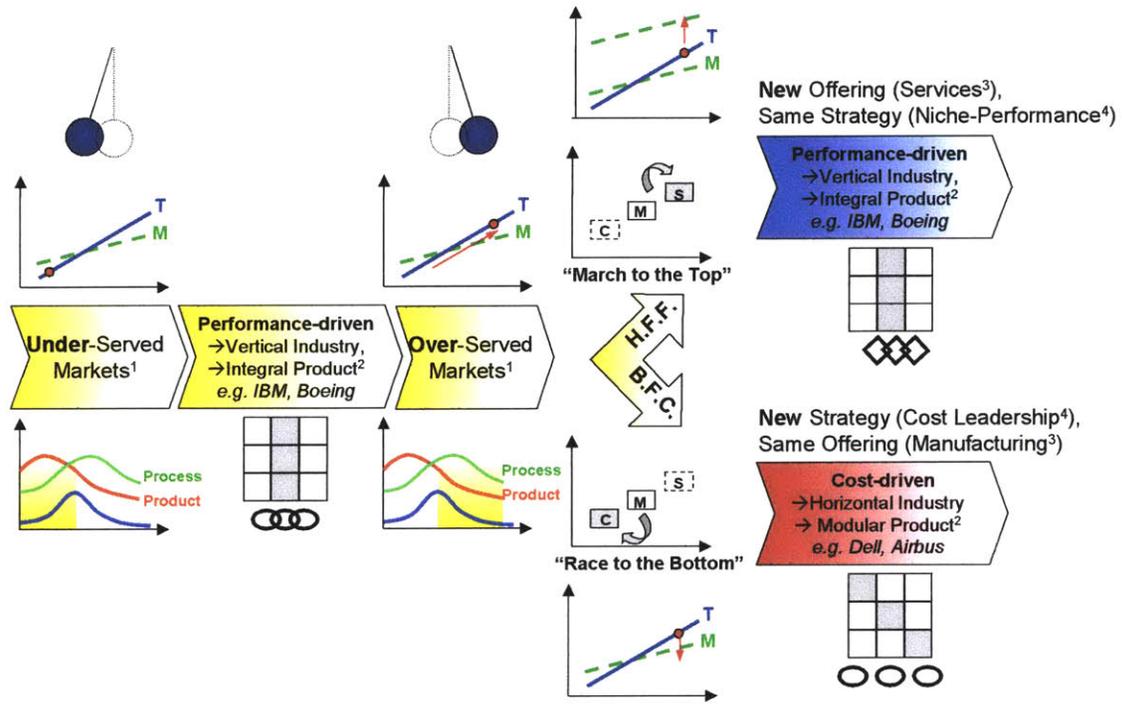
Finally, pulling together some of the concepts developed in this chapter, I offer an illustrative example to compare corporate strategic choices with the computer industry. I begin by observing that *Boeing's* corporate DNA is firmly rooted engineering and the ability to produce world-class high-performance products. This is obvious, as *Boeing* grew-up in the pre-dominant-design “higher, faster, farther” industrial phase. The commercial aerospace industry is currently in its post-dominant-design “better, faster, cheaper” industrial phase, and its current competitor, *Airbus* is a product of this phase.

In order to deliver its HFF products, *Boeing* evolved strong functional silos to support its integrated product and supply chain architectures. It had embarked on a path of developing “sustaining technologies” to “underserved” markets until *Airbus* entered the game. Conversely, in order for *Airbus* to deliver its BFC products, it chose the “race to the bottom” (line) by commoditizing its products. This called for a modular product and supply chain architecture.

Boeing, therefore has a choice, to enter the race to the bottom, by transitioning from its “niche performance” strategy towards a “cost leadership” strategy, or it can maintain its “niche performance” strategy, but march to the top of the economic offering away from manufacturing and toward services. In

this example, *Boeing* is like the classic computer powerhouse, *IBM*, which had a similar HFF DNA and transitioned successfully in their new march to the top. *Airbus* is like the new computer powerhouse, *Dell* which has the same BFC DNA and is committed to the race to the bottom. See figure 7.26 below.

Figure 7.26: “Race to the Bottom” vs. “March to the Top” Corporate Strategies



7.8 Chapter Summary

This chapter discussed the corporate and product strategy dynamics for the aerospace industry. We began by demonstrating how an exogenous shock in the markets reveals the underlying market differences of commercial and military aerospace products.

We then explored the 10-year dynamics of customer profitability and how it might affect the timing of new product introductions, particularly in the highly capital intensive, long lead-time world of commercial aviation.

We then explored the 100-year dynamics of industry innovation and consolidation, recognizing the industrial evolution from “higher, faster, farther” to “better, faster, cheaper” products is based on the emergence of a dominant design in an industry, which occurred in aerospace approximately 50 years ago.

We complemented this analysis with observations that [disruptive technologies](#) in commercial aviation are likely to continue to dissolve the network hub and spokes model toward more point-to-point, possibly even radically over time.

Finally, we discussed the notion of [game theory](#) as applied in the commercial aviation duopoly. We noted that there is an argument of [subsidized](#) new product introduction by *Airbus* is an effective strategy, due to the nature of their social enterprise.

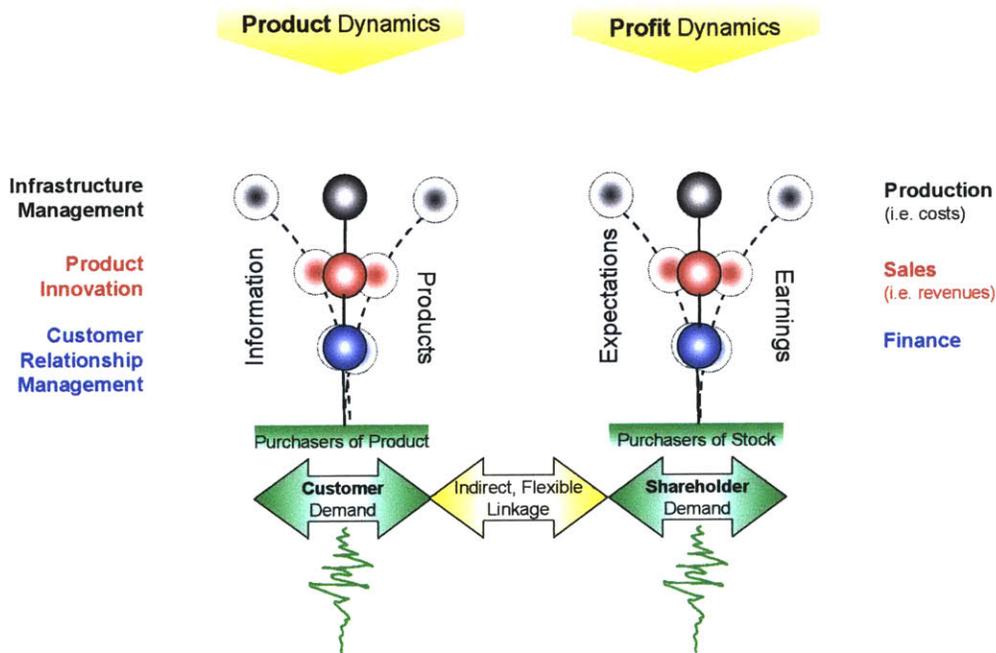
Chapter 8: The Architecture of Corporate Financial Dynamics

8.1 Product Markets vs. Capital Markets

We began in chapter 2 discussing a model of an enterprise where the dynamics of customer demand drives the dynamics of the corporation, as a wave of customer order information propagates up the value system and a wave of products is reflected back down the value system towards the customer as shown on the left side of figure 8.1 below.

In this chapter, we will examine another dynamic demand, this time not from customers demanding products, but from shareholders demanding profits (and growth), as a wave of shareholder expectations propagates up the value system and a wave of earnings is reflected back down the value system towards the shareholders as shown on the right side of figure 8.1 below²⁵⁹.

Figure 8.1: Structural Dynamics in the *Product Markets* as well as in the *Capital Markets*



Although one might conjecture that the two dynamics are the same (as fulfilling product orders should equate to profitability), there is “dynamic complexity” embedded in this system, where cause and

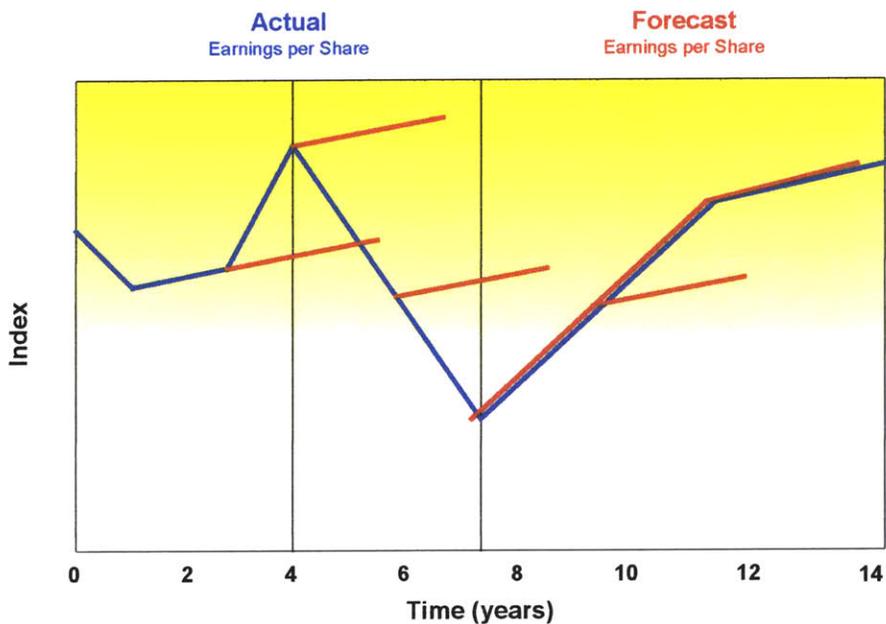
²⁵⁹ M.F.M. Osborne contentiously investigates whether or not a capital market is in fact a market for capital and just how important it is as a source of capital in *The Stock Market and Finance from a Physicist's Viewpoint*, 1977, pg. 6.

effect are distant in space and time. One of the many examples of this for durable goods like airplanes is that while demand for product is inherently very cyclical, the shareholder valuation of these cyclical companies is not. We shall discuss this next.

8.2 Valuing Cyclical Companies

Managers of cyclical companies who are focused primarily on shareholder value creation have a very difficult job, as *McKinsey & Company*²⁶⁰ notes that Wall Street forecasts of cyclical companies do not even acknowledge the existence of a cycle. Figure 8.2 below compares the actual earnings per share with the forecasted earnings per share. No matter where the company is in its cycle, the analyst's forward projections are the same. It is no wonder that it is so difficult to manage a cyclical company, when the stock markets can't even value it correctly. One must ask therefore, whether basing management decisions on metrics tied to poor valuation techniques is the right thing to do.

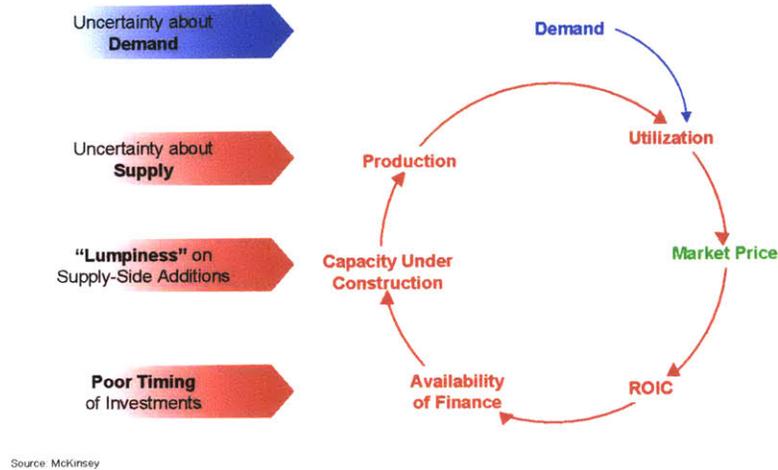
Figure 8.2: Valuing Cyclical Companies



²⁶⁰ *McKinsey Quarterly*, "Valuing Cyclical Companies", Marco de Heer and Timothy Koller, 1998.

The question of how to get investors to prevent cyclicality relies first on understanding the causes as show in figure 8.3 below.²⁶¹

Figure 8.3: Four Causes of Cyclicity



8.3 Expectations Clockspeed

This leaves us with the question, what metrics do the capital markets use to establish expectations?

Total Returns to Shareholders (TRS) that is the share price appreciation plus dividends is one of the cleanest ways to measure corporate performance. However, it does not cut through the noise of the market to articulate exactly how a corporation is creating value. It is the delivery of “surprises” that produces higher or lower total shareholder returns compared to the market. *McKinsey & Company*²⁶² notes that Wall Street resets its expectations in line with past performance – they have called it the “expectations treadmill”. Therefore the speed of the expectations treadmill – i.e. the market’s “expectations clockspeed” greatly defines a corporation’s TRS. I liken TRS therefore to a “rate” of value, which does not describe the whole picture of a corporation’s value. We must look for a complementary concept – a “stock” of value.

²⁶¹ “Wooing Investors to Prevent Cyclicity”, Paul Butler, Panos Ninios, Hendrik Sabert and John Morecroft, *McKinsey Quarterly*, 1998, Number 1.

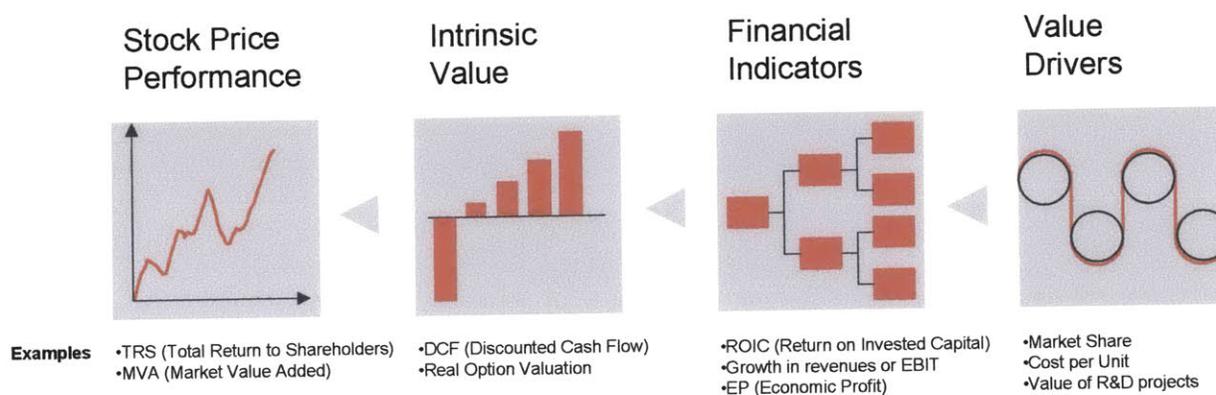
²⁶² *McKinsey Quarterly*, “The Expectations Treadmill”, Richard Dobbs and Timothy Koller, 1998.

Market Value-Added, (MVA), i.e. the difference between the market value of a company's debt and equity and the amount of capital invested can be thought of as the current speed of the treadmill, or the current level of the stock of value. Together TRS and MVA combine to give a more holistic view of the dynamics of corporate valuation.

8.4 Value Metrics

This leaves us with the question, "what metric(s) do managers use to drive shareholder value in cyclic companies?" Copeland et al. propose that there should be a comprehensive value metrics framework as shown in figure 8.4 below.²⁶³

Figure 8.4: Comprehensive Value Metrics Framework



We must keep these in mind as we look to for a high-level "architectural" metric that ensures stable growth over the long term.

8.5 The Profit-Growth Dynamic

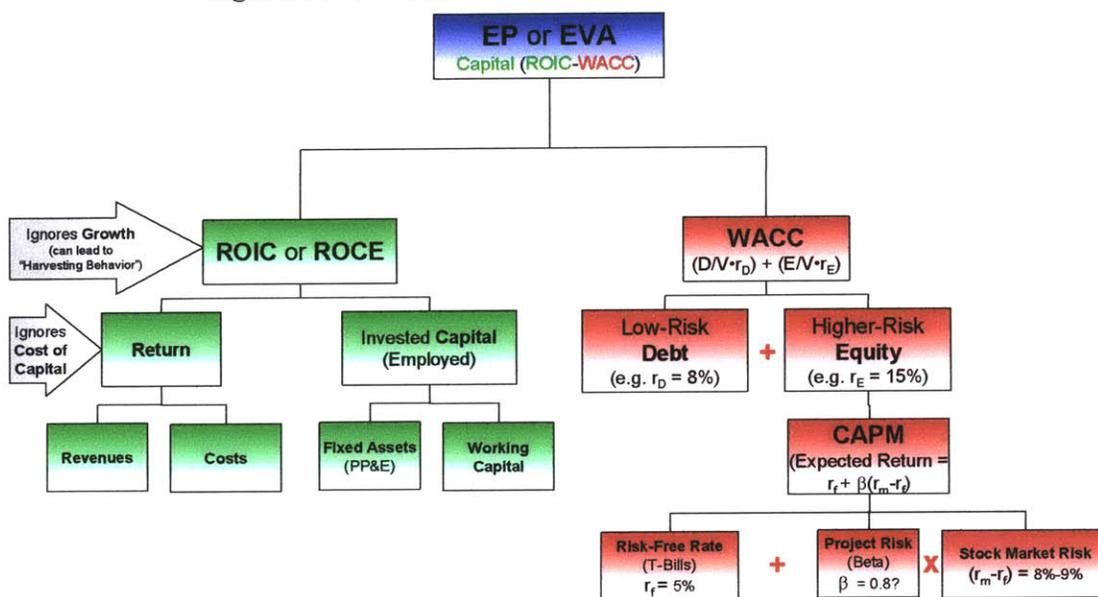
As with the generic structure of the oscillating pendulum, we saw trade-offs between velocity and displacement, workforce and inventory, product innovation and process innovation. The same is true in the area of financial metrics. The value that the financial markets assign to a company reflects its

²⁶³ Copeland, Koller, and Murrin, *Valuation*, pg. 56.

prospects for growth and profitability – but as with most things there is a dynamic interaction between the two.

A simple metric that is used by many companies which attempts to capture both quantities is Economic Value Added (EVA), or Economic Profit (EP) as shown in figure 8.5 below. Economic profit is simply the spread between the Return on Invested Capital (ROIC) minus the Weighted Average Cost of Capital (WACC) times the capital employed. If we considered the sustainability of the spread between ROIC and WACC, we would have a measure of the value of growth for the company.

Figure 8.5: Economic Value Added or Economic Profit



As pointed out by various researchers²⁶⁴, there is one potential flaw: economic profit can discourage growth. Olsen²⁶⁵ describes three fundamental distortions in manager’s decisions: 1) economic profit is biased against new assets, 2) economic profit is biased in favor of large, low-return businesses, and 3) economic profit encourages managers to harvest the business. The most interesting of these is that economic profit rewards harvesting or anti-growth behavior. The preferred way to run a business is to invest at rates of return that exceed the cost of capital. However it is often easier to improve economic

²⁶⁴ “Economic Value Added”, Eric E. Olsen, Boston Consulting Group’s *Perspectives on Strategy*, 1996.

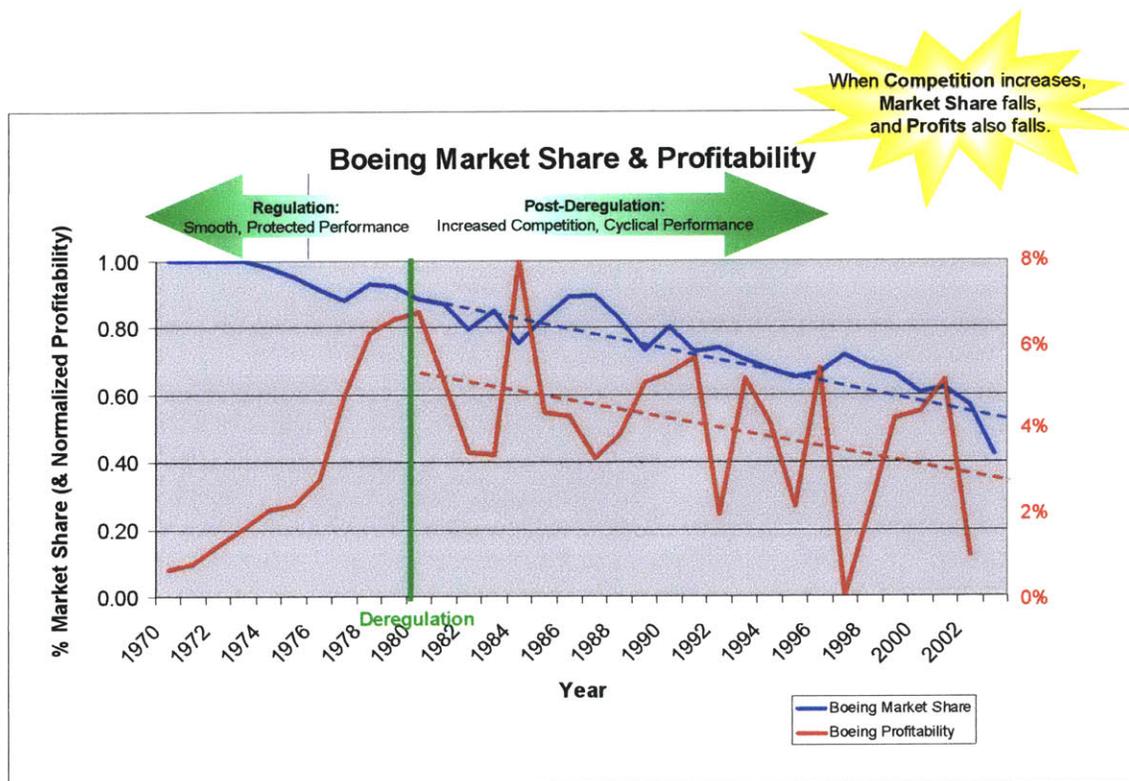
²⁶⁵ *Ibid*, pg. 192.

profit (at least in the short term) by reducing assets faster than earnings, otherwise known as “milking the business”. Short-term and long-term profit objectives must be considered.

This leads to the question of the value of market share in the quest for profitability. This profit-growth dynamic has caused a great deal of discussion and research over the past 30 years, particularly regarding the relationship between market share and profitability. One of the more well-known, extensive and controversial studies on this topic is the PIMS or *Profit Impact of Market Strategy* initiative²⁶⁶. The findings of this multi-company, multi-year research was that market share can be an important determinant of profitability, particularly in companies or firms which exhibit the positive feedback behavior of economies of scale, positive network externalities, etc.

A simple analysis of *Boeing’s* profitability and market share (vis a vis *Airbus*) over the past 25 years shows that there appears to be some correlation between market share and profitability (net income) in the commercial aircraft industry (see figure 8.6 below).

Figure 8.6: *Boeing’s* Market-Share and Profitability Relationship



²⁶⁶ Buzzell & Gale, *The PIMS Principles*, 1987.

8.6 Optimum Rate of Growth

In balancing the growth and profitability dynamic, there is an optimum (or sustainable, or balanced) rate of growth for an enterprise that is significantly slower than the maximum possible rate of growth. This leads to the observation that sales growth is not necessarily something to be maximized – a topic which we will discuss in the next chapter.

Higgins examines this optimum rate of growth as being dependent on financial resources.²⁶⁷ As increased sales requires more assets, retained profits and the accompanying new borrowing may generate some new cash, but unless the company is willing and able to sell new equity, there is a limit on growth. Higgins demonstrates that the growth rate in sales is limited by the rate at which owners' equity expands which can be expressed in the simple equation shown in figure 8.7 below. Note that Profit Margin and Asset Turnover are operating performance measures, while Retention Ratio and Financial Leverage are financial policies.

Figure 8.7: Equation for Sustainable Growth Rate

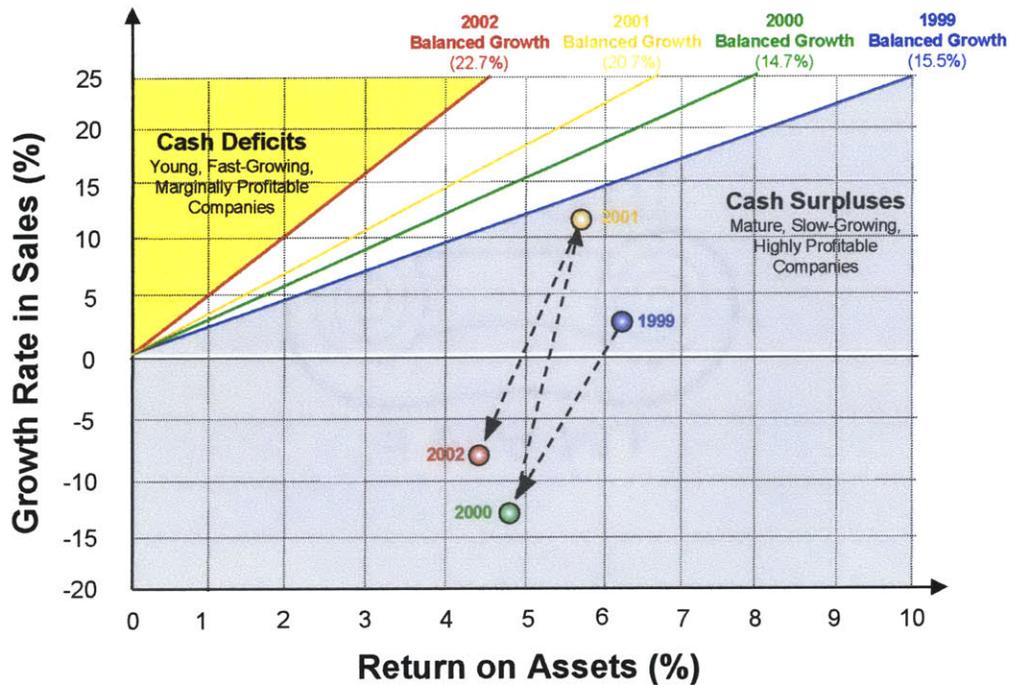
$$\text{Balanced Growth} = \text{Profit Margin} * \text{Retention Ratio} * \text{Asset Turnover} * \text{Financial Leverage}$$

When this type of financial analysis is applied to *The Boeing Company*²⁶⁸ over the past 4 years, it is clear that *Boeing's* actual growth rate is well below its sustainable growth, as can be seen from figure 8.8 below.

²⁶⁷ *Analysis for Financial Management*, Robert C. Higgins, 7th edition, McGraw-Hill, 2004, pgs. 115-138.

²⁶⁸ This analysis refers to *The Boeing Company* in full, and not just the *Boeing Commercial Airplanes Group*.

Figure 8.8: Boeing's Sustainable Growth Rate (1999-2002)

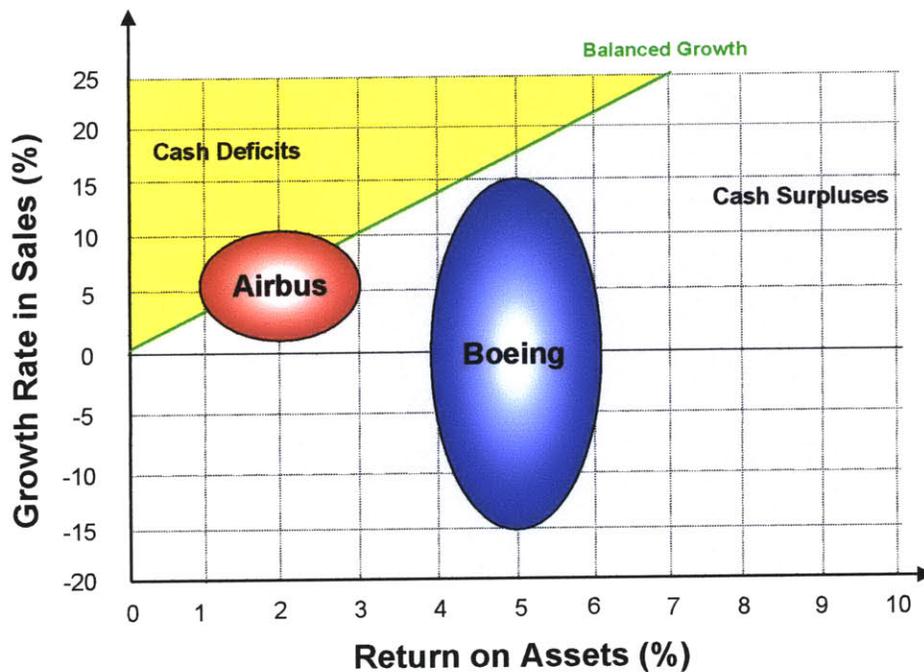


The diagonal lines represent *Boeing's* balanced growth rate. If above and to the left of these lines, a company is operating with cash deficits, that is the company is growing too quickly, while if below and to the right of the lines, a company is operating with cash surpluses and is growing more slowly than is balanced. *Boeing*, like many mature companies is faced with the dilemma of generating excess cash generated than is needed to run the business efficiently. From the equation above, it is clear that the solutions include returning more cash back to the shareholders in the form of greater dividends or buying growth, that is diversifying into other businesses, which is exactly what *Boeing* has done in the past 5-6 years with the acquisition of *McDonnell Douglas* aircraft and other space-related businesses. It is important to note that “buying growth” delivers shareholder value if and only if it is “good growth” that is the returns on invested capital exceed the cost of capital. And finally as Higgins points out, although diversified acquisitions appear to be logical, the financial evidence indicates that if shareholders wanted

the risk reduction benefits of a conglomerate merger, they could achieve them much more simply by owning shares of the two independent companies in their own portfolios.²⁶⁹

It is interesting to compare qualitatively *Boeing* and *Airbus*' relative positions with respect to sustainable growth. As was shown previously in figure 8.9, *Boeing* maintains relatively stable returns on assets, with more variable growth rates which largely reflect the demands in the market place. *Airbus* on the other hand is closer to balanced growth as it accepts lower returns on assets in exchange for consistent, positive sales growth. I will return to this topic in the next chapter under the topic of stability.

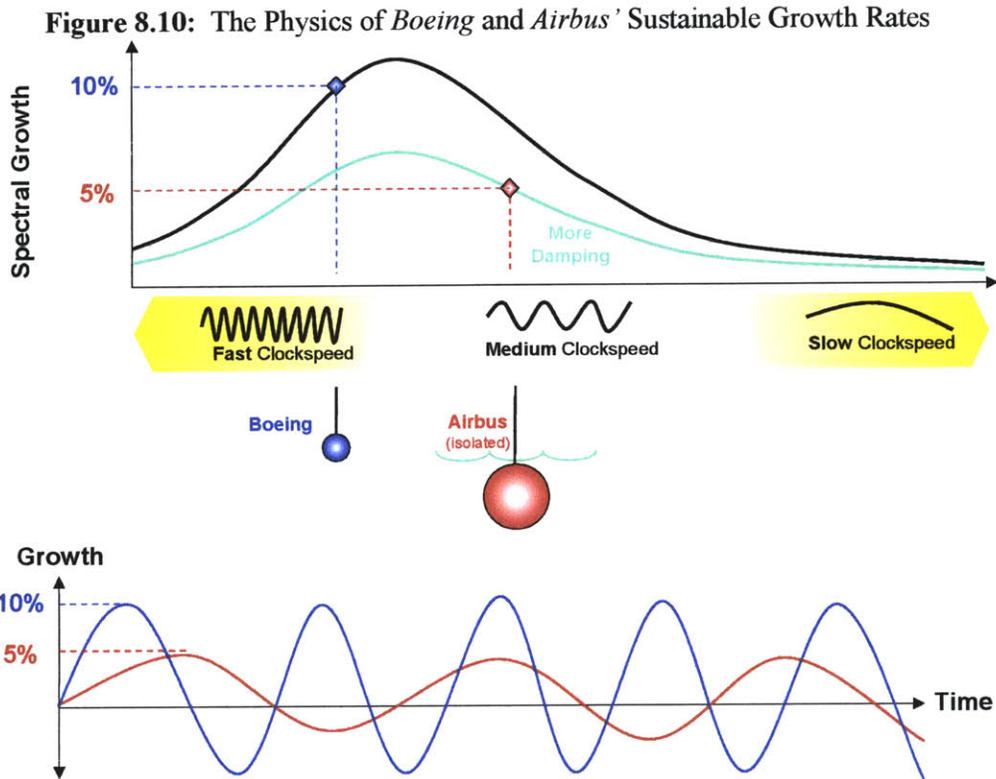
Figure 8.9: Qualitative Assessment of *Boeing* and *Airbus*' Sustainable Growth Rates



In order to qualitatively estimate the relationships between *Boeing* and *Airbus*' relative clockspeeds, we could map their respective growth rates onto a general enterprise response spectrum as shown in figure 8.10 below. *Boeing*'s relatively large dynamic amplification of the underlying demand signal indicates that they are in the resonance range having a fast-to-medium clockspeed. *Airbus*' relatively small dynamic amplification of the underlying demand signal indicates that they likely have a

²⁶⁹ *Analysis for Financial Management*, Robert C. Higgins, 7th edition, McGraw-Hill, 2004, pgs. 312-313.

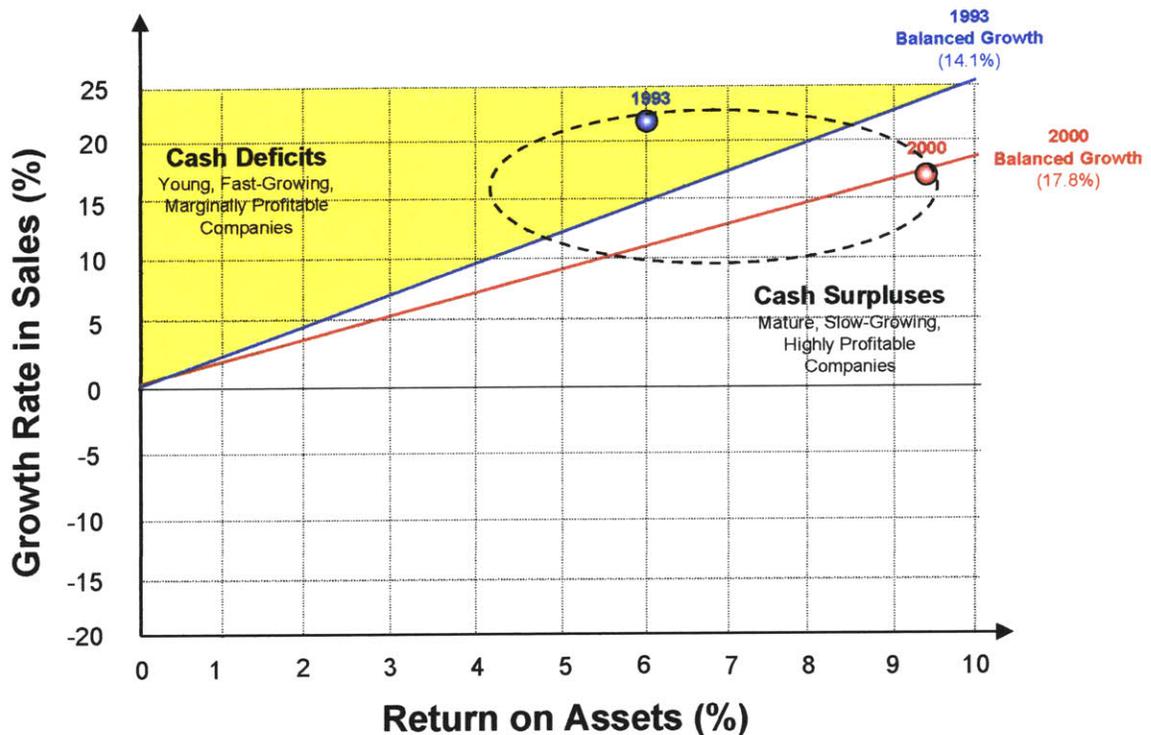
slower clockspeed (i.e. to the right of *Boeing*), and or they have more enterprise damping (i.e. on a lower curve than *Boeing*).



World-class companies like *Southwest Airlines* understand the simple dynamics of financial growth and profitability, and use more systemic metrics to drive long-term performance. Figure 8.11 below shows the extremes of the fastest and slowest balanced growth rates for *Southwest* from the years of 1993 – 2001.

There are a number of observations to make. First, the range of balanced growth rates is very small, demonstrating a stable metric. Second, *Southwest's* actual performance points are very close to the balanced targets. Third, the range of actual performance points from 1993-2001 ha a greater horizontal scatter than vertical scatter (as shown by the dotted ellipse). This indicates that stable growth seems to be sought at the expense of more variable returns.

Figure 8.11: Southwest Airline's Sustainable Growth Rates (1993-2001)



8.7 Financial Architecture

Finally, the relationship of the capital structure of firms (i.e. its strategic choice of debt and equity financing) and the competitive capabilities of firms has been observed in recent years.^{270,271} Simerly et al. present empirical evidence that firms in stable, static environments that exhibit high-performance have a relatively high leverage ratio, while firms in dynamic environments that exhibit high-performance have relative low leverage ratios.²⁷² In a development of Modigliani and Miller's Nobel prize-winning work²⁷³, it appears that financial architecture (i.e. capital structure) does in fact drive firm performance.

Stalk et al. note that the use of debt as a strategic weapon remains a powerful influence on competition. They state that, "Many North American companies are yielding an unfair competitive

²⁷⁰ Simerly (2000), pg. 32.

²⁷¹ Porter (1992).

²⁷² It is interesting to note that there is a positive reinforcing loop working as high leverage creates a more stable environment for the firm which leads to higher firm performance, which leads to sustained debt load. Conversely, low leverage creates a less stable environment for the firm which leads to higher firm performance, which leads to low sustained debt levels.

²⁷³ Modigliani and Miller, (1958).

advantage to their Japanese and European competitors by refusing to remove the debt umbrella they hold over their less-strong competitors”.²⁷⁴ Their colleague Bruce Henderson provocatively warns, “use more debt than your competition or get out of the business.”²⁷⁵

On a macro-level, the *MIT Commission on Industrial Productivity* noted that “Japanese firms have been willing to take on high levels of debt in order to invest in new production capacity and marketing infrastructure...in effect they have been investing to grow demand. U.S. companies are usually reluctant to adopt such policies, because they entail a sacrifice of short-term profits and higher risks to shareholders. This concern with short-term profitability undermined or inhibited cooperative relationships.”²⁷⁶

More interestingly was their hypothesis for the explanation of the short-term bias in American industry, which they noted was due to a higher cost of capital in the US than in Japan. This was a function of Japanese (and European) desire to raise capital in the debt markets and less from the open sales of securities in the capital markets. Finally, this can be attributed from a macro-economic point of view to the relatively low rate of personal savings and high rate of government deficit spending in the US.

In fact the differences in financial architecture and corporate strategy can be seen in the following rankings of corporate objectives in both the US and Japan (see figure 8.12 below).²⁷⁷

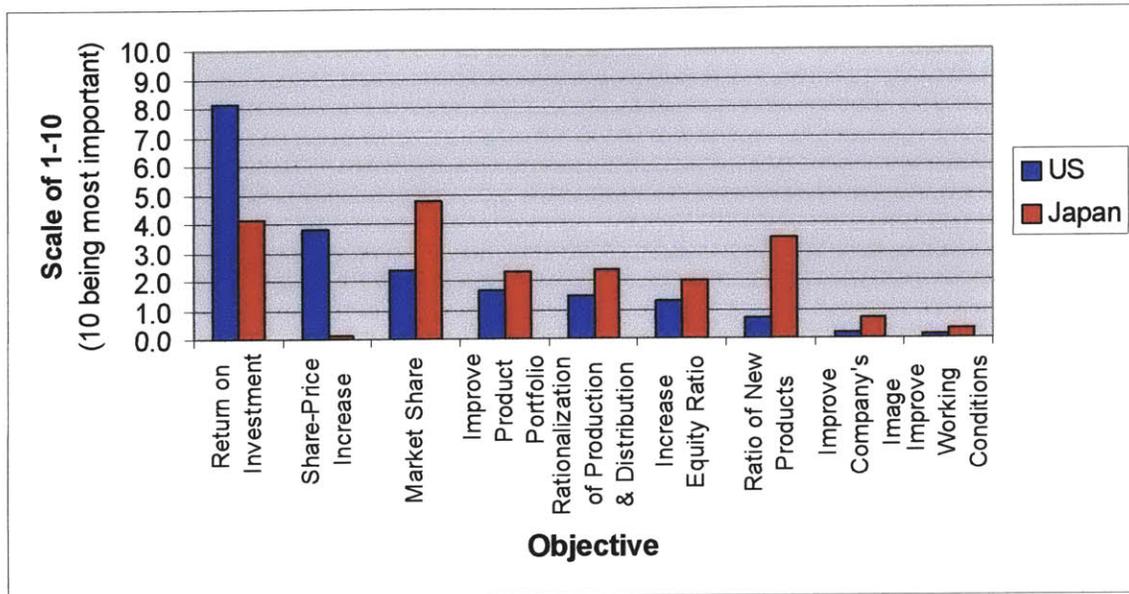
²⁷⁴ Stalk et al., pg. 21.

²⁷⁵ Ibid.

²⁷⁶ Dertouzos et al. pp. 53-63.

²⁷⁷ Dertouzos et al. (1989) pg. 63.

Figure 8.12: U.S. and Japanese Ranking of Corporate Objectives



This ranking is particularly telling of the industrial strategies of Japanese and European firms pursuing slow growth, market share based strategies, particularly when one views market share as a proxy for long-term investment as proposed by Henderson.²⁷⁸

8.8 Chapter Summary

This chapter introduced the dynamics of corporate finance. First, I introduced the oscillatory dynamic nature of revenue growth and profit or earnings growth. This uncovered the need for a unified metric, **Economic Profit**, which is an important integrative measure, but taken by itself can lead to short-term company harvesting.

Then, we explored the dynamics of shareholder value as represented by the stock and flow analogy of Market Value Added (MVA) and Total Return to Shareholders (TRS), finally noting that the markets do not explicitly **value the cyclicity** of cyclic companies, making it very difficult to manage these companies.

²⁷⁸ Bruce Henderson, (1979).

Finally, we looked at the [financial architecture](#) of a corporation, recognizing that an equity-weighted architecture is an excellent structure for high-growth companies, while a high-leverage architecture ensure financial discipline in older, more mature companies, particularly in industries with slow project growth rates, like aerospace.

Chapter 9: Architecting Innovative Enterprise Solutions

Having put in place some simple analytical frameworks to define the dynamic characteristics of enterprises, I now turn briefly to explore some possibly innovative and counterintuitive enterprise design solutions. In fact, I will propose a definition of “Lean” based on the principles of enterprise physics that were derived in Part I.

9.1 What is Lean?

The Toyota Production System (a.k.a. “Lean”) has been studied extensively since the 1980s.²⁷⁹ One of the easiest ways to picture complex phenomena is via a metaphor. A lean enterprise is a difficult and often counterintuitive way to conceive a business. One way to visualize it and compare it to the traditional mass enterprise is via the metaphor shown in figure 9.1 below.

Figure 9.1: Mass vs. Lean Enterprise Metaphor



The traditional “mass enterprise” grew out of rapidly-growing homogenous markets with large customer inflows (e.g. Henry Ford’s Model T). The optimum solution in such an environment is to construct a large, expensive inflexible monument to capture all the value. In such an environment, specialization of tasks into vertical functional silos tends to mean poor integration along the value stream,

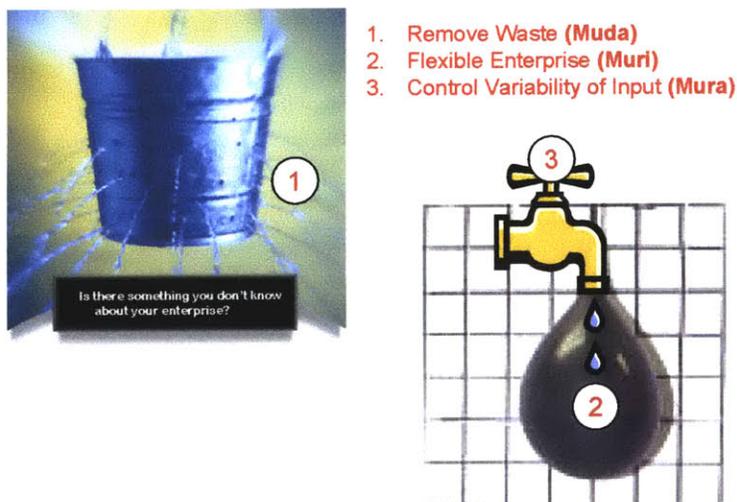
²⁷⁹ See Appendix H for a chronology of research on Lean.

leaving many opportunities for holes in the infrastructure through which value leaks out (i.e. waste). The “lean enterprise” on the other hand grew out of mature, saturated markets with reduced and variable customer in-flows. The optimum solution in such an environment is to construct a right-sized, integrated flexible enterprise to capture the value so that waste is eliminated and flexibility is maximized.

9.2 Lean and the “Three Evils”

The architect of the Toyota Production System, Taiichi Ohno, identified the “three evils” of lean: *muda*, *muri* and *mura*²⁸⁰. These define “what” is lean, while the sequence of: flow, takt and pull, define the “how” to achieve lean. Figure 9.2 below shows how a lean enterprise maps to eliminate the “three evils”. Step 1 is to plug up the holes or the sources of waste (*muda*). One important way to do this from an architectural level is to redesign the enterprise to be less vertical functional siloed and more horizontal customer flow focused. The second step is to make the rigid monument more flexible (to eliminate *muri*), like the water balloon that expands and contracts to capture the value of the customer. Finally, the value chain leader needs to control variability (*mura*) of flow into the enterprise via controlling the faucet spigot.

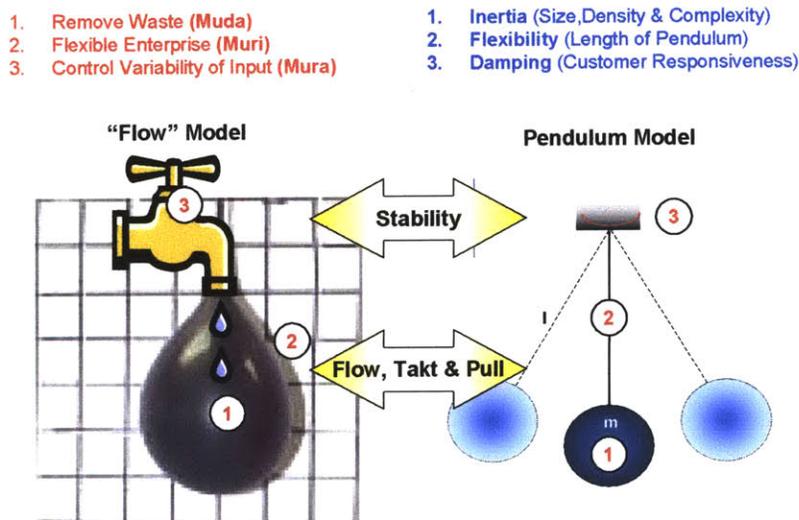
Figure 9.2: Lean Enterprise and the “Three Evils”



²⁸⁰ *Toyota Production System*, Taiichi Ohno, Productivity Press, 1978, pg. 41.

Finally Figure 9.3 below ties this metaphor back to the enterprise dynamics methodology, in which the lean enterprise is compared to a pendulum. Stability or elimination of *mura* is the first and most necessary step. Various researchers have noted that most process improvement methodologies mandate the establishment of stability prior to the implementation of “flow” and “pull”.²⁸¹ In the pendulum this is achieved through damping or “base isolating” the enterprise from the input signal. The achievement of “flow”, “takt” and “pull” are subsequent steps to focus on speeding up the enterprise clockspeed, matching it to “resonate” with the customer clockspeed (or “takt”), which in the pendulum analogy consists of shortening the length of the pendulum and decreasing the size of the inertial mass.

Figure 9.3: Lean Enterprise and Enterprise Physics



Before we leave this topic, it is interesting to note that the above achievement of a lean enterprise via the elimination of the three evils of *muda*, *muri* and *mura* is very similar to the design of a servo-feedback control system. As Graham and McRuer noted in 1961, “any useful feedback control system is designed to secure, usually in turn: *stability*, *accuracy* and *speed of response*. Unfortunately, the same factors which tend to improve speed and accuracy often produce instability, and if the system oscillates

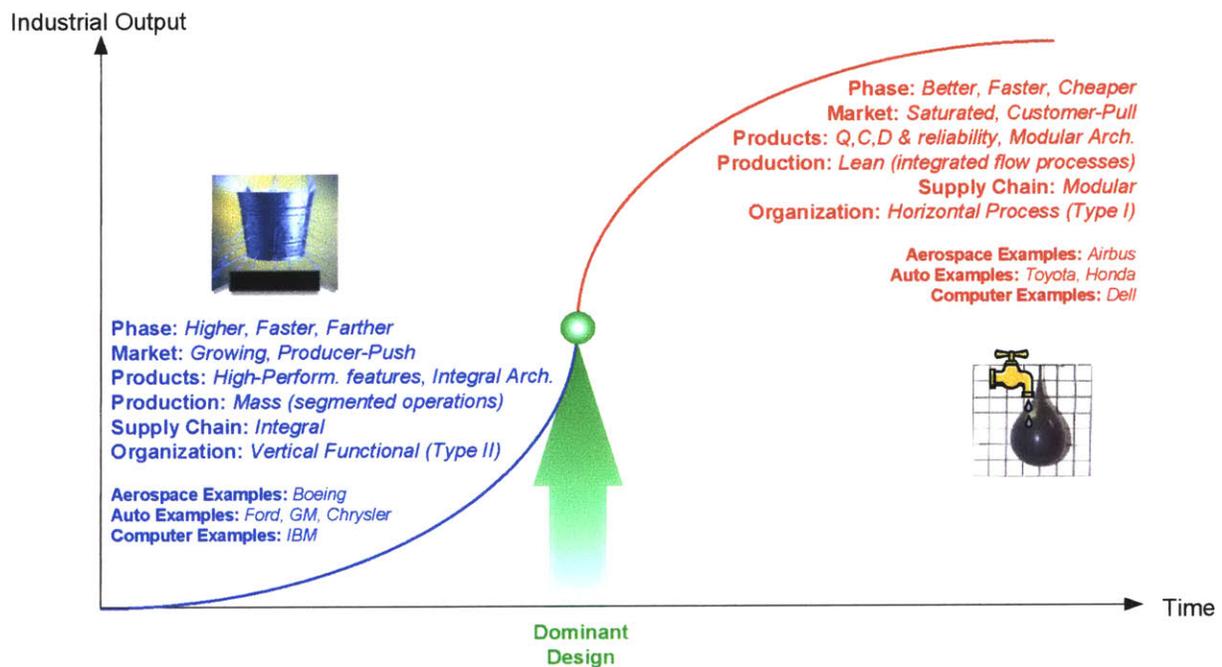
²⁸¹ Cutcher-Gershenfeld, J. and Rebentisch, E., “The Impact of Instability on Complex Social and Technical Systems”, *Proceedings of the ESD Internal Symposium*, May 29-30, 2002, Massachusetts Institute of Technology, Engineering Systems Division, Cambridge, Massachusetts, pp. 69-90.

wildly, it is useless.²⁸² Although many corporations have noted this apparent tradeoff, I will describe below three generic enterprise architectural solutions, with some being more capable of delivering a more robust enterprise with stability, accuracy and speed of response.

9.3 The Industrial Evolution

The mass and lean models can be seen as industrial archetypes which were born out of the economic conditions of their time. Industries, like all growing organisms and organizations, have an S-shaped growth profile. One can therefore conceptually map the industrial archetypes to the evolutionary growth patterns of an industry as is shown in figure 9.4 below.

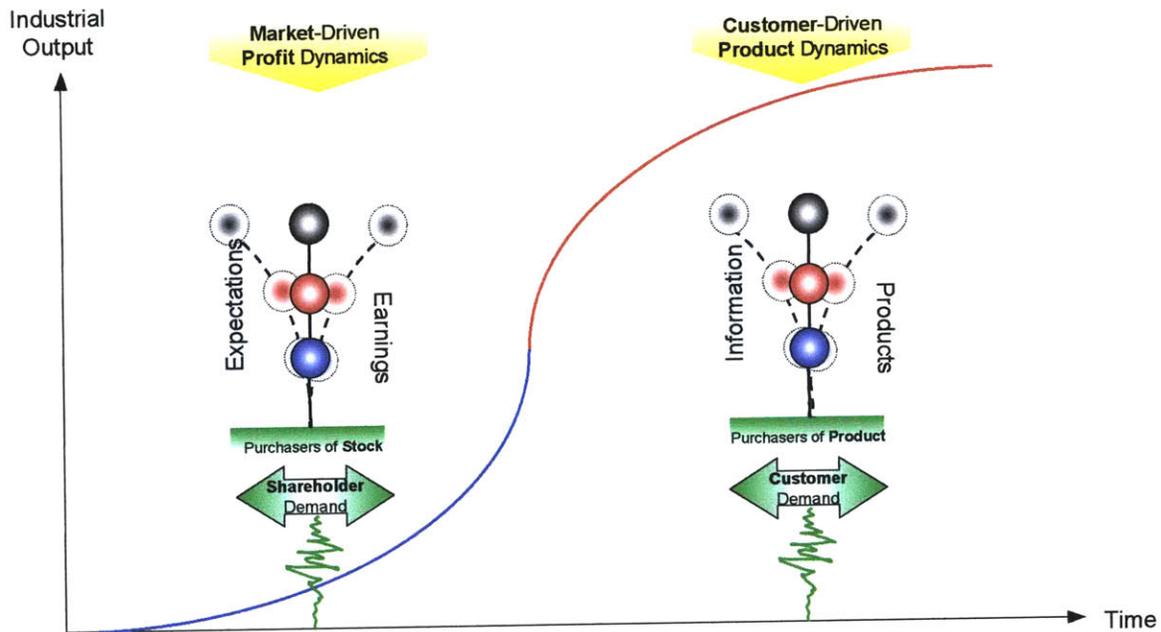
Figure 9.4: The Industrial Evolution



While an enterprise experiences many types of exogenous shocks during its lifetime, there are undoubtedly primary drivers which govern the dynamics of the enterprise. As shown in figure 9.5 below, the governing dynamics of each industrial archetype are different.

²⁸² *Analysis of Nonlinear Control Systems*, Dunstan Graham and Duane McRuer, John Wiley and Sons, 1961. pg. 3.

Figure 9.5: Dynamic Drivers of the Industrial Evolution

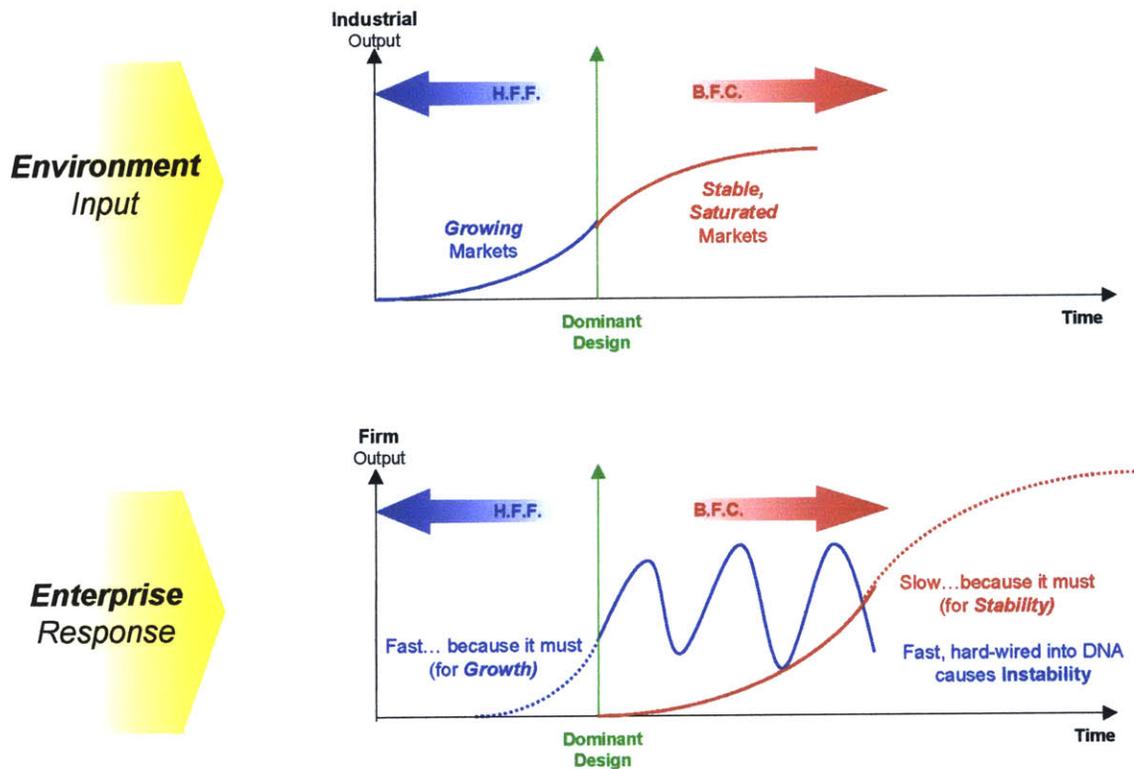


For the mass enterprise, growth is an important driver, and with growth comes risk. As a result, mass enterprises find themselves subject to the dynamic demands of the capital markets. Once an industry matures beyond its dominant design, growth becomes overtaken by the need for stability as the power in an industry shifts from the producer to the consumer.

Noting the different drivers of the different industrial phases, (i.e. *growth* dominating the higher-faster-farther world and *stability* dominating the better-faster-cheaper world.) we can now see how firms in these industries are “hardwired” to respond to changing environments, using the principles of enterprise physics that we laid out in Part I.

As seen in figure 9.6 below, mass-oriented enterprises possess architectures that are built for rapid growth, they are hard-wired to move without delays in the higher-faster-farther world because they can and because they must. Uninhibited exponential growth defines the dynamic behavior of such enterprises. Once a dominant design emerges followed by a consolidation and shakeout of the industry, the better-faster-cheaper world begins, giving birth to lean enterprises that possess architectures that are built for stability (i.e. restrained growth), while mass enterprises overshoot & oscillate.

Figure 9.6: HFF Architecture: Built For *Growth*; BFC Architecture: Built for *Stability*

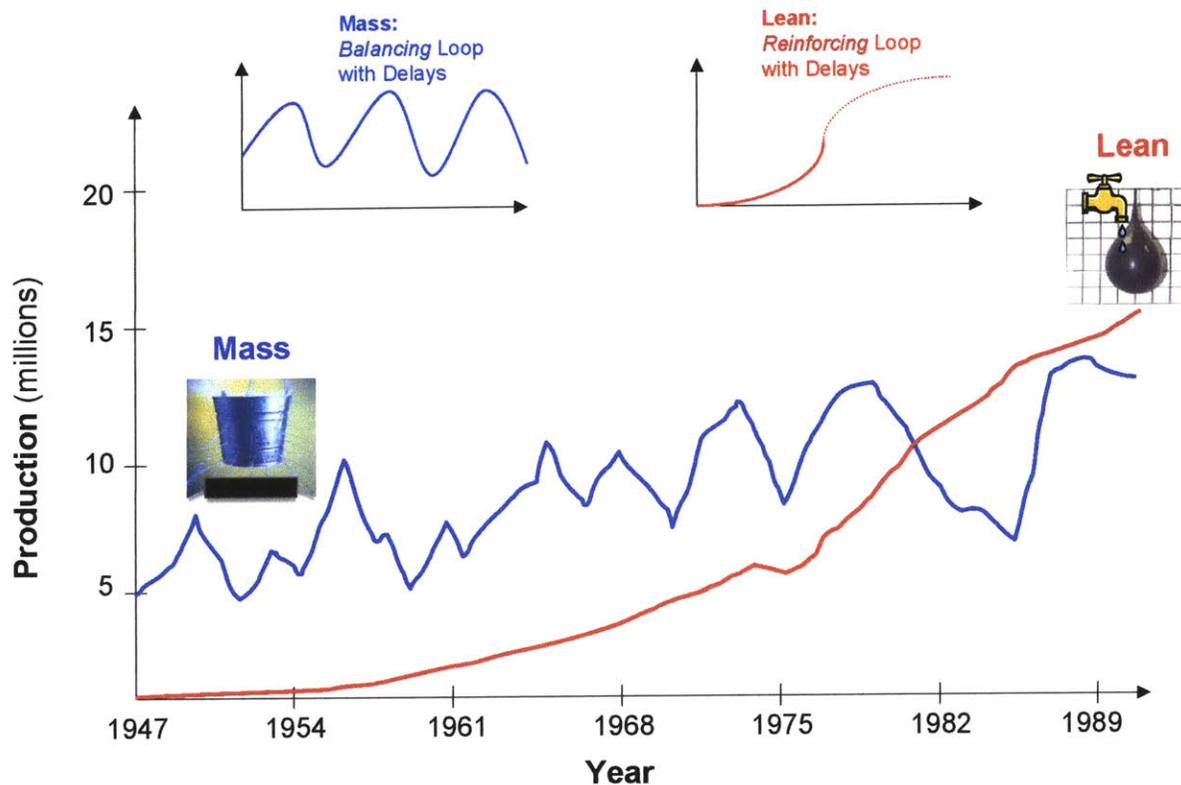


In order to test the above hypothesis about the dynamic nature of the different architectures, we return to the dataset of a dynamically complex industry: the international automotive industry.²⁸³

When one looks at the growth of an industry like the automotive industry for example, one can see the underlying dynamic modes of the mass model (as typified by the U.S. producers who were “born” in the pre-dominant design era) and the lean model (as typified by the Japanese producers who were “born” in the post-dominant-design era). As can be seen in figure 9.7 below, the mass producers are locked into an oscillating mode characterized by a balancing loop with delays, while the lean producers are still on an exponential growth pattern characterized by a reinforcing loop.

²⁸³ Again, data is taken from Womack, Jones & Roos, *The Machine that Changed the World*, 1990.

Figure 9.7: Dynamic Modes of Mass and Lean Enterprises in the Automotive Industry

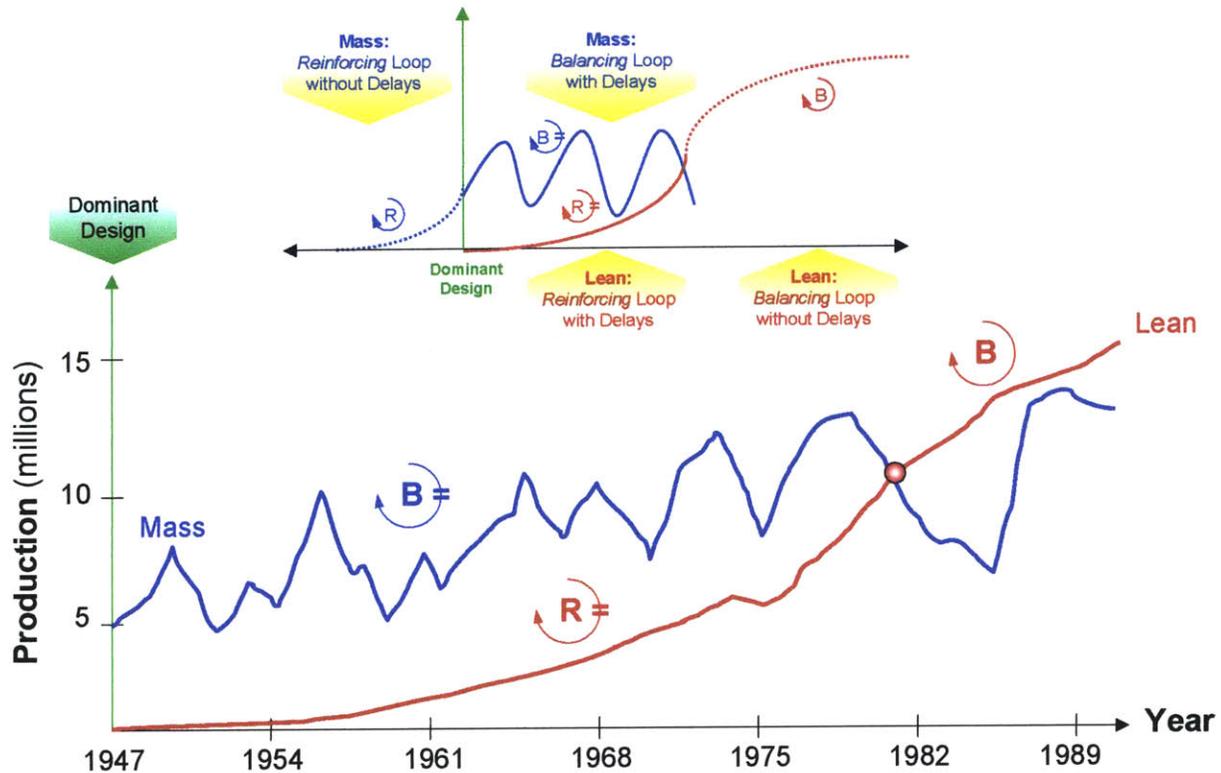


A more careful examination of the above dynamic response of the two architectures reveals something deeper in the dynamic structure and behavior. As shown in figure 9.8 below, the mass enterprise transitions from *reinforcing* behavior *without delays* to *balancing* behavior *with delays* (causing oscillation) after the dominant design. Conversely, the lean enterprise (which begins its life near the emergence of a dominant design) begins its life with *reinforcing* behavior *with delays* (i.e. restrained growth), and transitions to *balancing* behavior *without delays* (suppressing oscillation).

As both types of architectures each begin to grow (separated in time by almost 50 years), one can see the effects of delays on positive, reinforcing (exponential) growth in the form of “flatter” growth curves in the case of the lean architecture.

Note also that it appears that the lean enterprises in the automotive industry have reached an inflection point in their growth trajectory around 1980, beyond which balancing (or goal-seeking) behavior has taken hold.

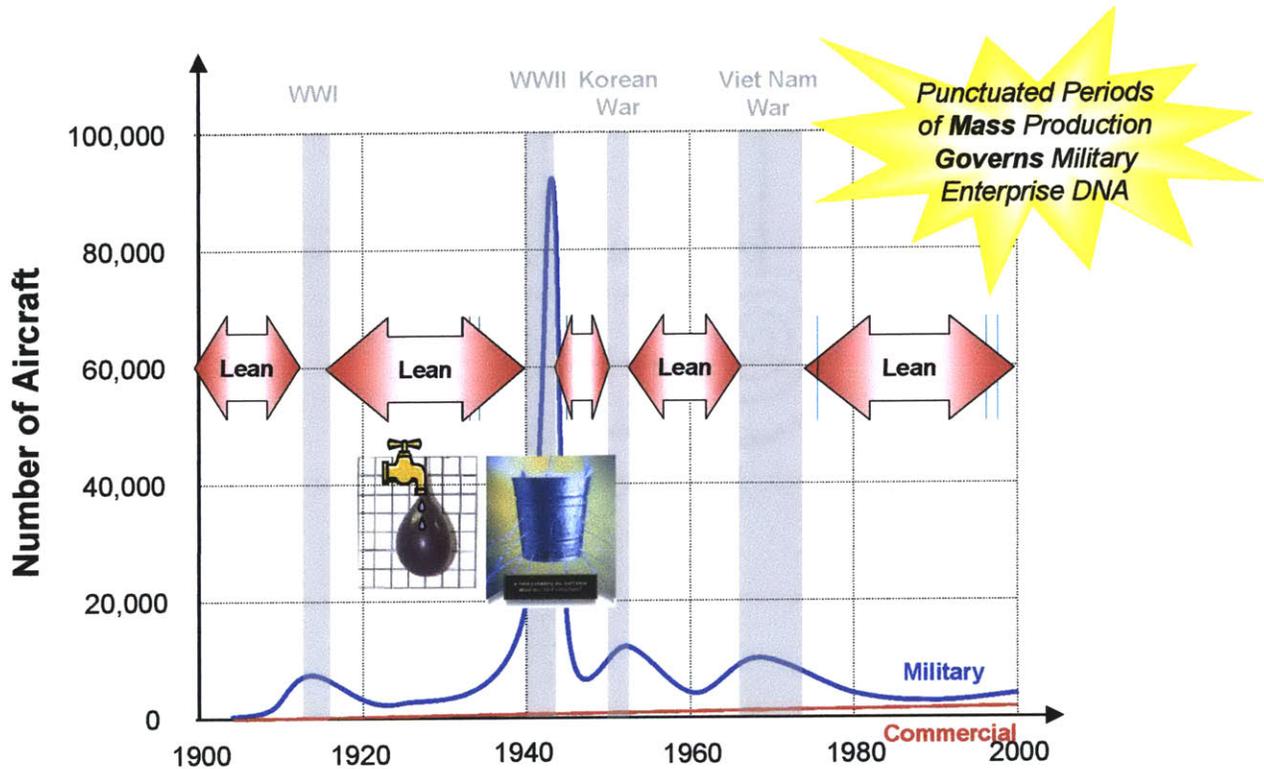
Figure 9.8: The Structures Behind the Architectures



In order to understand and apply the archetypal models of mass and lean, let us next study the case of military and commercial airplane production. As can be seen in figure 9.9 below, the total output of *commercial* airplanes over the past 100 years has been growing relatively slowly with total annual production today varying between of around between 500 and 1,000 aircraft. This is in response to a steady growth in demand of passenger-kilometers of around 5% per year.

The total output of *military* airplanes exhibits wildly varying behavior, as annual output in between wars averages around 5,000, while wartime production can range from a doubling to more than a ten-fold increase. Such variable conditions are not well-suited for the elastic balloon of the lean metaphor, which is designed to control and accommodate slow, incremental growth. Any doubling (let alone quadrupling) in annual output will simply exceed the breaking strength of the fabric of the enterprise, as human capital is not only stretched beyond its limits, but more importantly, there is the inevitable downsizing which is unwanted in the lean world.

Figure 9.9: Lean vs. Mass Strategies in the Aircraft Industry



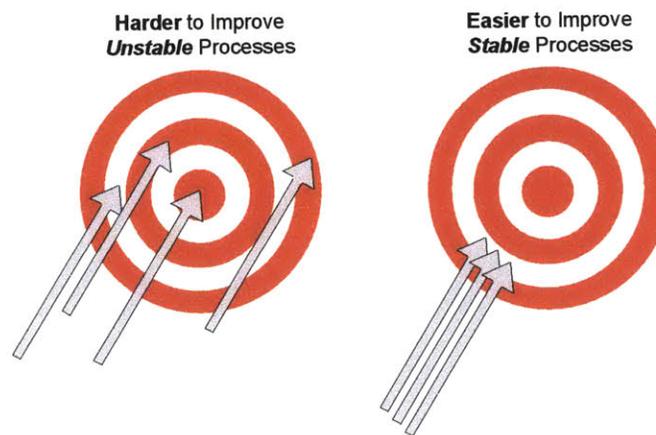
It is clear therefore that different strategies for the commercial and military sectors may be warranted. As the military sector must be prepared for punctuated periods of extremely rapid growth (both in terms of technology development and production rates), followed by significant downsizing and longer periods of relatively stable growth, the mass archetype may be the most effective. The commercial sector on the other hand has much less volatile production and technology needs, and therefore, a lean archetype may prove to be more suitable.

One could argue that in the military sector, the optimum strategy is actually a mass archetype during war followed by a lean archetype in times of peace. One should consider however the incredibly long time it took for true mass producers like *Ford*, *GM* and *Boeing* to program their mass DNA as well as for the very long time that it took lean producers like *Toyota* and *Southwest* to grow their lean DNA.

9.4 Enterprise Goal #1: *Stability*

The primary importance of stability or the elimination of *mura* was famously noted by Deming in the well-known principle of statistical process control (SPC).²⁸⁴ As shown in figure 9.10 below, the proverbial marksman with a stable but off-center shot has an easier path to improvement than the less stable, but higher scoring marksman.

Figure 9.10: Deming’s Stability-Requirement in Improvement Processes

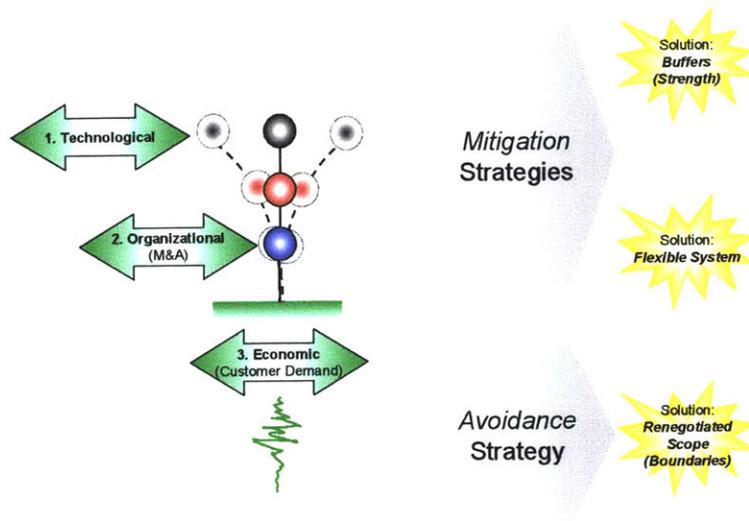


Cutcher-Gershenfeld and Rebentisch conducted empirical research in the aerospace industry that pointed to the existence of three classes of instability: technological, organizational and economic (as shown superimposed on the inverted cantilever value chain in figure 9.11 below).²⁸⁵ They have also identified three different solution archetypes ranging from adding system buffers in the simplest case, to making the system more flexible to finally redefining the boundaries of the system or “co-opting the environment”. These solution strategies (and others) will be discussed further later in this chapter.

²⁸⁴ Deming, W. Edwards, *Out of the Crisis*, Cambridge: MIT CAES, 1986.

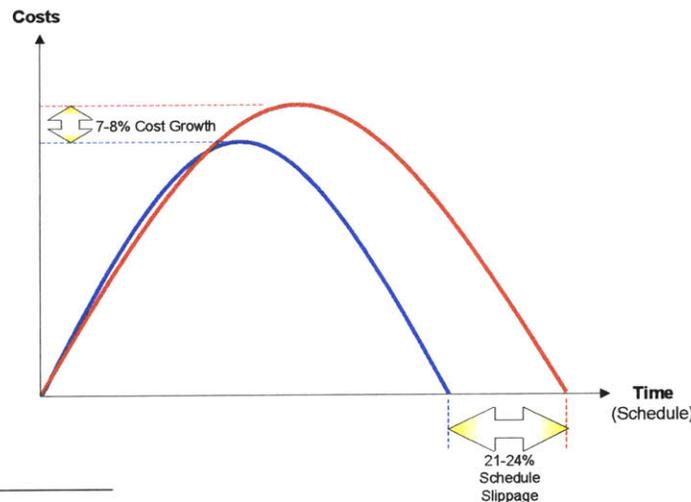
²⁸⁵ Cutcher-Gershenfeld, J., and Rebentisch, E. “The Impact of Instability on Complex Social and Technical Systems”, MIT Engineering Systems Division Internal Symposium, April 2002.

Figure 9.11: Three Sources of Enterprise Instability



Cutcher-Gershenfeld and Rebenitsch have also begun to capture the costs of these instabilities. As shown in figure 9.12 below, instability has been demonstrated to cause 7-8% annual cost growth and 21-24% overall schedule slippage in the aerospace industry²⁸⁶. These instabilities are caused by a number of sources, including changes in product demand and changes in customer requirements. It is well-documented²⁸⁷ for example that changes in customer requirements causes an expensive feedback rework cycle that extends planned schedules and cost estimates.

Figure 9.12: Effects of Instability on Cost and Schedule



²⁸⁶ Cutcher-Gershenfeld, J., and Rebenitsch, E. "The Impact of Instability on Complex Social and Technical Systems", MIT Engineering Systems Division Internal Symposium, April 2002.

²⁸⁷ Sterman, *Business Dynamics* (2001) and Lyneis et al., "Strategic Management of Complex Projects", 2001.

The effects of instability can be thought of using the metaphor of building castles in the sand. The challenge in business can be thought to be building the largest sand castle that is located the closest to the shoreline (with the waves being customer demand) as shown in figure 9.13 below.

Figure 9.13: Building Castles in the Sand

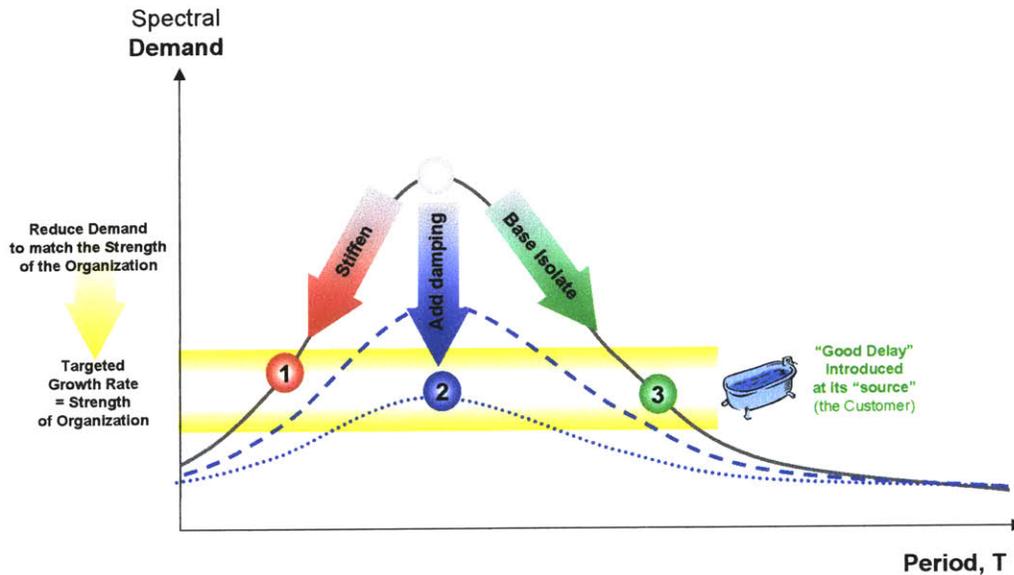


Those who build too close to the tide, find their enterprise periodically destroyed, only to have to rebuild. Those who build too far from the tide are too far from the customer. However, those few companies (like Toyota) who invest in stability first, build a dam near the shoreline, which simultaneously puts them as close as possible to the customer, while protecting them from the damage of market cycles. Even if they start with lower enterprise capabilities, over time they are given the chance to learn and improve.

9.5 Three Generic Enterprise Architectural Solutions

If a lean enterprise is characterized by the elimination of waste, inflexibility and variability, and it is achieved through the sequenced creation of stability, flow, takt and pull, then we can create a suite of architectural solutions which begin this process. I begin by defining three generic enterprise architectures which ensure stability in a dynamic environment. As shown in figure 9.14 below, these are: Stiffening, Damping and Base Isolating.

Figure 9.14: Three Generic Enterprise Architectural Solutions



From the theory of structural dynamics, stiffening acts to increase an enterprise’s clockspeed (i.e. decrease its natural period of vibration) and move its dynamic response away from the resonant energy of the dynamic input. This is usually appropriate for relatively short period, fast clockspeed enterprises. In the “building as enterprise” metaphor, this is like adding a vertical brace between floors.

From the theory of system dynamics, stiffening is the addition of cross-links between subsystems. As Graham points out, “this increases the ability of one subsystem to communicate with another by adding a direct link between them.”²⁸⁸

From the theory of structural dynamics, damping acts not to (significantly) modify an enterprise’s clockspeed, but to increase the amount of energy dissipative capacity of the enterprise. This is usually appropriate for intermediate period enterprises at or near resonance. In the “building as enterprise” metaphor, this is like adding a vertical damper between floors.

From the theory of system dynamics, damping is the addition of a minor positive loop with a delay. As Graham points out, “If a minor positive loop with a delay is added around a level already on an oscillatory loop, the added loop forms another pathway through which disturbances in the level can

²⁸⁸ “Principles on the Relationship Between Structure and Behavior of Dynamic Systems”, Alan K. Graham, MIT PhD thesis, 1977, pg. 161.

propagate back to the level. When the additional disturbance returns to the level, it retards the movement of the level towards its steady-state value, which results in a longer period and more stable oscillations.”²⁸⁹

From the theory of structural dynamics, base isolation acts to decrease an enterprise’s clockspeed and move its dynamic response away from the resonant energy of the dynamic input. This is usually appropriate for relatively long period, medium clockspeed enterprises. In the “building as enterprise” metaphor, this is like inserting a flexible, highly dissipative element at the base of the building. We will discuss this in detail in the next sections.

From the theory of system dynamics, base isolation is the reduction to an effectively-first-order system. As Graham points out, “An oscillatory system can be made not to oscillate by changing it to an effectively-first-order system, so that when the remaining effective level passes through its equilibrium value, the entire system does so, and no further movement occurs.”²⁹⁰

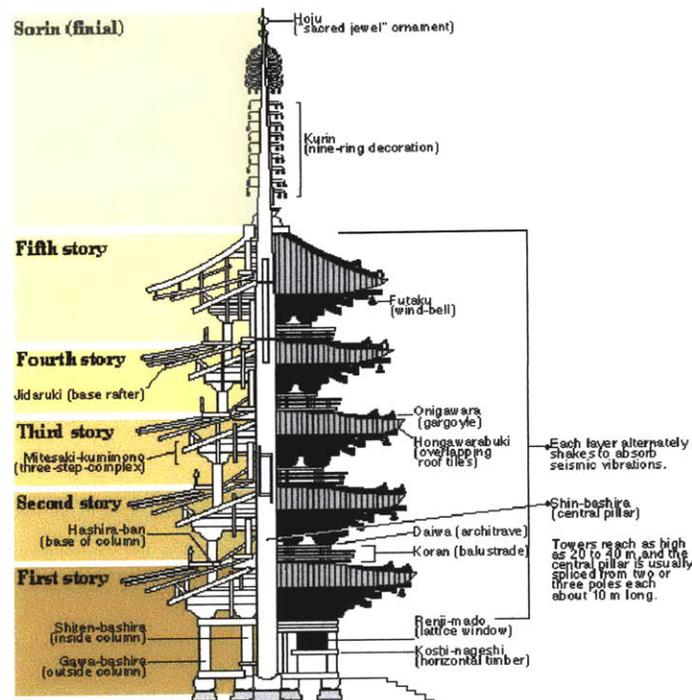
9.6 From *Physical Enterprises* to *Human Enterprises*

In chapter one, I began with an assertion about the earthquake survival of such physical enterprises as the Japanese pagodas. The secret to their excellent performance when subjected to dynamic input lies in the structural design and dynamics of the pagoda itself. Most buildings are comprised of columns which are supported on the ground via foundations and which rise up through the structure supporting all of the floors. As can be seen from a cross-section of a pagoda in figure 9.15 below, the central column, known as a “shinbashira” appears to serve this function.

²⁸⁹ “Principles on the Relationship Between Structure and Behavior of Dynamic Systems”, Alan K. Graham, MIT PhD thesis, 1977, pg. 322.

²⁹⁰ Ibid, pg. 321.

Figure 9.15: The Secret to the Survival of the Pagoda as a Physical Enterprise



However what the ancient master builders intuitively understood was that in order to withstand powerful earthquakes, the trick is not to try to be strong in the face of oncoming vibrations, with the central column rigidly attached to the ground. The secret lies in the exact opposite solution: allow the earth to shake below the building, and let the superstructure flex and bend. In this way, the shinbashira was actually a massive central “column” that was not connected to the ground at its base, but in fact was hung from the roof of the pagoda, and the weight of the shinbashira and the rest of the pagoda was in fact supported by the perimeter columns.

This counter-intuitive solution allows the dynamics of the physical enterprise to work with, not against the dynamics of the earthquake. When the earth begins to shake from side to side, the shinbashira acts as a large pendulum changing the dynamic characteristics of the structure, making it more flexible (i.e. giving it a slower clockspeed). In this way, the pagoda’s fundamental period of vibration was shifted away from the damaging frequencies of vibration of the earthquake ground motion.

Next, I shall explore other ways to transform the dynamics of a physical enterprise like a building, in order to protect it from the potentially damaging dynamics of the environment, before we move onto translating these principles to human enterprises.

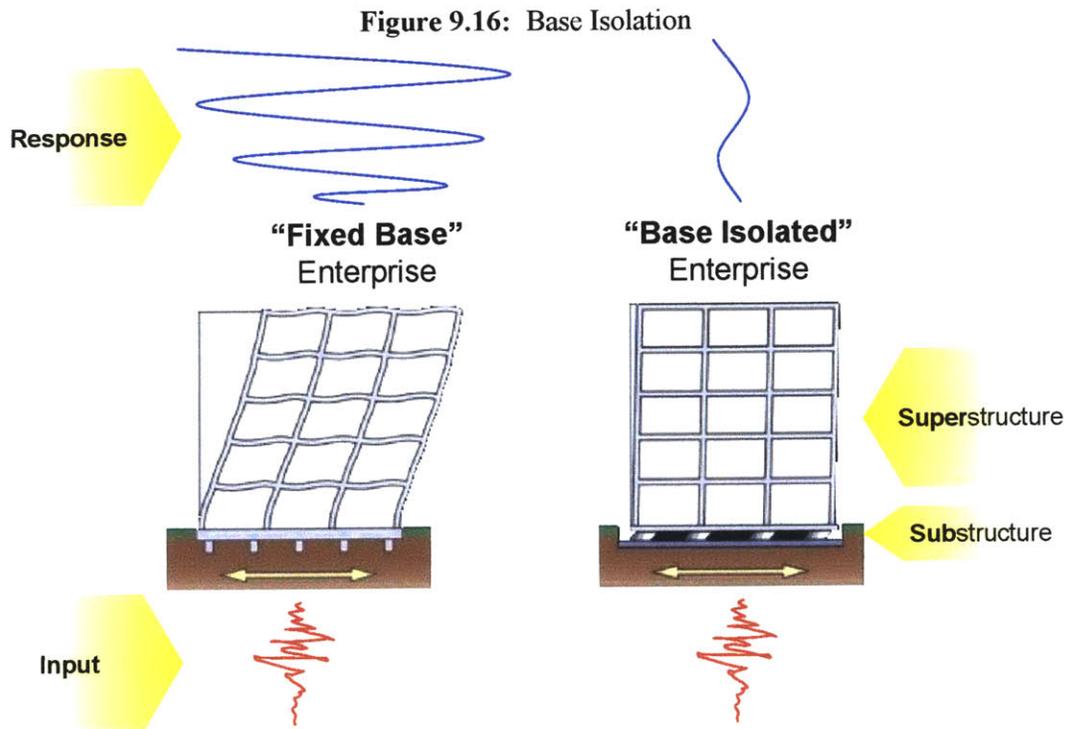
9.7 Enterprise “Base Isolation”

The goal of Base Isolation is to significantly modify the key dynamics of the enterprise, by driving the fundamental modes of vibration (or dominant feedback loops) away from the energy in the input signal. Graham noted that, “An oscillatory system can be made not to oscillate by changing it to an effectively first-order system, so that when the remaining effective level passes through its equilibrium value, the entire system does so, and no further movement occurs”.²⁹¹ An effectively first-order system is, “A system in which the response time of one level significantly exceeds (perhaps by a factor of ten) those of other phase-lag subsystems in the system, which thus effectively become gain elements with respect to the movements of the remaining level.”²⁹²

As can be seen from figure 9.16 below, a conventional multistory building (enterprise), rigidly attached to the ground (i.e. rigidly linked to the customer demand) will attract and amplify the motions of the earthquake (customer demand signal). As you can never know with certainty, the maximum customer demand, if you want to capture market share, you have to provide a building strong enough to survive the “maximum credible earthquake” (i.e. have the enterprise capacity available to survive the maximum customer demand). But as one can imagine, this is both expensive and wasteful.

²⁹¹ “Principles on the Relationship Between Structure and Behavior of Dynamic Systems”, Alan K. Graham, MIT PhD thesis, 1977, pg. 150.

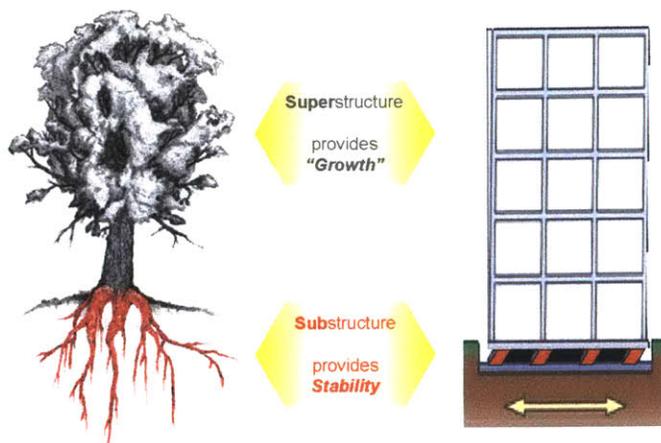
²⁹² Ibid, pg. 149



Enterprise designers must design two separate components to work together as a coherent system: the “substructure” (or base isolator level), and the “superstructure” level. Designers can take out the demand uncertainty by installing a base isolator under the building (i.e. at the interface with the customer). This limits and controls the amount of demand that can enter the enterprise, making it possible to take out wasted structure and capacity in the superstructure of the enterprise (i.e. define the weakest link and subordinate all others to it). A building on a base isolator in its substructure will greatly reduce the damaging oscillations in the superstructure.

Recall from chapter one that General Systems Theory notes that all higher-ordered (e.g. human) systems or enterprises have the concurrent goals of stability and growth. This architecture of substructure providing stability and superstructure providing growth potential is seen in various physical enterprise architectures as shown in figure 9.17 below.

Figure 9.17: Physical Enterprise Architectures



Although the isolator could in theory be located anywhere in the enterprise, the greatest benefit to the largest portions of the enterprise occurs when the isolator is located at the source of the vibration – at the customer interface with the enterprise. Within a functional organization, the location of this isolator would lie in the Marketing/Sales organization – a key to achievement of enterprise stability. In fact from an enterprise process point of view, the enterprise substructure is actually the underlying and enabling enterprise leadership processes which support the enabling infrastructure and lifecycle processes as shown in figure 9.18 below.²⁹³

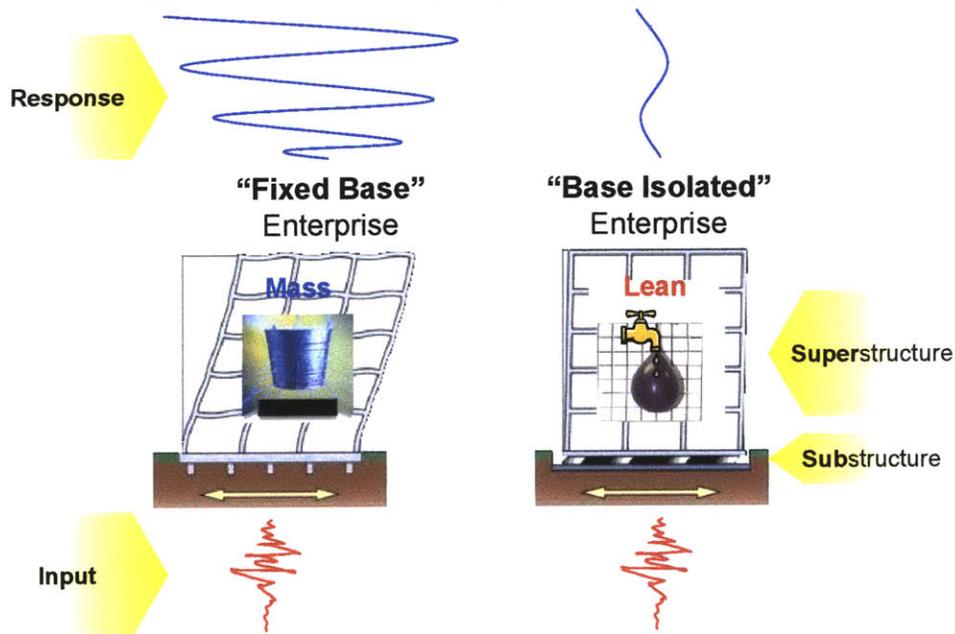
Figure 9.18: Enterprise Process Architecture & the Leadership Substructure



²⁹³ *Lean Enterprise Value*, Murman et al.

Let us observe that the fixed-base enterprise is analogous to the a mass-production enterprise, in that it tries to win the “Strength Game”, by providing all the capacity it takes to withstand the largest earthquake shocks. It takes the incoming oscillations and amplifies them. The base-isolated enterprise on the other hand is analogous to the lean-production enterprise, in that it limits that capacity to grow, thereby decoupling itself from the uncertainties of the marketplace. This is shown in figure 9.19 below.

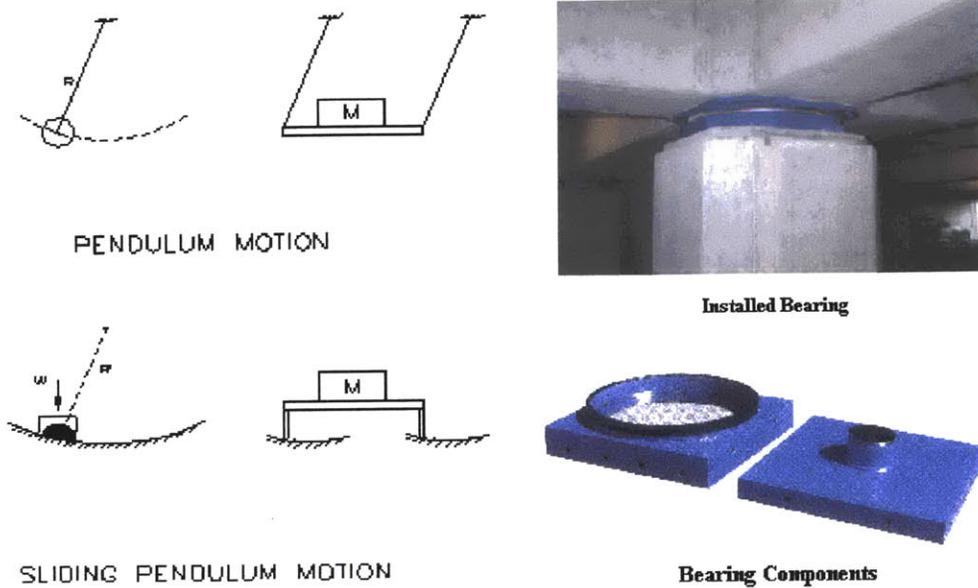
Figure 9.19: Fixed-Base (Mass) and Base-Isolated (Lean)



Before we begin to define the characteristics of a human enterprise isolation system, it would be instructive to quickly examine those of a physical isolation system. The system in question is known as the “Friction Pendulum System” (FPS)²⁹⁴ and it is used to protect buildings from earthquake ground shaking. As shown in figure 9.18 below, the FPS ‘tricks’ the superstructure that it is “hanging from the clouds”, so that it is isolated from the damaging ground motion. In reality, the kinematics of being hung from the clouds can be achieved more cost-effectively by resting the building in special curved “dishes” that simulate the dynamic motions of a pendulum as also shown in figure 9.20. As the superstructure gently swings from side to side, a small amount of friction absorbs or dissipates some of the earthquake energy.

²⁹⁴ From *Earthquake Protection Systems Inc.*, a system the author helped develop while a graduate student and researcher at the University of California at Berkeley.

Figure 9.20: Friction Pendulum Base Isolation System (source: *EPS Inc.*)

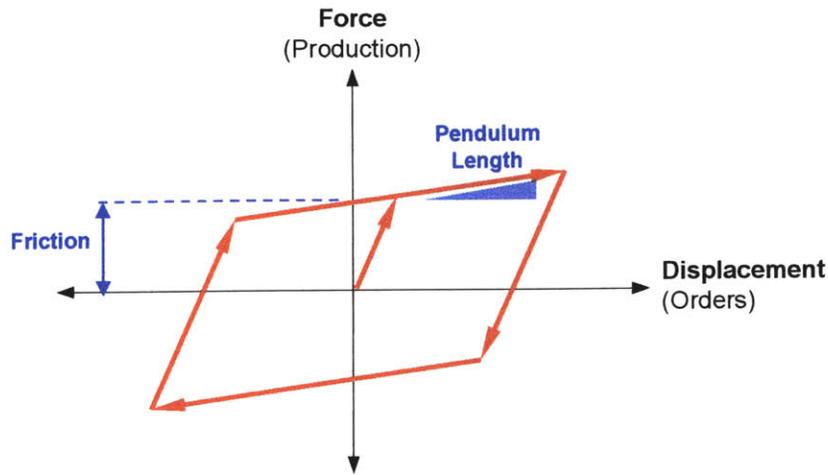


Basic Principles

The enterprise designer (or structural engineer in this case) only has to select two simple design parameters: the length of the pendulum (or equivalently, the curvature of the dish) and the amount of friction to completely alter and control the dynamic characteristics of the enterprise. The pendulum length defines the natural period of vibration of the supported superstructure, and the friction defines how much damping the enterprise contains. With this simple architecture, enterprise designers can therefore control and alter their enterprise's clockspeed to significantly reduce the dynamic demands on the enterprise superstructure therefore take costs out of the enterprise.

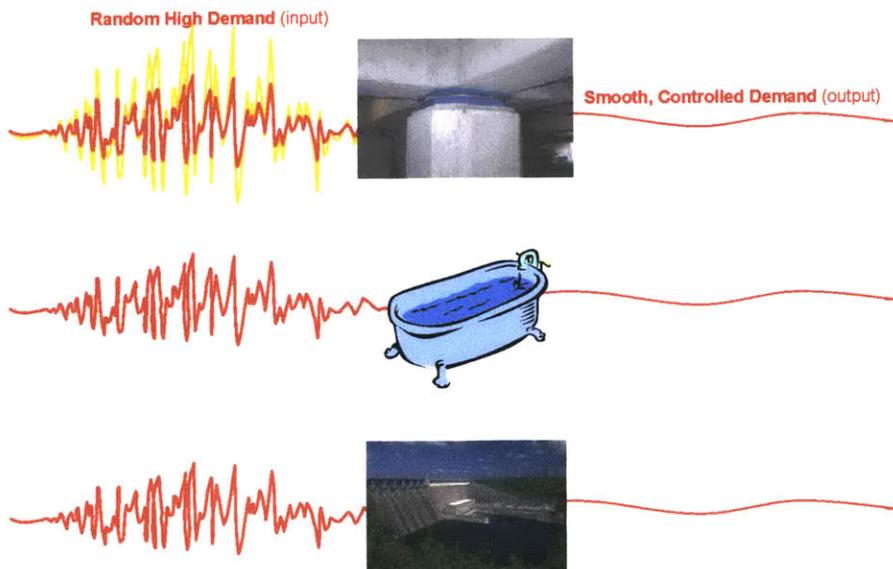
These two design quantities can be plotted on a graph representing the enterprise's hysteresis, or ability to absorb dynamic demand inputs without being damaged. Corporate hysteresis is therefore a good thing. As shown in figure 9.21 below, the horizontal axis is displacement of the isolator (or backlog of customer orders) and the vertical axis shows the force entering the superstructure (or the production requirements of the enterprise).

Figure 9.21: Enterprise Hysteresis



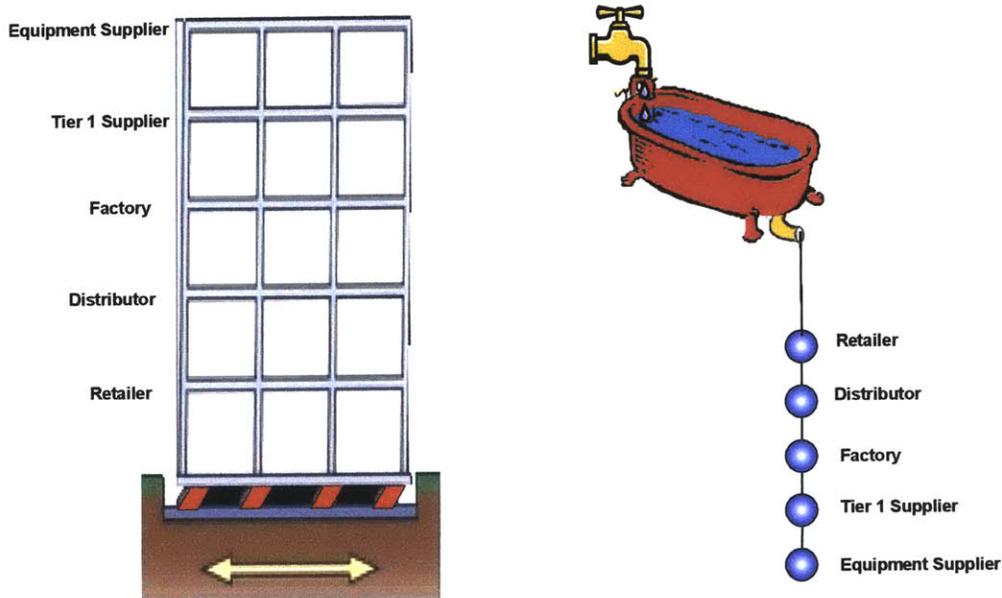
As we begin away from the physical parameters of structural dynamics and move closer toward organizational parameters, it may be instructive to map base isolation onto its equivalent metaphor in system dynamics: the bathtub. The bathtub represents a stock which accumulates things like orders, finished goods, etc. The enterprise architect using system dynamics therefore also has two design parameters to consider: the size of the bathtub (that is the amount of time the water is in the tub) and the size of the drain. As shown in figure 9.22 below there are many physical metaphors for creating stability in the “upstream” superstructure.

Figure 9.22: Base Isolation Metaphors



As shown in the pendulum analogy in figure 9.23 below, the base isolator is the entity closest to the customer that absorbs all of the variability and protects the rest of the enterprise from the variable demands of the market.

Figure 9.23: Base Isolation in Structural and System Dynamics



It is interesting to note that the “optimum” isolation system completely protects the superstructure ensuring that there is not oscillation. In the case of the FPS, this means having no friction and an infinitely long pendulum length (or zero curvature flat plate). In the case of the bathtub or dam, this means having an infinitely large bathtub without a drain. Note how stability is maximized in these cases, which is the goal of a closed system. However, open systems like corporate enterprises seek growth as a goal, therefore some optimum amount of earthquake shaking or bathtub drain flow is vital.

Note that although I have presented a structural/mechanical analogue for base isolation, there are other successful and equally-insightful applications from electronics, notably the field of control theory and the use of filters (high-pass, low-pass, etc.)²⁹⁵

²⁹⁵ Bose Amar G. and Stevens Kenneth N., *Introductory Network Theory*, 1965.

9.8 Base Isolation and the Theory of Constraints

Recall from chapter 3 (figure 3.10) the potentially interesting behavior that resulted from limiting the capacity of the enterprise. The “theory of constraints”²⁹⁶ argues that every enterprise has a constraint, and it is up to the enterprise designer to carefully select where and why she would like to position the constraint to control the behavior of the entire enterprise.

In the field of earthquake engineering, building designers can reduce the governing load case by an order of magnitude by introducing a “constraint” or fuse or isolator at the base of the building. When located at the base of the building, it is called base isolation. The base isolator acts to decrease the stiffness and increase the damping of the entire enterprise. In essence it significantly slows down the clockspeed of the enterprise – which may sound counter-intuitive and counter-productive. But this is a necessary condition that allows an enterprise to speed-up the clockspeed of the isolated superstructure.

As shown in figure 9.24 below, the theory of constraints well describes how to design an enterprise base isolation system. I will argue later that a lean enterprise in fact utilizes the theory of constraints philosophy in order to achieve sustainable business results²⁹⁷.

Figure 9.24: Enterprise Design and the Theory of Constraints



Identify the system’s constraint.
Decide how to **exploit** the system’s constraint.
Subordinate everything else to the above decisions.
Elevate the system’s constraint.
Don’t allow **inertia** to become the system’s constraint. When a constraint is broken, go back to step one.

²⁹⁶ *The Goal*, Eliyahu M. Goldratt and Jeff Cox, 1993.

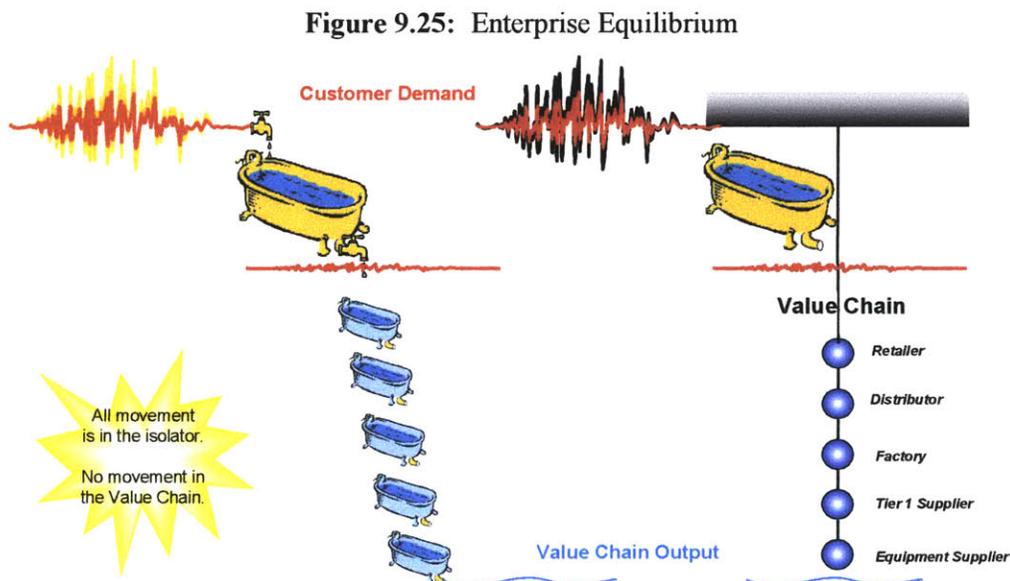
²⁹⁷ “The Theory of Constraints and Lean Manufacturing: Friends or Foes?”, Richard Moore and Lisa Schienkopf, 1998.

9.9 Little's Law and Enterprise Design

Metaphorically, the isolator can be thought of as a bathtub that collects the variable flows of the customers and allows a constant trickle to go through the drain at a rate (defined by the enterprise “gate-keeper”). If the flow throughout the entire isolated enterprise is constant, then the system is in equilibrium and Little's Law applies. Little's Law²⁹⁸ states that the time the water is in the tub (i.e. the Cycle Time) equals the amount of water in the tub (WIP) divided by the rate at which water is draining out (Throughput). Mathematically:

$$CT = WIP / TH$$

From Little's Law, we know that when constant rate of flow enters an enterprise, there will be no shaking of the bullwhip – i.e. the value chain cannot oscillate. If this is the case, there is considerable cost that can be taken of the entire superstructure. Sizing this enterprise's capacity then becomes trivial, as the size of the bathtubs (WIP) equal the time delay the water is in the tub (or in pendulum-speak, the length of the pendulum) times the throughput (which is constant in this case). The pendulum does not shake, the design of the enterprise is then governed by known, static forces as shown in figure 9.25 below.



²⁹⁸ *Factory Physics*, Wallace J. Hopp and Mark L. Spearman, 2000, pg. 223-226.

9.10 Managing to the *Signal*, not the *Noise*

What is noise to the CEO is signal to the day trader.²⁹⁹ A high-performance enterprise must distinguish between the two, and smooth out the noise using the appropriate techniques. Another way to describe this “base isolation” technique, is simply applying a filter to the “base” of the enterprise, i.e. between the customer demand and the chain of supply. This is actually an exponential smoothing technique that describes the decision maker’s tendency to gradually react to changes in information³⁰⁰. Decisions based on smoothed information do two things: actions are delayed, and fluctuations are filtered out. This allows people to manage to the signal, not to the noise. As Jay Forrester once noted, “people usually react too quickly and do too much. They forget that often the right advice is, “Don’t just do something, stand there.”³⁰¹

From an emotional point of view however, filtering out the noise is not easy to do. Turning away customer orders that exceed the planned growth limit of the signal requires long-term focus, courage and confidence. The opposite situation, i.e. continuing production in a downturn possibly requires even more courage. But the important ingredient that makes such “courageous” decisions easier is deep knowledge of the long-term market dynamics – which is why chapter 3 was so important. If it is known with great confidence that the market *will* return in 18 months for example, the intense short-term pressures to rapidly reduce variable costs will diminish, and the whole notion of “variable” costs will take on a new meaning.³⁰²

As shown in figure 9.26 below, when an enterprise is subjected to a step input, there is a spectrum of ways to react and respond. If one stock is added, the first order dynamics govern and the enterprise is quick to *react*, but slow to *respond*.

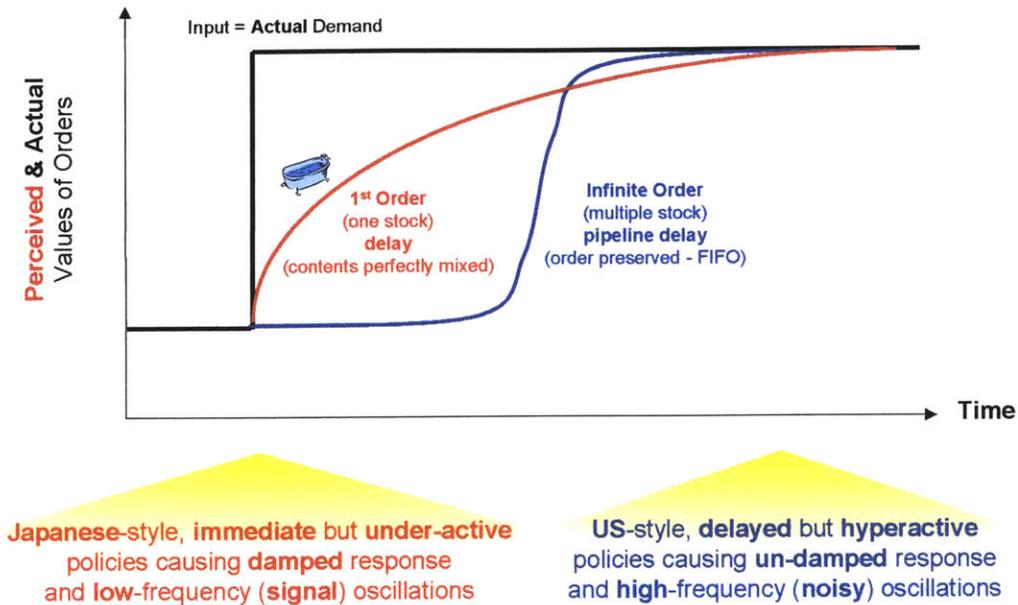
²⁹⁹ Foster, Richard and Kaplan, Sarah, *Creative Destruction: Why Companies That are Built to Last Underperform the Market – and How to Successfully Transform Them*, Currency, 2001, pg. 326.

³⁰⁰ “Generic Structures: Exponential Smoothing”, Kevin M. Stange, MIT System Dynamics in Education Project, document D-4782, 1999.

³⁰¹ Keough, Mark and Doman, Andrew, “The CEO as Organization Designer: An Interview with Prof. Jay W. Forrester”, *The McKinsey Quarterly*, 1992 Number 2, pp. 3-30.

³⁰² Thanks to Noel Nightingale of MIT’s *Lean Aerospace Initiative*, who brought this insight.

Figure 9.26: Decisions to React-Respond



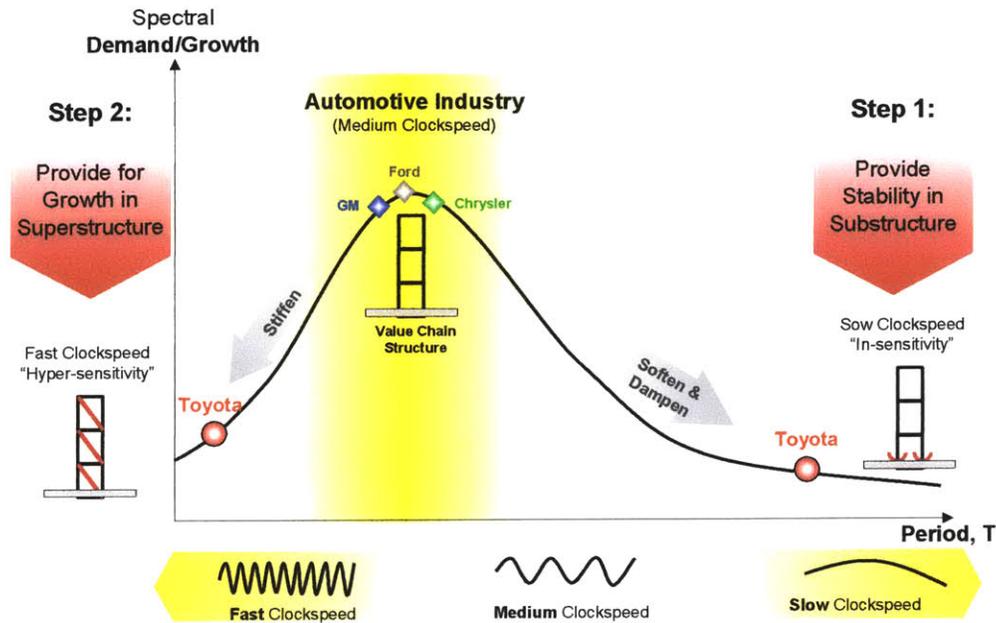
Companies like *Toyota* and *Southwest Airlines* have this type of decision architecture. The physics of the architecture produces a pendulum having fast clockspeed with damping – ideal for managing to the signal. On the other hand, if infinite stocks are added, multi-ordered dynamics govern the enterprise. This is known as a “pipeline delay”, in which the enterprise is slow to *react* but quick to *respond*.

9.11 The Fable of the Lean Enterprise: Tortoise vs. Hare

Controlling the dynamic response of an enterprise is essential in achieving excellent performance. World-class “lean” companies like *Toyota* and *Southwest Airlines* achieve this through enterprise base isolation. Base Isolation’s “going slow to go fast” philosophy is illustrated in figure 9.27 below.

Again, we are looking at an Enterprise Response Spectrum, this time for the automotive industry. As we can see, most automotive companies have clockspeeds that cluster around the medium clockspeed range. Therefore, if the customer demand increases, there is an opportunity for significant amplification (i.e. growth). In response to this potential for high growth, *Ford*, *GM* and *Chrysler* have all constructed massive, non-reactive enterprises that define their clockspeed.

Figure 9.27: Ideal Enterprise Architecture – the idea



Toyota, on the other hand has taken the dynamic design into their own hands as an endogenous variable that they control. Their approach is two fold. First, introduce a flexible, damped substructure that significantly reduces the clockspeed of the enterprise. This pushes them far out to the right of the response spectrum, where the growth potential is lower. Their enterprise base isolator therefore delivers much lower and less variable demands into their value chain. Second, this allows them to reduce the waste and over-capacity in their superstructure, making it much faster clockspeed and more responsive to the customers. In this way, they are attacking the three evils of Muri (variability), Mura (inflexibility) and Muda (waste)³⁰³. They are simultaneously slow and “insensitive” to growth opportunities, so that they can make themselves fast and hypersensitive to the immediate demands of customers.

McKinsey and Company recently published a document defining “lean” in which it identifies the sequential activities of how to achieve lean: Stability, Flow, Takt and Pull³⁰⁴. It is clear from this dynamics-based definition of Lean, that the achievement of a flexible, damped substructure, is

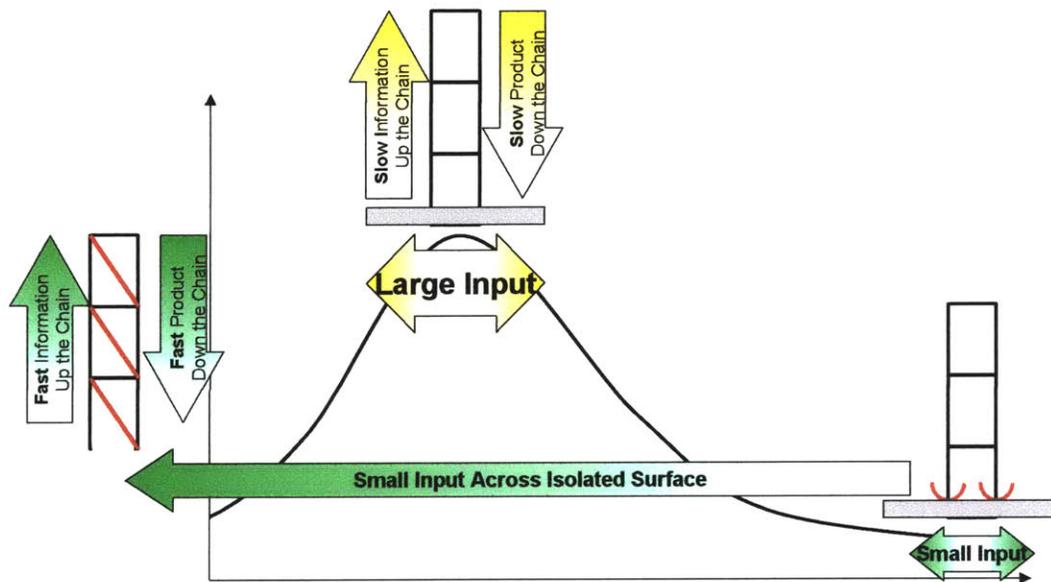
³⁰³ *Toyota Production System*, Taiichi Ohno, 1978.

³⁰⁴ *McKinsey & Company*, Operations Strategy and Effectiveness Practice document, August 2002.

fundamental in achieving a lean enterprise – it provides the stability. The following step of achieving a stiff, responsive superstructure corresponds to the final three tasks of flow-takt and pull.

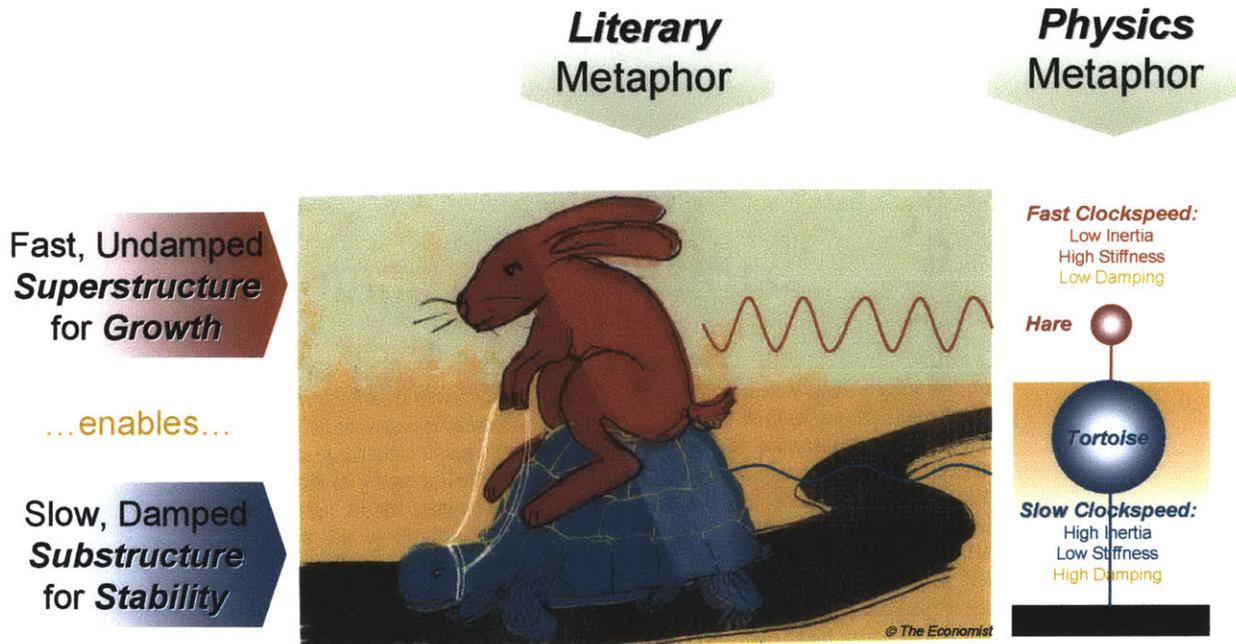
Figure 9.28 below summarizes the strategies. For *Ford & GM*, build a stiff un-damped substructure supporting a flexible superstructure. For *Toyota*, it is a flexible damped substructure, supporting a stiff reactive superstructure.

Figure 9.28: Ideal Enterprise Architecture – the mechanics



We are now in a position to compare the literary metaphor of the tortoise and the hare with the physics-based metaphor of the pendulum analogs for the tortoise and the hare. As shown in figure 9.29 below, the winning strategy exhibited by world-class enterprises like *Toyota* seems to be a counter-intuitive combination of tortoise *and* hare – explaining why such organizations seem to defy the laws of physics. The answer seems to be, that like the ancient master builders of pagodas, these enterprises master dynamic complexity explicitly through their architectural design.

Figure 9.29: The Structure of the Tortoise *and* the Hare



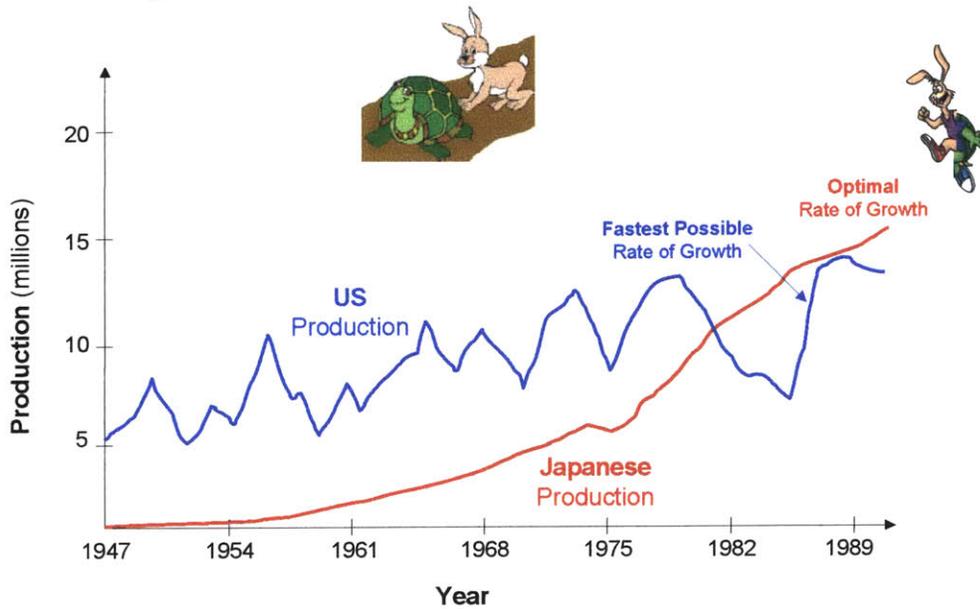
9.12 Enterprise Goal #2: *Growth*

Finally, the results of these automotive strategies are illustrated in figure 9.30 below. Like the proverbial hare, US automotive companies chase the fastest possible growth, which is faster than the optimum rate of growth. Their enterprise architectures therefore lack stability, creating boom & bust, hire & fire, unstable learning cycles.

Like the proverbial tortoise however, the Japanese automotive companies first define their optimum growth rate that maximizes the long-term learning within their value system. They base isolate beyond this level, which allows them to continuously improve, remove waste, and generally increase their speed, so that they “go slow to go fast”. They are practicing the simultaneous yin and yang of being both tortoise *and* hare by defeating the tyranny of the “or”.³⁰⁵ The long-term results demonstrate the effectiveness of this strategy of controlling the dynamics of your enterprise for maximum competitive advantage.

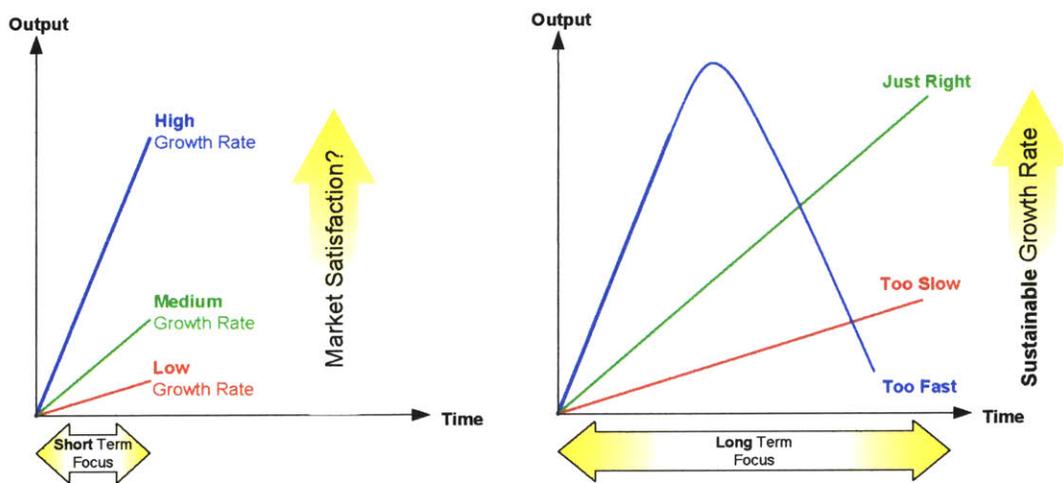
³⁰⁵ Collins, James C. and Porras, Jerry I., *Built To Last: Successful Habits of Visionary Companies*, Harper Business Essentials, 1994.

Figure 9.30: The Behavior of the Tortoise *and* The Hare



The notion of an optimum growth rate is discussed in the literature³⁰⁶⁻³⁰⁷, and is well-documented in business simulations, like the “*People Express*” flight simulator³⁰⁸. *People Express* essentially demonstrates that an airline’s rapid growth strategy can lead to excessive long-term strains in its human capital leading to reduced service quality, loss of market share, inability to fund rapid capital expenditure expansions leading to the collapse of its share price and its eventual downfall (see figure 9.31 below).

Figure 9.31: Optimum Growth Rate



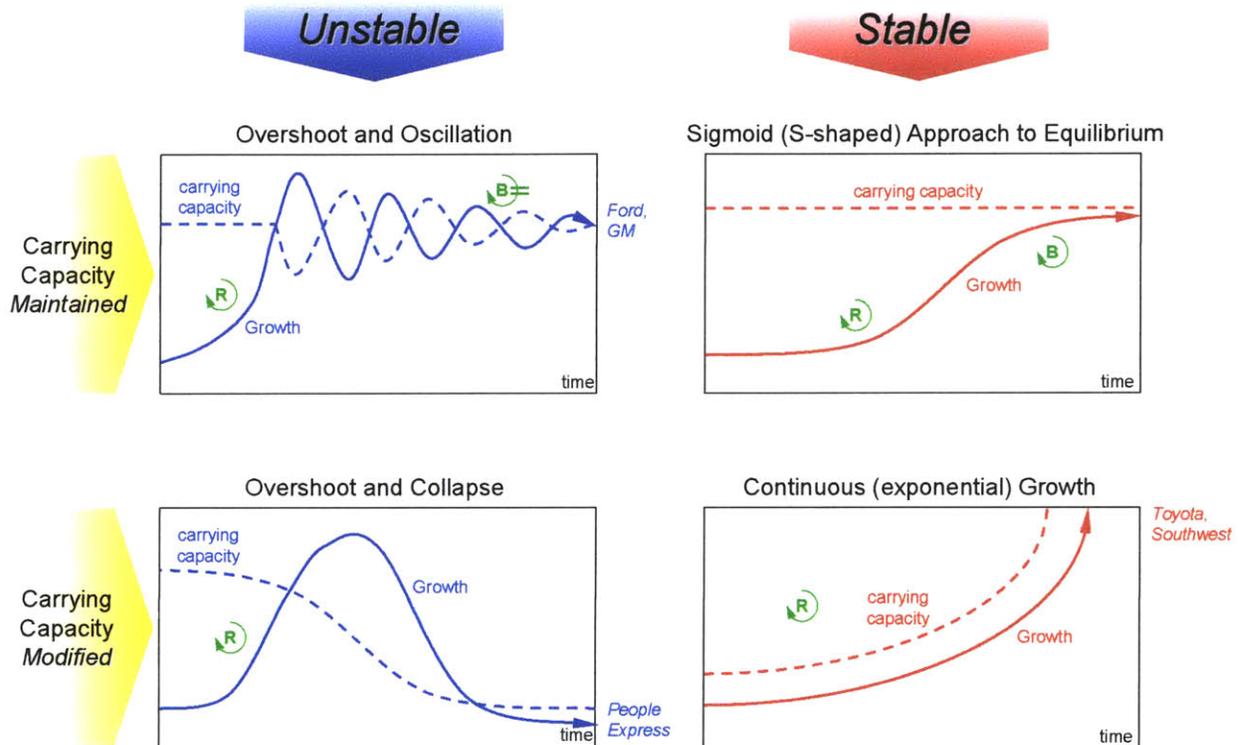
³⁰⁶ *Competitive Strategy Dynamics*, Kim Warren, 2002.

³⁰⁷ PRAT methodology from: R.C. Higgins, *Analysis for Financial Management*, 7th edition, Irvin, McGraw-Hill.

³⁰⁸ *People Express Management Flight Simulator: simulation game, briefing book, and simulator guide*. J.D. Serman, 1988.

Enterprises which grow fast must have commensurately fast adjustment or control times to ensure that they do not exceed their organizational “carrying capacity” (i.e. their “breaking strength”), otherwise instabilities will ensue as shown in figure 9.32 below.

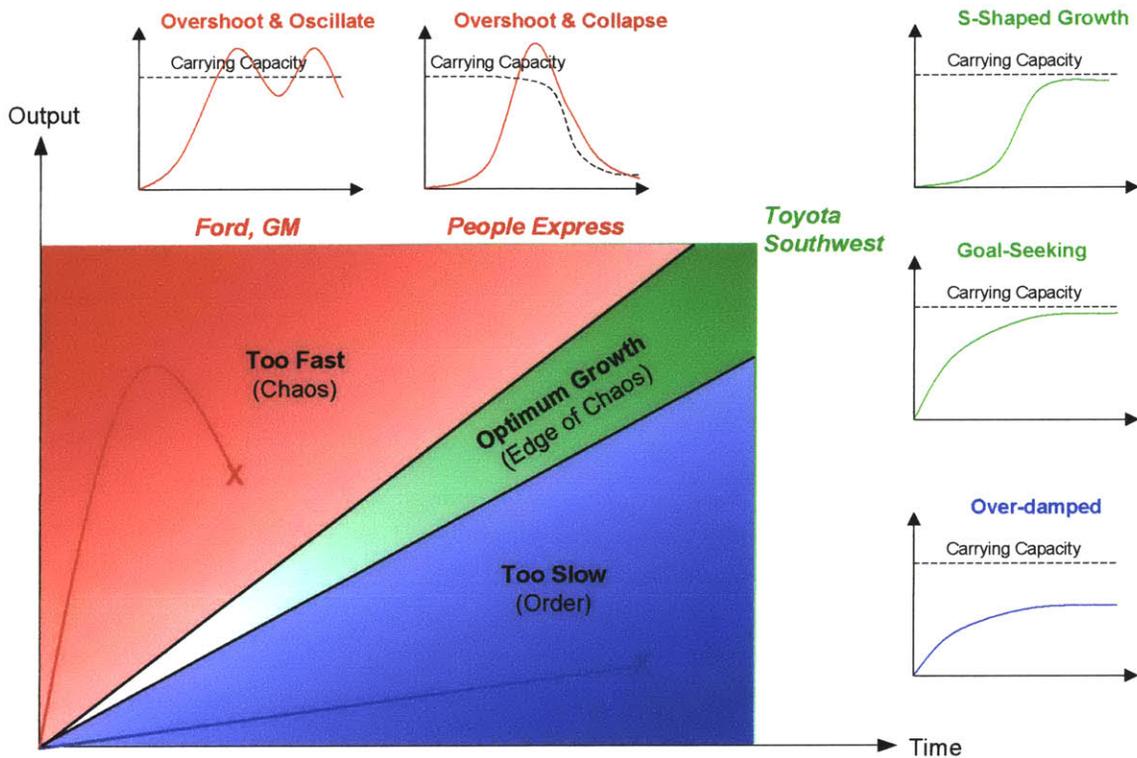
Figure 9.32: Demand-Capacity Reference Modes



As shown in figure 9.33 below, companies that grow too slowly typically operate in an environment with too much order, making them susceptible to acquisition or takeover. Companies that grow too quickly, typically operate in an environment with too much chaos, making their survival difficult. The optimum growth rate occupies a relatively narrow band of successful growth – an area that some researchers have called “The Edge of Chaos”.³⁰⁹

³⁰⁹ Waldrop, M. Mitchell, *Complexity: The Emerging Science at the Edge of Order and Chaos*, Simon & Schuster, New York, 1992.

Figure 9.33: Managing at the Edge of Chaos



Economist, Kenneth Boulding, in his proposals for a General Systems Theory postulated the existence of “equilibrium rates of growth such that higher (or lower) growth rates may seriously disturb the functioning of the system even to the point of its collapse and death.”³¹⁰ In fact, he points out evidence from the plant world that too rapid growth rate kills the organism – some very effective weed killers have been developed based on this principle, using growth hormones.

Other economists Harrod and Domar suggest that there are “appropriate” rates of growth for a system which will yield continuous full employment. They go on to suggest that such continuous equilibrium rate of growth may be impossible because consumption, for example, does not keep pace with the rise in capacity which causes accelerated growth on other elements of the economy like investment.³¹¹⁻³¹²

³¹⁰ Boulding, Kenneth E. “Towards a General Theory of Growth”, *The Canadian Journal of Economics and Political Science*, Vol. 19, No. 3, (Aug. 1953), pg. 339.

³¹¹ Harrod, R. F., “An Essay in Dynamic Theory”, *The Economic Journal*, Vol. 49 (March, 1939), pp. 14-33.

Finally, there is a body of research in the system dynamics community which postulates that harmful effects occur when growth exceeds the “carrying capacity” or organizational “breaking strength”. Jay Forrester noted in *Urban Dynamics* that a city might choose to limit its own growth and preserve the quality of life for its residents.³¹³ Later, Forrester points out in *World Dynamics* that neither population growth nor pollution growth per se is the problem for global sustainability, but rather economic growth or the incessant increase in consumption per person.³¹⁴

9.13 Corporate Eating Disorders: *Bulimic Lean* and *Anorexic Lean*

As we have seen, the optimum enterprise growth rate is less than the maximum possible growth rate. Those enterprises that chase the fastest possible growth rate (i.e. the “hare” mentality) suffer from what I refer to as a corporate consumption disorder, known as bulimia or the binge and purge (e.g. hire and fire) cycle. What is the purpose of negative growth - you cannot shrink your way to greatness. There is no lean without learning, and there is no learning without stability. In fact, there are direct disincentives towards lean continuous improvement in an environment of pending mass-layoffs. People resist improvement if the results will be loss of their own jobs.

In another “base-isolated” enterprise, we see in figure 9.34 below that *Southwest Airlines* grew at a rate much slower than the maximum possible, which enabled it to protect its employees to learn slowly and steadily and apply this to customer satisfaction and low costs.

³¹² Domar, Evsey D., *Essays in the Theory of Economic Growth*, Oxford University Press, 1957.

³¹³ Forrester, Jay, *Urban Dynamics*, 1969.

³¹⁴ Forrester, Jay, *World Dynamics*, 1971. Observation made by Peter Senge in class discussion, Fall 2003.

Figure 9.34: Southwest Airlines' Slow Rise to the Top

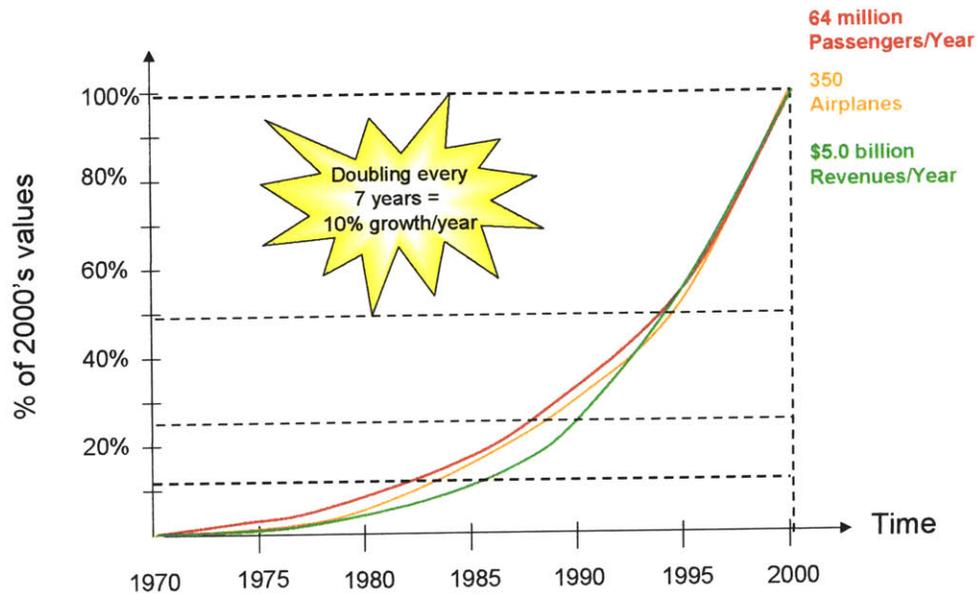
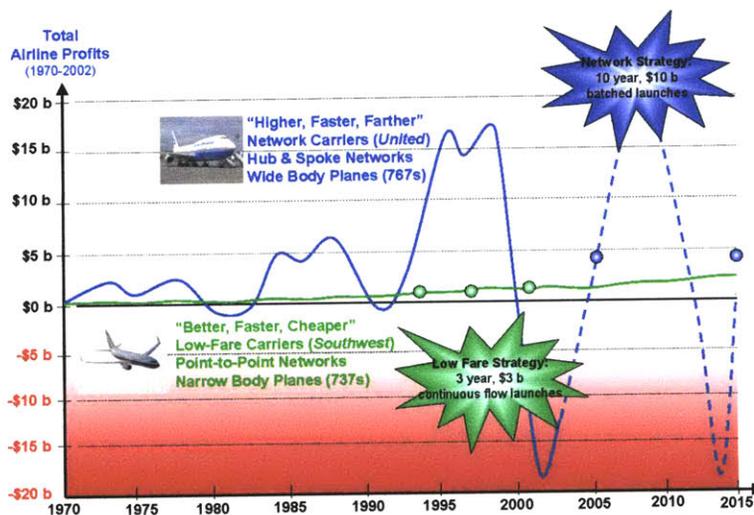


Figure 9.35 below shows how this slow steady growth maps onto the airline profitability figure that we saw in chapter 7. As we will later see, *Southwest*, which ignores the stock market demands for insatiable growth is greatly rewarded with market capitalization equal to the next ten largest competitors.

Figure 9.35: Profitability of Southwest Airlines' vs. the Competitors



The other type of corporate consumption disorder is “anorexic lean”, in which companies starve themselves of critical nourishment, driven by measures like Economic Profit, which as previously discussed, encourage harvesting behavior or “milking” the business.

9.14 Enterprise Goal #3: *Interaction (Learn to Lean, Lean to Learn)*

In fact, we can now discover what sort of enterprise can exist downstream of a smooth, predictable flow of information and product throughout the enterprise at the optimum rate (i.e. that which maximizes the building of capabilities).

Recall from chapter 4 that one of the drivers of capabilities, which in turn drives resources, which in turn drives sustained competitive advantage is learning. Senge notes that over the long run, superior performance depends on superior learning.³¹⁵ The base isolation metaphor that helps understand this is a dam upstream of a city as shown in figure 9.36 below. Note that the dam, (the base isolator) that decouples the highly variable customer demand does not allow the city downstream to be overwhelmed or underwhelmed (starved) of the ability to generate electricity – a metaphor for learning.

Figure 9.36: Damming Demand to Create an Optimum Learning Environment



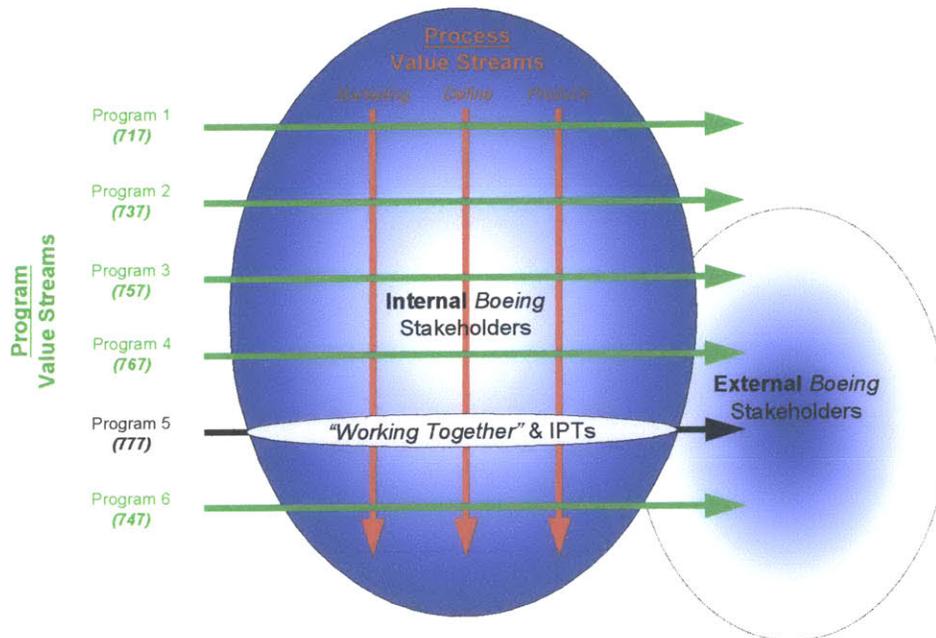
9.15 Architecting *Boeing's* Enterprise

Having established some of the principles and heuristics of the Lean Enterprise, we can now begin to understand how they are applied at *Boeing*. First, it is important to recognize where *Boeing* has made significant steps in achieving this vision. As shown in figure 9.37 below, *Boeing's Working Together* philosophy, together with its *Integrated Product Teams* (IPTs) illustrate how the design-build process can integrate across the three core business processes³¹⁶ or internal functions of marketing, define and produce.

³¹⁵ Senge, Peter, "The Leader's New Work: Building Learning Organizations", *MIT Sloan Management Review*, 7 Fall 1990.

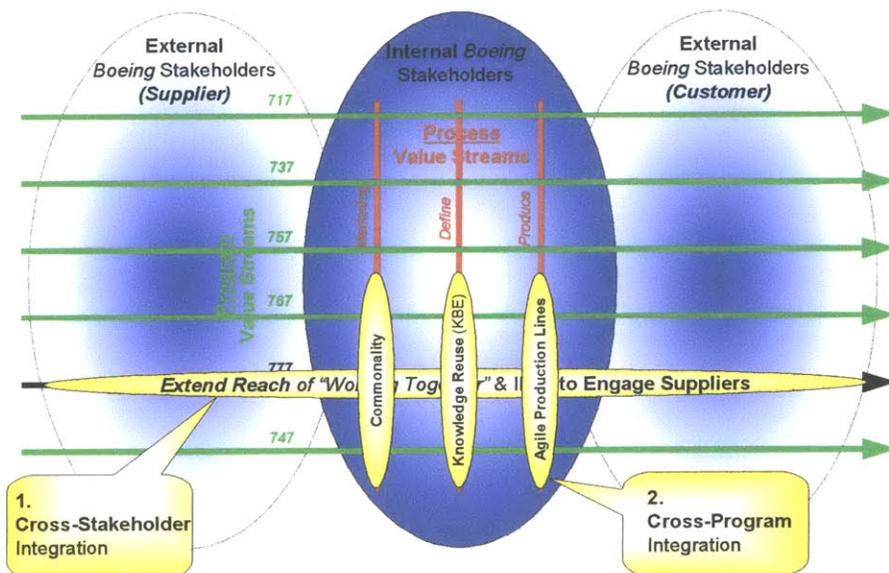
³¹⁶ Hagel III, John and Singer Marc, "Unbundling the Corporation", *Harvard Business Review*, August 2000.

Figure 9.37: Boeing's Integrated Product Teams



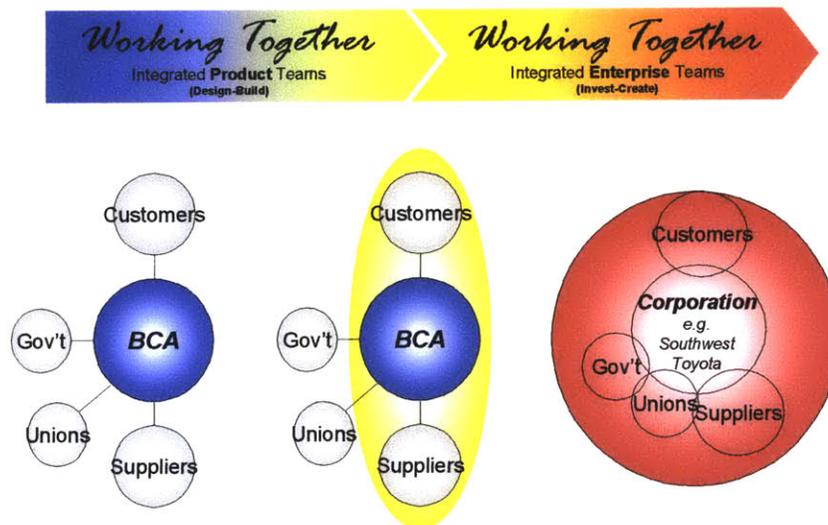
Beyond this, the 777 airplane program of the 1990's extended the range of the *Working Together* philosophy to reach out into the extended enterprise to include both Customers and Suppliers as shown in figure 9.38 below. Additional efforts have been made to attempt to integrate across product platforms in all three primary functional areas: Product Commonality in the marketing offering, Knowledge Reuse (e.g. 3-Dimensional Model-Based Definition and Knowledge-Based Engineering) in the define organization, and Agile Production Lines (with multi-product moving lines) in the produce organization.

Figure 9.38: Boeing's Product-Focused Integrated Enterprise Teams



Further efforts in this direction can be made to leverage the success of *Working Together* and IPTs in breaking down the barriers between the historically-disparate functions not just at the product level, but at the leadership or executive level. As shown in figure 9.39 below, a further evolution can be made by extending the *Working Together* philosophy to more explicitly engage more of the important stakeholders, including “the Hill” (i.e. Government and Labor Unions) and “The Street” (i.e. Investors) to form Integrated Enterprise Teams which attempt to break down the barriers between historically-disparate functions of capital suppliers or investors and value suppliers or the corporation.

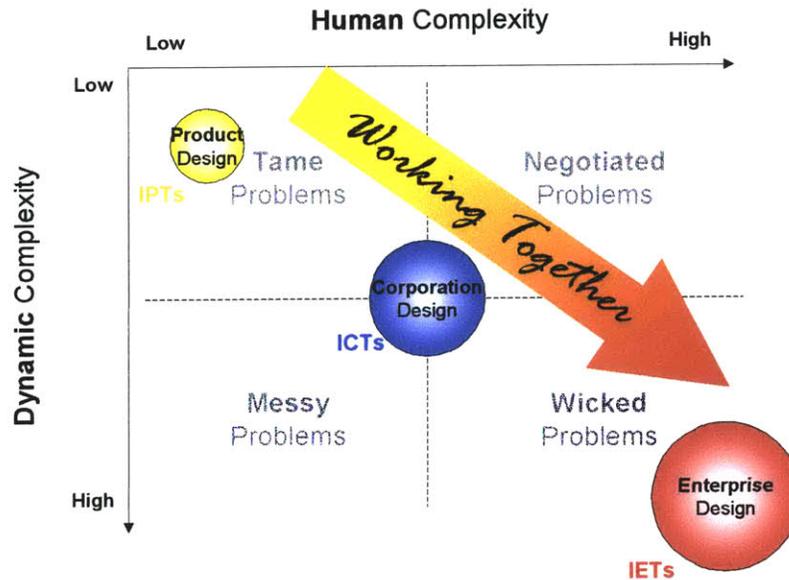
Figure 9.39: Boeing’s Integrated Enterprise Teams



This evolution can be depicted in figure 9.40 below which describes the architecture required to solve the class of “wicked problems” that was introduced at the beginning of this thesis. Given the dynamic complexity inherent in the industry, a lean or “systemic” enterprise architecture offers competitive advantage over traditional architectural forms which emphasize “divide and conquer” functional optimization and is characterized by “boundedly rational” of its management. As Russell Ackoff noted, “If each part of a system, considered separately, is made to operate as *efficiently* as possible, the system as a whole, will not operate as *effectively* as possible”.³¹⁷

³¹⁷ Russell Ackoff, *Ackoff’s Best: His Classic Writings on Management*, 1999, pg. 18.

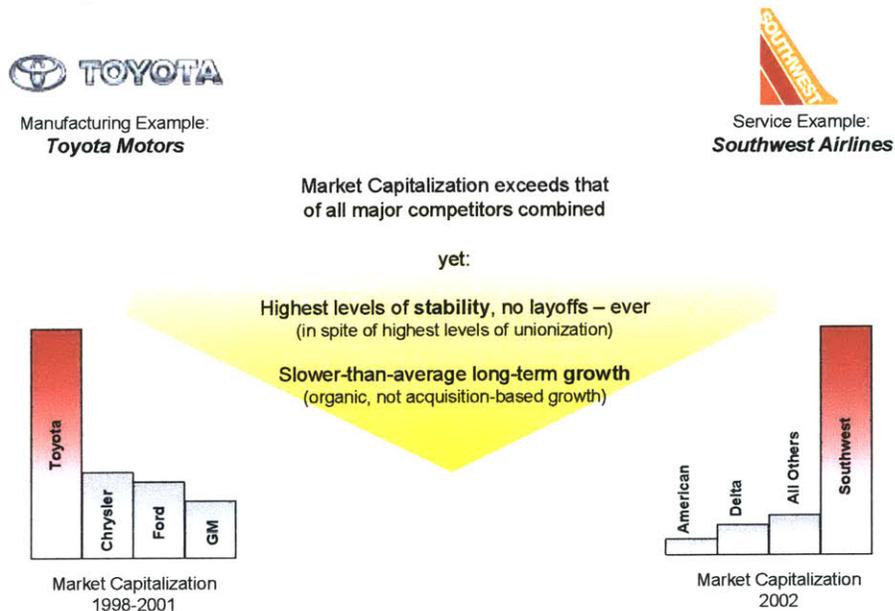
Figure 9.40: Integrated *Enterprise* Teams, the Solution to “Wicked” Problems



9.16 World-Class Enterprises: Defying the Laws of Organizational Physics

In an attempt to demonstrate the viability of such organizational architectures, I briefly draw a comparison to two world-class lean enterprises, one (*Toyota*) representing manufacturing and one (*Southwest Airlines*) representing services sector enterprise as shown below in figure 9.41.

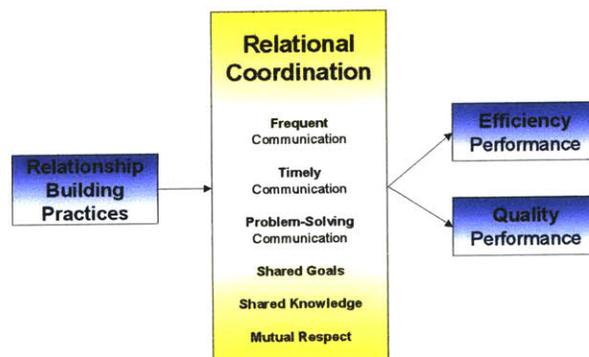
Figure 9.41: World-Class Examples of Integrated *Enterprise* Teams



It is clear that uncommon corporate performance can be achieved through the counter-intuitive enterprise designs. *Toyota* and *Southwest Airlines* have both achieved stock market capitalizations greater than the sum of all of their major competitors in recent years through the adoption of lean enterprise architecture.

Their success lies in the counter-intuitive notions of extending the boundaries of their respective enterprises to include the those stakeholders which can influence shareholder value, and then work to build long-term win-win relationships with them. As such, they have taken the counterintuitive steps to ensure no layoffs in the 50 and 30 year corporate histories of their companies amidst industry norms quite to the contrary. They have also demonstrated the courageous restraint by growing (largely) organically at the rate which can sustain learning within their core strategic assets, their people. This rate, which has been approximately constant at 10% over the lives of their corporations is substantially lower than the maximum possible growth rate that the markets demand. They have designed into their “integrated enterprise teams” (IETs) a base isolation fuse which mandates that they manage to the signal of the customer markets and not the noise of the capital markets. The irony is that they are highly valued by those same capital markets, that it is in their enterprise architecture to ignore. They recognize that maximization of shareholder value is achieved via management of stakeholder value. For *Southwest Airlines* this has been achieved via the establishment of “relational coordination”³¹⁸ across the enterprise, as shown in figure 9.42 below.

Figure 9.42: *Southwest Airline’s* “Relational Coordination”



³¹⁸ Gittel, Jody Hoffer, *The Southwest Airlines Way: Using the Power of Relationships to Achieve High Performance*, McGraw-Hill, 2003.

As can be seen, the elements of this “relational coordination” do not appear to be significantly different from *Boeing*’s “Working Together” principles. In fact, the prime difference is that *Southwest* has been successful in leveraging its “relational coordination” outside its corporate boundaries to its key stakeholders (e.g. labor unions).

For *Boeing* to engage in a continued evolution toward a lean enterprise, the potential benefits to the enterprise and therefore to the shareholders could be significant. A first order approximation of the reversal of market share slippage of around 2% per year (which was cited in figure 1.13 as the *raison d’etre* for this thesis) could result in net revenue increases of \$500 million per year. The elusive, yet crucial property of Stability, would allow *Boeing* to reap the benefits of its world-class Flow, Takt and Pull successes. Although the work presented herein relies on understanding dynamic complexity and using *systems thinking* to arrive at insights into the nature of the structural problem, the real challenge lies in the translation of such insights into actions, via *systems action* in the way that *Toyota* and *Southwest Airlines* have built their respective world-class enterprises

9.17 Enterprise Retrofitting

As the principles of enterprise design allow us to “predictively architect enterprises”, this is obviously useful for new or “green field” enterprises. The reality however is that the majority of such design will take place on existing or “brown field” enterprises.³¹⁹ In the realm of physical enterprises, this is analogous to the principles of earthquake-resistant design of buildings. While command of such knowledge allows designers to create sophisticated, elegant or merely robust buildings, the vast majority of work for earthquake engineers lies in the seismic retrofitting of existing buildings, as these are the most deficient enterprises. As in human enterprises, this is far more challenging than working with a blank sheet of paper, as human *inertia* (like its physical counterpart) resists such changes.

³¹⁹ In the *Lean Aerospace Initiative*’s recent “Transition to Lean” work, I note that the operative word is “transition”, implying that existing enterprises need to be “retrofitted” to meet the demands of a new environment.

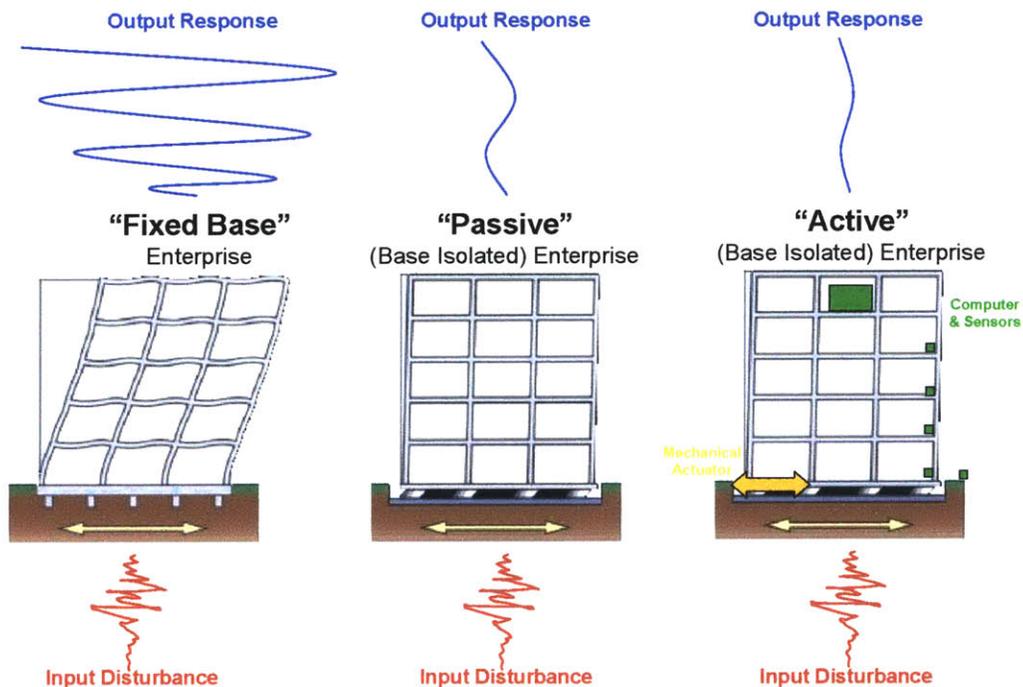
In fact, it is in the area of “retrofitting” that some of the more sophisticated enterprise design solutions (like base isolation) first emerged. It seems that necessity is truly the mother of invention.

9.18 “Active” Control Solutions

The enterprise design solutions discussed so far have been “passive” control systems. This means that once they are designed they have the same structural characteristics throughout the life of the enterprise. In addition, they sit passively awaiting the incoming dynamic disturbance and respond as designed to it.

There is a more sophisticated class of enterprise design solutions known as “active” control as shown in figure 9.43 below. In this case the system participates actively in its own design as information about the incoming dynamic disturbance (or about the structural response) is sensed and feedback controllers modify the dynamic properties of the enterprise in real time to minimize or control the effect of the input disturbance. Such active control systems require an energy source to run the enterprise’s “brain, nervous system and muscles”.

Figure 9.43: *Actively Controlled Enterprise*



An active system is typically much more expensive than its passive cousin and there are heuristic rules of thumb for relative performance levels of physical enterprises like earthquake-resistant buildings. Typically, the benefit of going from a conventional physical enterprise to a passively controlled enterprise is a ten-fold reduction in demand with an associated 10% increase in initial enterprise costs. The benefit of going from a passively controlled enterprise to an actively controlled enterprise is an additional two-fold reduction in demand with an additional 10% increase in initial enterprise costs. Therefore, due to lower initial costs, simplicity, reliability and diminishing marginal performance returns, most passively-controlled enterprises win the cost-benefit analysis over active control.

9.19 Complex Adaptive Enterprises

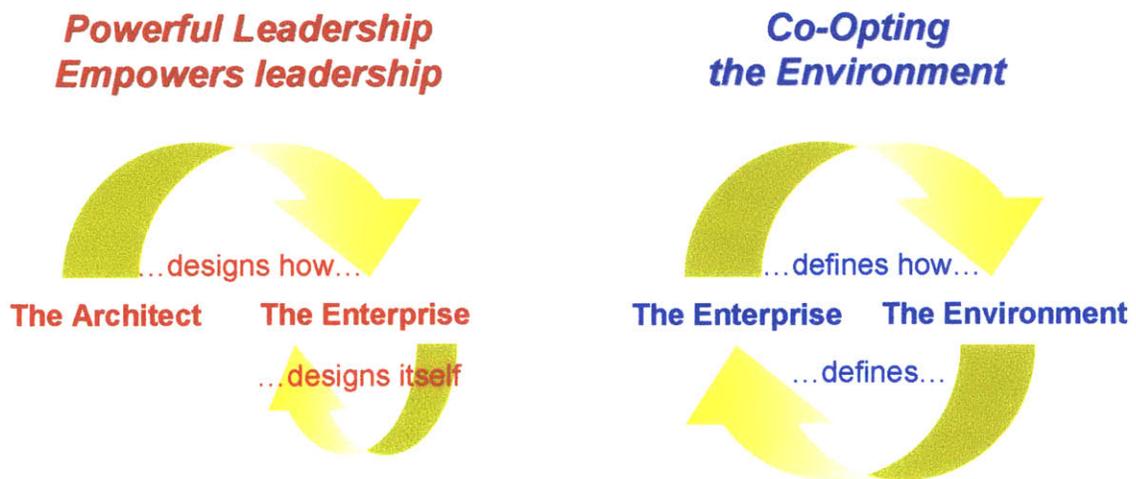
We began this work with a discussion of General Systems Theory of the 1950s, and we shall end it with a brief discussion of its successor, Complex Adaptive Systems (CAS) of the 21st century. The hallmark of complex systems is adaptability and emergence, self-organization and continuous improvement.³²⁰ While this work has focused on developing the science of enterprise design, one of the remaining topics touches on the lifeblood of the design process – that is the art of enterprise design. When faced with the question: “Is enterprise design a top-down or a bottom-up activity?” “Is it a self-conscious or unselfconscious activity?” “Is it rigid and deterministic or flexible and emergent?” I offer that in each of these questions, it is both.

As is seen in the archetypal cases of *Toyota* and *Southwest*, the “enterprise architects” were not self-conscious, top-down, command-and-control, deterministic, designers – but neither did these successful enterprises arise spontaneously from a pure bottom-up environment. It is the premise of this thesis that such *complex adaptive enterprises* are the result a feedback in which very strong leadership (or effective architecting) designed how the enterprise would design itself. In a sense, “powerful” leadership empowers leadership. This leads to distributed decision-making.

³²⁰ Amaral and Ottino, “Complex Systems and Networks: Challenges and Opportunities for Chemical and Biological Engineers,” *Elsevier Science*, 17 September 2003.

In addition, enterprise architects establish another important feedback – namely the ability for the enterprise to define how the environment defines the enterprise. This “loose coupling” or “cooption of the environment” demonstrates one of the most important design activities of the architect – namely the definition of the boundaries of the system. The example illustrated throughout this chapter is the optimum growth rate for the enterprise, which for *Toyota* was defined by the rate at which its workers could experiment, learn and improve and for *Southwest*, was defined by the rate at which they could hire the best people who could maintain the culture of “fun” and customer service. In both of these cases, the vision of the enterprise lead to growth rates that were constraints on the growth opportunities that were available in the market. Both feedbacks are shown in figure 9.44 below.

Figure 9.44: The Role of Design Leadership in Complex Adaptive Enterprises



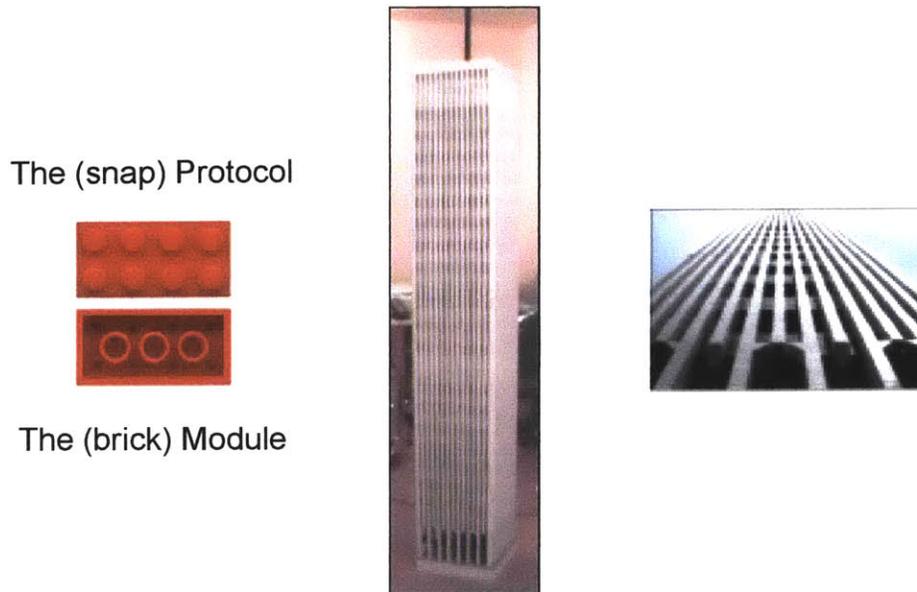
As socio-technical researchers observed when decoding the DNA of the Toyota Production System³²¹ and biological researchers observed when decoding the DNA of complex biological and engineered systems,³²² architects used very simple “rules” or protocols which allowed the enterprise to evolve and adapt itself at the lowest levels. A strong analogy can be made with the “inventor” of the

³²¹ Spear and Bowen, “Decoding the DNA of the Toyota Production System”, *Harvard Business Review*, September-October, 1999.

³²² Csete, Marie & Doyle John, “Reverse Engineering of Biological Complexity,” *Science*, Vol. 295, 1 March 2002.

Lego toys who defined a simple but powerful “snap” protocol along with the bricks as basic modules which allowed generations of physical enterprises to be designed as shown in figure 9.45 below.

Figure 9.45: Enterprise Protocols and Modules (Rules and Tools)



9.20 Chapter Summary

In this chapter, I introduced the concept of “[enterprise base isolation](#)” as a potentially highly effective means to control the dynamics of an enterprise to its benefit. The physics of base isolation is rooted in the [theory of constraints](#), whereby the enterprise leader explicitly defines and designs the [bottleneck policy](#), to achieve stability in the enterprise. I then explain how to define this policy, which entails injecting flexibility and damping into the enterprise at its “substructure” which allows the “superstructure” of the enterprise to be made more efficient.

From this, I argue that this physics-based policy can be seen as a scientific definition of a “Lean Enterprise”. Using the laws of enterprise physics, I describe “lean” as the eradication of [waste](#), [inflexibility and variability](#) and I note that the way to implement lean is through [stability, flow, takt and pull](#). I observe that world-class lean enterprises like *Toyota* and *Southwest Airlines* expertly utilize enterprise base isolation to their great benefit.

Chapter 10: Conclusion

10.1 Lessons & Generalizations

The purpose of this thesis was to consider enterprise design in conditions where dynamic complexity was important. As such, the commercial aerospace industry has provided a good source of research, and specifically *The Boeing Company*, as a dominant leader for many years has provided a rich platform to study. This thesis argued that *Boeing's* enterprise architecture, which has been responsible for its near-century long dominance is markedly different that the enterprise architecture of its current competitor *Airbus*. This thesis attempted to compare and contrast these two architectures and how each deal with dynamic complexity. While the emphasis of this thesis was not on which architecture is better in absolute terms, the focus was more on exploring the structural differences between architectures and acknowledging that *structure drives behavior*, making relative enterprise performance contextual and understandable.

More generally, this thesis attempted to explore and explain how enterprise archetypes that grew out the “higher, faster, farther” environments in any industry (but particularly those with higher dynamic complexity) are different from those that evolve in a “better, faster, cheaper” environment. The significant successes and the challenges going forward are not necessarily unique to *Boeing*, but it is hypothesized common to firms of common architectural archetypes.

10.2 Recommendations for Future Research

The scope of this project was intended to be very broad, covering the important aspects of various functional disciplines within a typical enterprise. In order to create the high-level heuristics that arise from this purposefully interdisciplinary approach, this work could best be described as “a mile wide, and an inch deep”. As this work was admittedly focused on *synthesis* as opposed to *analysis*, the most fruitful extension of this work therefore would probably lie in more in-depth analyses to prove the laws and

develop the heuristics created herein. I offer some recommendations for future research from each of the two parts of this thesis:

In “Enterprise Engineering”, further work could be done to define, develop and verify the appropriate enterprise structural quantities of: inertia, responsiveness and reactivity. That is, use further empirical case-based field data from enterprises having different clockspeeds (e.g. fast-clockspeed computer industry, the medium-clockspeed automotive industry and the slow-clockspeed aerospace or construction industry) to determine what operational variables and metrics more accurately define enterprise inertia, responsiveness and reactivity. Then calculate the enterprise’s clockspeed and finally estimate the enterprise’s key response quantities of sales/production, throughput and growth.

In “Enterprise Architecting”, further work could be done to: define successful enterprise design archetypes^{323,324,325}, define how to implement them, and define what financial (and non-financial) metrics accurately monitor their successful operation.

10.3 Final Thoughts

Having articulated the “laws” of enterprise dynamics so that we could engineer the enterprise, we then articulated the “heuristics” of enterprise architecture, which allowed us “*to create more successful management policies and organizational structures*” as Jay Forrester had articulated over 40 years ago. As we have seen, although it can be analyzed using the principles of science, the design and delivery is very much rooted in art.

From the hard “laws” of enterprise physics, we end our journey with the “soft” unquantifiable heuristics of enterprise leadership. The best I can do is to point out the obvious: *courage* is required on the part of the isolator (enterprise champion), while *trust* is required on the part of the isolated enterprise.

³²³ Collins, James C. and Porras, Jerry I., *Built To Last: Successful Habits of Visionary Companies*, Harper Business Essentials, 1994.

³²⁴ Collins, James C. *Good to Great: Why Some Companies Make the Leap...and Others Don't*, Harper Business Essentials, 2001.

³²⁵ Foster, Richard and Kaplan, Sarah, *Creative Destruction: Why Companies That are Built to Last Underperform the Market – and How to Successfully Transform Them*, Currency, 2001.

It is not impossible – recall just as a decade ago, that US companies thought that stopping the production line for a quality problem was not possible. The bad news is that it is hard to do – the good news is that it is hard to imitate. This is therefore a source of true sustained advantage for value chain leaders like *Toyota* and *Southwest Airlines* who earn supernormal profits over the long term and dominate industries.

The methodologies presented herein (namely, system and structural dynamics) are not intended to give an organization or enterprise yet another tool to predict or optimize, but it is meant as a means for its leaders to share mental models about their perceptions of how their enterprise works, and to collectively change their way of thinking about the dynamic complexity of their organization. Some enterprises, like those in commercial aerospace, are so dynamically complex that they require a complete rethinking of how to design effective solutions. As Albert Einstein noted: “We won’t solve our problems with the same kind of thinking that we used when we created them.”³²⁶

As Arie deGeus of head of strategic planning at *Shell* noted, “the ability to learn faster than your competitors may be the only sustainable competitive advantage.”³²⁷ DeGeus also believed in the process not the product of strategic planning, when he noted that “planning means changing minds, not making plans”,³²⁸ or as President Eisenhower noted: “Its not the plans but the planning that matters.”³²⁹ At *Shell*, like the world-class companies discusses herein, the use of these methodologies leads to better decision-making.

Finally, I end with two quotes. The first is from Russell Ackoff, one of the greatest systems thinkers of the 20th century, which seems to sum up what this thesis has aspired to deliver³³⁰:

“Wisdom is the ability to see the long-run consequences of current actions, the willingness to sacrifice short-run gains for long-run benefits, and the ability to control what is controllable and not to fret over what is not. Therefore the essence of wisdom is concern for the future. It is not the type of concern with the future that the fortune teller has; he only tries to predict it. The wise man tries to control it.”

³²⁶ *Competitive Strategy Dynamics*, Kim Warren, 2002.

³²⁷ “Planning as Learning”, Arie P. deGeus, *Harvard Business Review*, March-April 1988.

³²⁸ “Planning as Learning”, Arie P. deGeus, *Harvard Business Review*, March-April 1988.

³²⁹ *Analysis for Financial Management*, Robert C. Higgins, 7th edition, McGraw-Hill, 2004, pg. 100.

³³⁰ Ackoff, Russell L., *Ackoff's Best: His Classic Writings on Management*, 1999, pg. 99.

Ackoff's words echo those attributed to the 5th century Roman philosopher, Boethius who gives inspiration to those brave (and humble) enough to endeavor to architect social enterprises:

*“Grant me the **serenity** to accept the things I can not change, the **courage** to change the things I can, and the **wisdom** to know the difference”.*

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Appendix A: Glossary

Architecting: The design process of mapping form onto function. [*Rechtin*: The process of creating and building architectures, including those of organizations, especially during the conceptual and certification phases. Generally synthesis-based, insightful, and inductive.]³³¹

Architectonics: The science of architecture.

Architecture, Organizational: The structure – in terms of organizational units, reporting and directing channels, factors or features, constraints and rationale – of an organization. Includes technical tasks, context, and outputs, as well as structure, people, strategy, processes, managerial, culture, and goals.³³²

Base Isolation: A device located in the substructure of a system or enterprise that acts to decouple the superstructure from the input motions at the base of the system or enterprise. The base isolation system typically acts to lengthen the period of vibration and damping of the supported superstructure. Synonyms include: filter, fuse, decoupling device.

Bounded Rationality: A principle originated at the Carnegie School in the 1950s and 1960s by H. A. Simon which states that: “The capacity of the human mind for formulating and solving complex problems is very small compared with the size of the problems whose solution is required for objectively rational behavior in the real world or even for a reasonable approximation to such objective rationality.”³³³

Capacity: A property of a system that describes its ability to withstand inputs. Synonyms include: strength.

Chaos: A science of complexity theory focusing on deterministic non-linear dynamics. [*Rechtin*: Complex but structured behavior now known to result from nonlinearities, fixed time delays, memory, and interconnections. Found in such organizational contexts as stock markets, inventory, and business cycles and communication networking.]³³⁴

Clockspeed: A property of a socio-technical enterprise. It is the time it takes for the enterprise to complete one full cycle of oscillation. Clockspeed is the organizational equivalent of “Natural (or Fundamental) Period of Vibration” for physical enterprises.

Contingency Theory: The fundamental dogma of modern organization theory that the structure of organizations depends on the environments that they have to relate to, thus emphasizing the uniqueness of each situation.

Cooptation: The process of absorbing new elements into the leadership or policy-determining structure of an organization as a means of averting threats to its stability or existence.³³⁵

³³¹ Rechtin (2000), pg. 235.

³³² Rechtin, (2000), pg. 236.

³³³ Simon, (1957).

³³⁴ Rechtin (2000), pg. 236.

³³⁵ Selznick, (1984), pg. 13.

Cybernetics: c. 1945. Literally, “the science of government”. The science constituted of theories relative to communications and to the regulation within the living being and the machine. (Linear theory).

Damping: A property of a system that describes its ability to absorb energy. Antonyms include: responsiveness. The damping force is proportional to velocity.

Design Spectrum: A graph depicting a smoothed response spectrum. (see *Response Spectrum*).

Dynamic Amplification Factor: The ratio between the peak input quantity and the peak response quantity in a response spectrum. Synonyms include: gain.

Effectiveness: A measure of a system’s ability to meet the objectives of its stakeholders. It has therefore an architectural or outward-focus or external view as contrasted with “efficiency”.³³⁶ [The ratio of function(s) achieved to the totality of functions desired.]³³⁷

Efficiency: A measure of a system’s ability to achieve its objectives with the least amount of waste or non-value-added effort. It has therefore an engineering or internal-focus as contrasted with “effectiveness”. [The ratio of function(s) achieved to resources used.]³³⁸

Engineering: The design process of mapping structure onto form. [*Rechtin:* The process of applying science and mathematics to practical ends.]³³⁹

Engineering Systems: A system designed by humans having some purpose; large scale and complex engineering systems, which are of most interest to the Engineering Systems Division, will have a management or social dimension as well as a technical one.³⁴⁰

Enterprise: A defined scope of economic organization or activity, which will return value to the participants through their interaction and contribution.³⁴¹

Entrainment: The coupling of modes of vibration due the presence of large amounts of damping (i.e. beyond critical damping).

Gain: The ratio of the amplitude of the output sinusoid to the amplitude of the disturbance sinusoid. Gain measures amplification or attenuation of the disturbance as it propagates through the system to the output variable.³⁴² Synonyms include: dynamic amplification factor.

Heijunka: Japanese word meaning “production smoothing” or “level scheduling”.

Hysteresis: A property of a system that describes its force-deflection history. It is a measure of the amount of nonlinear damping.

³³⁶ See Miller & Lessard (2000).

³³⁷ MIT Engineering Systems Division (ESD) “ESD Terms and Definitions”, ESD Working Paper 2002-01.

³³⁸ *Ibid.*

³³⁹ Rechtin (2000), pg. 237.

³⁴⁰ MIT Engineering Systems Division (ESD) “ESD Terms and Definitions”, ESD Working Paper 2002-01.

³⁴¹ ESD Symposium Committee, “ESD Symposium Committee Overview: Engineering Systems Research and Practice”, May 29-30, 2002, pg. 24.

³⁴² See Nathan B. Forrester’s 1982 PhD dissertation, pp. 41-42.

Inertia: A property of a system that describes its resistance to change. Synonyms include: mass. Antonyms include: agility. The inertial force is proportional to acceleration.

Momentum: In physics, momentum equals mass (a property of the system) times velocity (a response quantity or state variable). In enterprise physics, organizational momentum equals inertia times speed.

Muda: Japanese word meaning “waste”, used in the definition of the *Toyota Production System*.

Mura: Japanese word meaning “inconsistency” or variability, used in the definition of the *Toyota Production System*.

Muri: Japanese word meaning “unreasonableness” or inflexibility, used in the definition of the *Toyota Production System*.

Planning: A formalized procedure to produce an articulated result, in the form of an integrated system of decisions.³⁴³ Uses *analysis*, as opposed to the *synthesis* of strategy.

Reasoning, Deductive: Proceeding from an established principle to its application. Characteristic of applied sciences and engineering and based on the principles of mathematics and science. Contrasts with inductive reasoning.³⁴⁴

Reasoning, Inductive: Extrapolating the results of examples to a more general insight or principle. Characteristic of most of the arts and, in particular, the art of organizational architecting.³⁴⁵

Response Spectrum: A graph depicting the response of an infinite series of single degree of freedom systems to a given dynamic input signal.

Stability: A dynamic pattern of stimulus and response in which events become successively less predictable or controllable.³⁴⁶

Stiffness: A property of a system that describes its resistance to movement. Synonyms include: rigidity, reactivity. Antonyms include: flexibility. The stiffness force is proportional to displacement.

Takt: German word for “heartbeat”. Used in the *Toyota Production System* to define the velocity of production. Equals the customer demand divided by the available production time.

Theory of Constraints (TOC): TOC applies to human-based systems (individuals and organizations), the definitions, beliefs and methods that are used by the physical sciences to understand and manage the material world.³⁴⁷

Toughness: A property of a system that describes its ability to deform without failure. Synonyms include: ductility. Antonyms include: brittleness.

³⁴³ Mintzberg, Henry, *The Rise and Fall of Strategic Planning: Reconceiving Roles for Planning, Plans and Planners*, The Free Press, 1994, pg. 12.

³⁴⁴ Rechtin (2000), pg. 236.

³⁴⁵ Rechtin (2000), pg. 237.

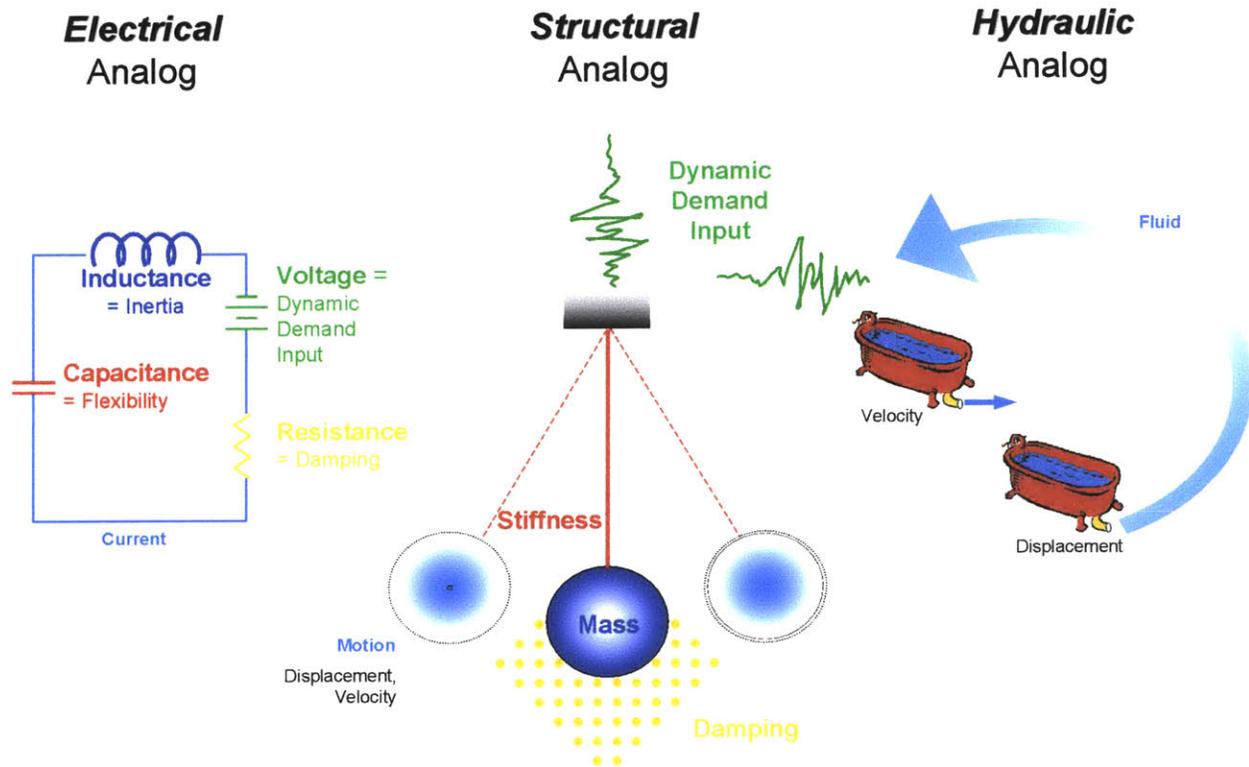
³⁴⁶ Cutcher-Gershenfeld and Reberich, 2002, pg. 3

³⁴⁷ From the A. Goldratt Institute.

Appendix B: Equivalence of Hydro-Electro-Mechanical Systems

The engineering dynamics can be represented in a number of different physical systems ranging from electrical circuits to mechanical/structures to hydraulics as shown in figure B1 below.³⁴⁸ In each, the three basic forces of inertia (inductance), damping (resistance) and stiffness (capacitance) apply.

Figure B1: Equivalence of Hydro-Electro-Mechanical Systems



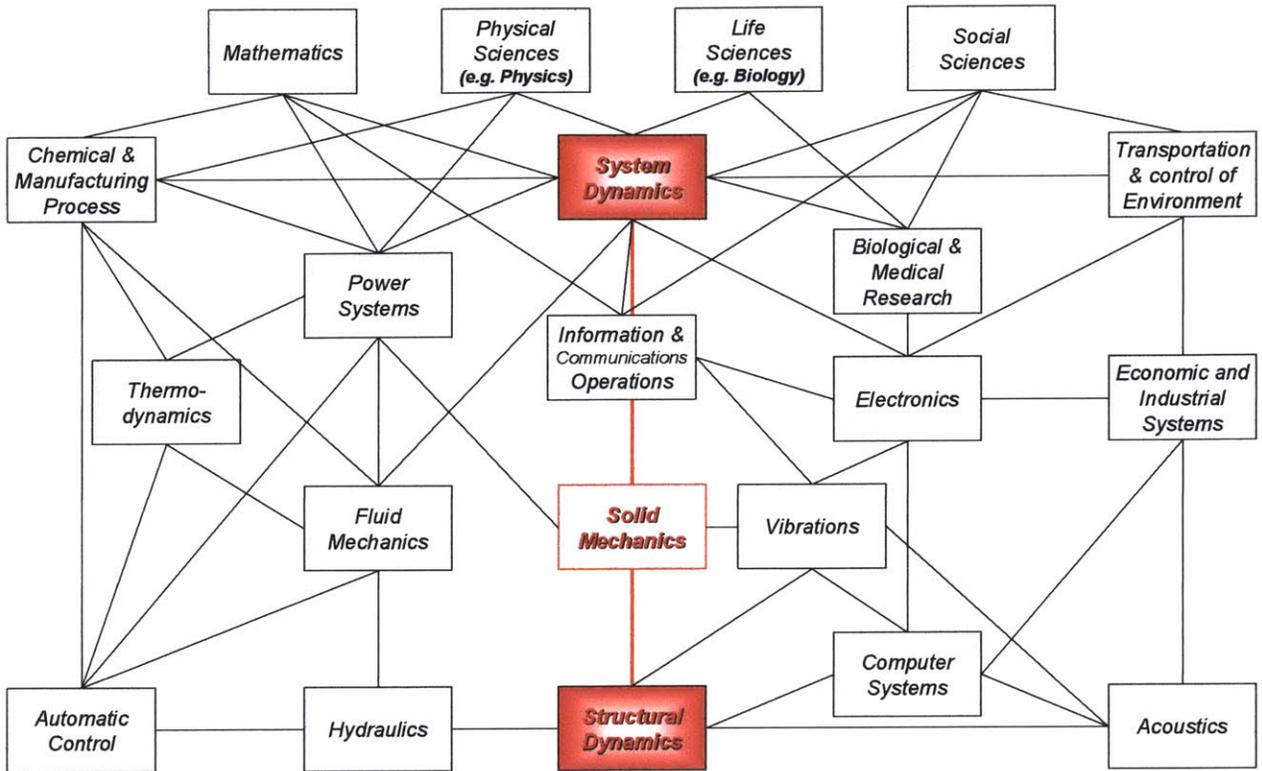
It is instructive to compare these different analog representations of dynamic systems (known as “isomorphic structures”³⁴⁹) within the context of their respective scientific fields of endeavor as shown in figure B2 below.³⁵⁰ Note particularly the relationship between System Dynamics and Structural Dynamics, the two primary fields used in this work.

³⁴⁸ See *Introduction to System Dynamics*, Shearer, Murphy & Richardson, 1967.

³⁴⁹ Ashby, *An Introduction to Cybernetics*, pp. 94-97, 1956.

³⁵⁰ *Introduction to System Dynamics*, Shearer, Murphy & Richardson, 1967, pg. 9.

Figure B2: Comparison of the fields of Dynamic Systems

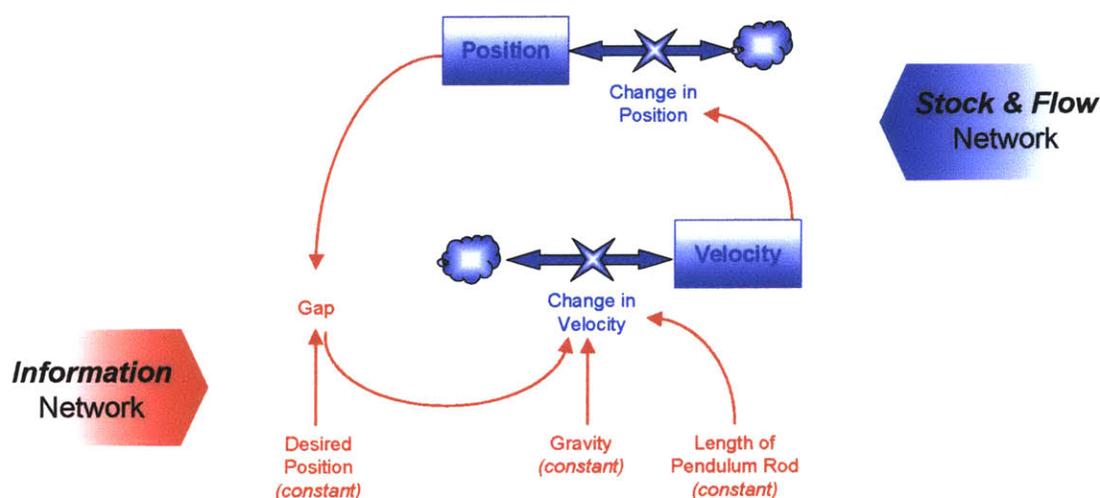


Appendix C: Basics of System Dynamics

System dynamics was founded in the late 1950's by Jay Forrester at MIT. It is a discipline which quantifies the dynamic behavior of complex socio-technical systems. System dynamics is characterized by four components: causal loop diagrams (which indicate feedback structures), stock and flow diagrams (which indicate state variables), time delays and nonlinear behavior.

As shown in figure C1 below, the structure of system dynamics models is formalized by two components: a stock & flow network and an information network. Stocks capture the inertia of a system. The flow rates are determined by the information network and depend on the various stocks in the system. The rates can be interpreted as the output of policies or decision-making processes.³⁵¹

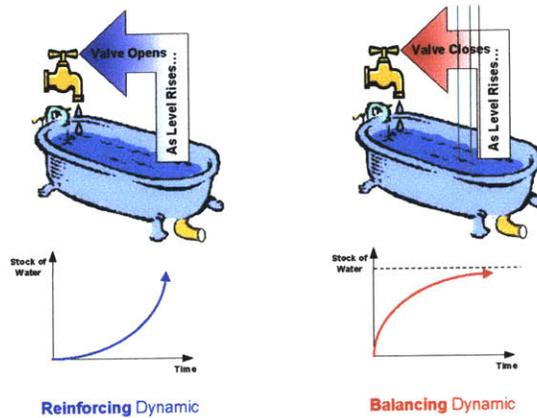
Figure C1: Basic Structure of a System Dynamics Model



The simplest example that demonstrates many aspects of system dynamics is shown in figure C2 below. Stocks (like bathtubs) are variables that accumulate flows. If one were to float a boat in the tub, which was attached via a lever to the faucet handle, we can intuit the response of the system.

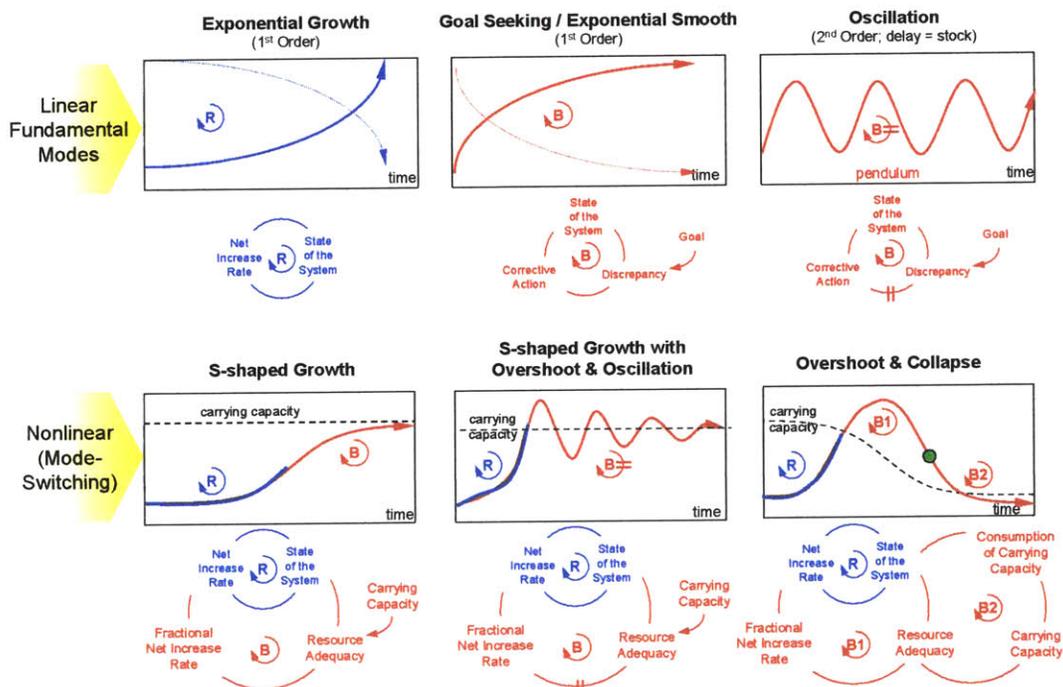
³⁵¹ Smith, Peter C. and van Ackere, Ann, "A Note on the Integration of System Dynamics and Economic Models," *Journal of Economic Dynamics and Control*, Vol. 26, No.1, 2002, pp. 1-10.

Figure C2: Fundamental (linear) Reference Modes



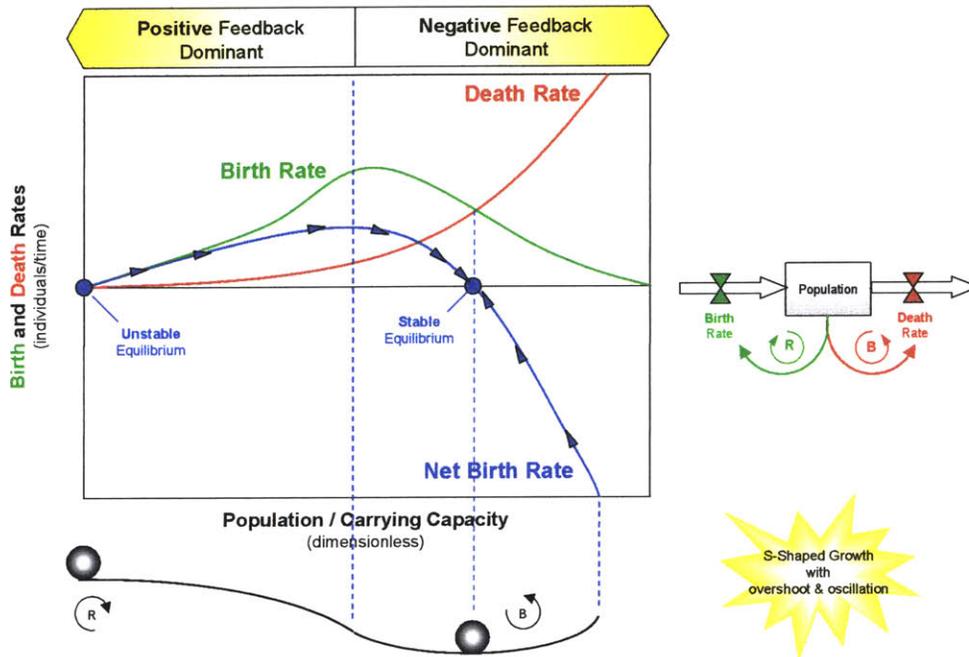
As the water level rises in the figure on the left, the boat and its lever rise, causing the faucet to be opened further, which causes “reinforcing” behavior. Mathematically, this is equivalent to “high exponent” behavior (e.g. $x = y^2$). Conversely, if as the water level rises in the figure on the right, the boat and its lever rise causing the faucet to be closed, which causes balancing behavior. Mathematically, this is equivalent to “low exponent” behavior (e.g. $x = \sqrt{y}$). A more complete set of reference modes are shown in figure C3 below.

Figure C3: Fundamental Reference Modes (source: Sterman).



From the three basic linear reference modes one can construct other three more complex nonlinear reference modes including S-shaped growth, S-shaped growth with overshoot and oscillation, and overshoot and collapse as shown in figure C3 above. They are nonlinear in that they exhibit “mode switching” as demonstrated in the population example (an associated physical analog) in figure C4 below.

Figure C4: The Mechanics of Nonlinear “Mode Switching”

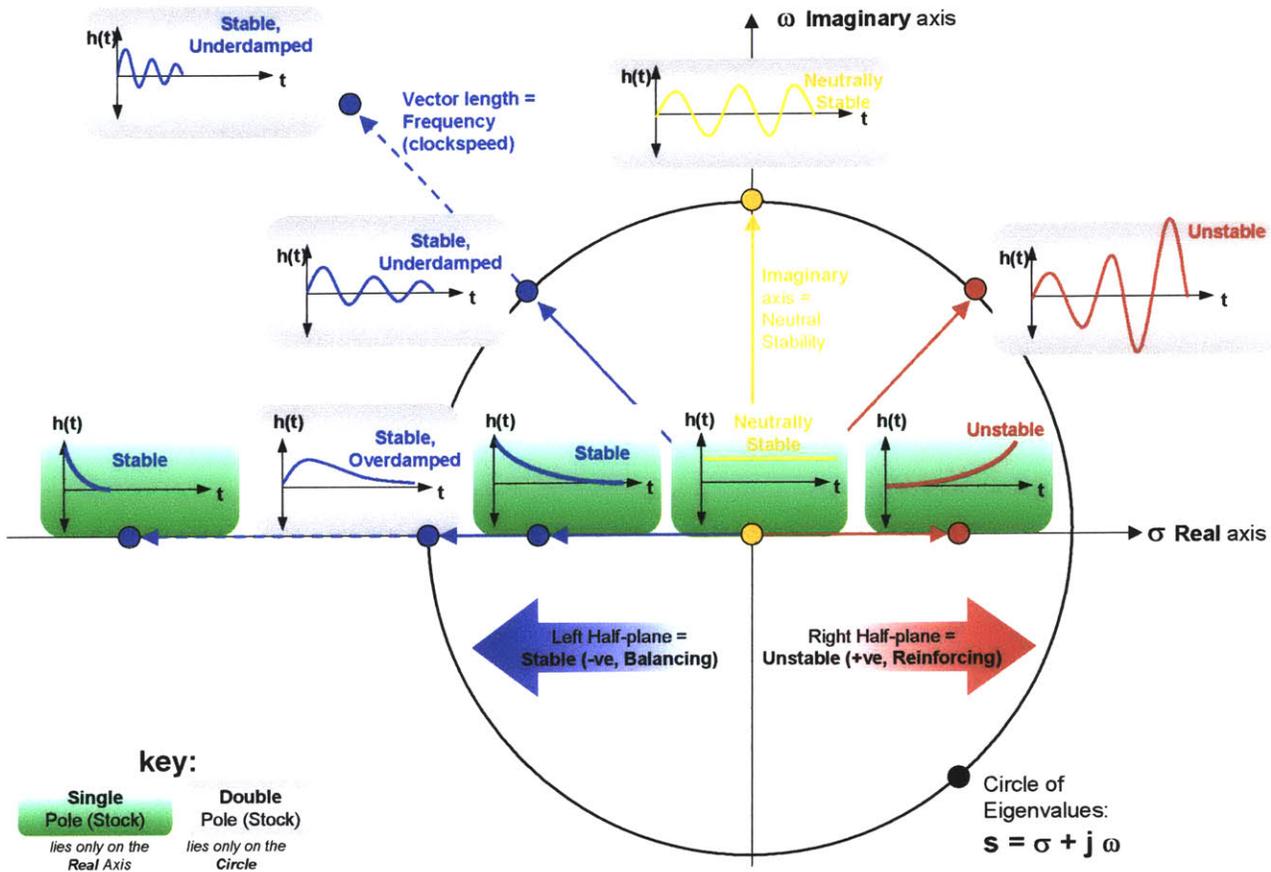


One can begin to better understand the basic dynamics of complex nonlinear social systems (i.e. their governing “modes of vibration” or “loop dominance”) by exploring their response under small perturbations where the system remains in its linear state. Instead of solving the equations of motion in the time domain for nonlinear systems, one can linearize the system and solving the eigen-problem in the frequency domain to take the “dynamic pulse” of the system in the absence of dynamic inputs.³⁵² As is shown in figure C5 below, one can plot the behaviors in the complex plane for one- and two-stock (i.e. single- and multi-degree of freedom systems).³⁵³

³⁵² See for example Alan K. Graham (1977) and Nathan B Forrester’s (1982) MIT PhD dissertations.

³⁵³ Taken from J.H. Muslim, *Positive Feedback*, Pergamon Press, 1968, pg. 55.

Figure C5: Response in the Complex Plane



Other than stocks & flows and feedback, another important component of system dynamics is the effect of *delays* on the system. Essentially, delays are a special class of stocks that decouple inputs from outputs. They can be decomposed into two types: material and information - the formulation of each is summarized in figure C6 below. Delays tend to give systems inertia.³⁵⁴ They can be either bad (when they cause oscillation) or good when they filter out unwanted and distracting noise. Delays can be modeled using from one stock (first order) to multiple stocks. Although the more stocks used, the less damping of high frequency oscillations, Forrester notes that “systems will usually not be very sensitive to the time response of the delay representation.”³⁵⁵

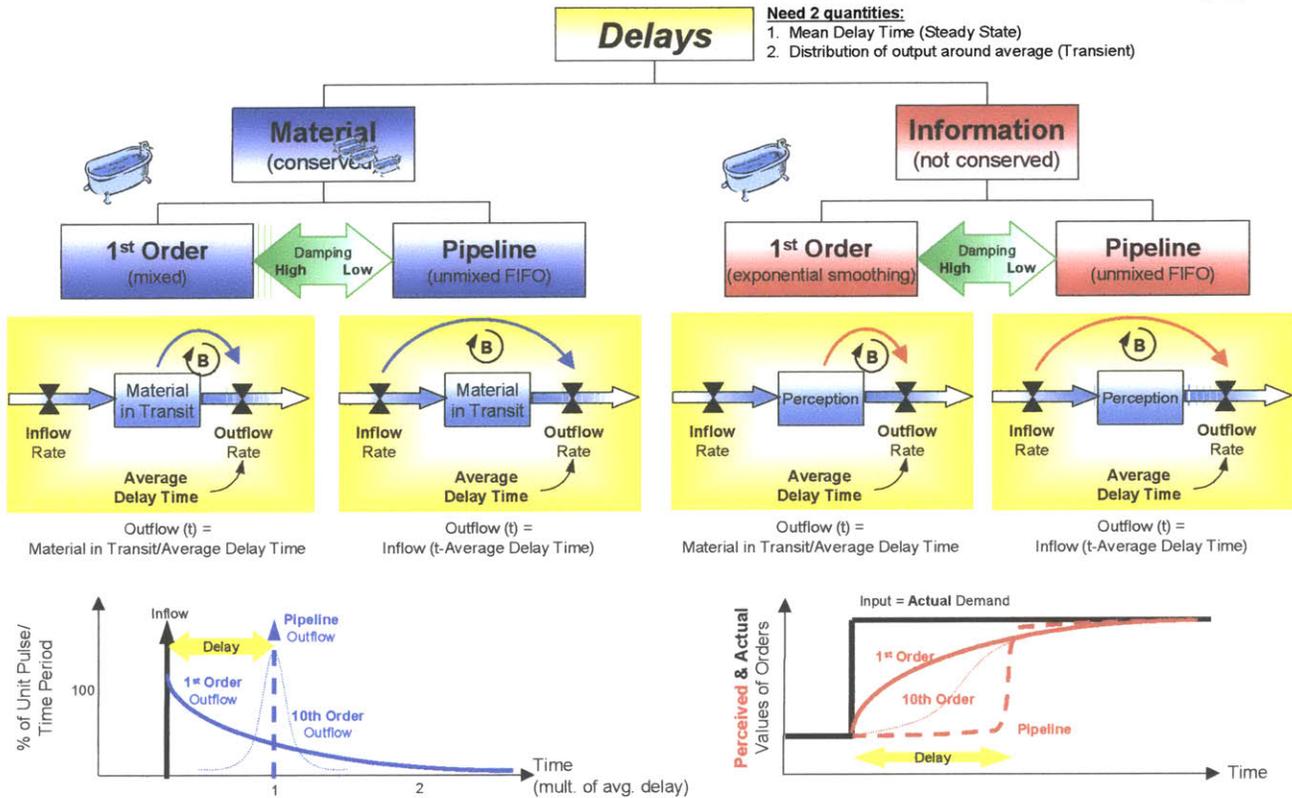
³⁵⁴ Sterman, John, *Business Dynamics*, 2000, pp. 423.

³⁵⁵ Forrester, Jay, *Industrial Dynamics*, 1961, pp. 419.

Figure C6: Summary of Delays

Delays are stocks that de-couple inputs from outputs

- They can be **bad** because they can cause *oscillation* (flexibility).
- They can be **good** because they *smooth* information and limit over-reaction (damping).

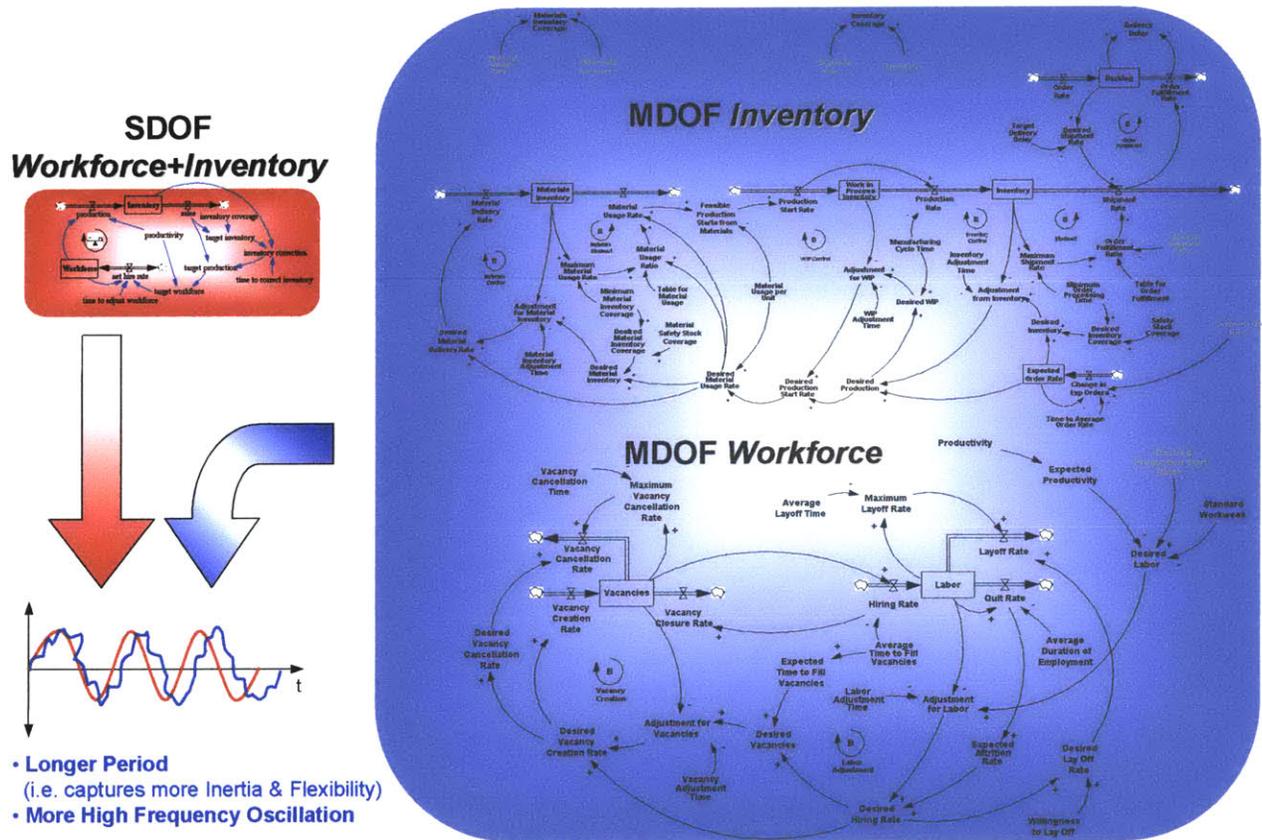


Finally, a brief comment on model complexity is worth making. To paraphrase Albert Einstein: “The best analysis is the simplest that will do the job”. In any nonlinear dynamic analysis of technical or social systems, it is important to capture the most salient features of behavior in the simplest way. Using the Workforce-Inventory model from chapter 2, one can see that a two-stock, single loop (single degree of freedom) model will produce the salient dynamics of oscillation. However a much more detailed model of this enterprise containing greater disaggregation, releasing more dynamic degrees of freedom can be developed.³⁵⁶

³⁵⁶ From John D. Sterman’s *Business Dynamics*.

As is shown in figure C7 below, the two models are compared with stylized response histories. Intuitively, one would expect the more detailed model to capture higher mode oscillations and typically have a longer fundamental mode of vibration (as more detailed modeling frequently captures more inertia and flexibility).

Figure C7: Comparing Single Degree of Freedom vs. Multi-Degree of Freedom Models



There is an important point to make here. In order to be sure that one has actually captured the relevant dynamic modes of behavior, one must “challenge the clouds” (i.e. expand the boundaries of the model) as well as disaggregate the model and test for robustness by using extreme values of the variables. Once done, the modeler can (via eigenvalue analysis or via removing pieces of the model) determine the simplest structure that captures the dynamics of the system, commensurate with the purposes of the model.

Appendix D: Clockspeed Formula

The formula for clockspeed given in chapter 2 (shown in figure D1 below) assumes that the enterprise is undamped.

Figure D1: *Undamped* Formula for Clockspeed

$$T_n = 2\pi \sqrt{\frac{\text{Enterprise Inertia}}{\text{Enterprise Reactivity}}}$$

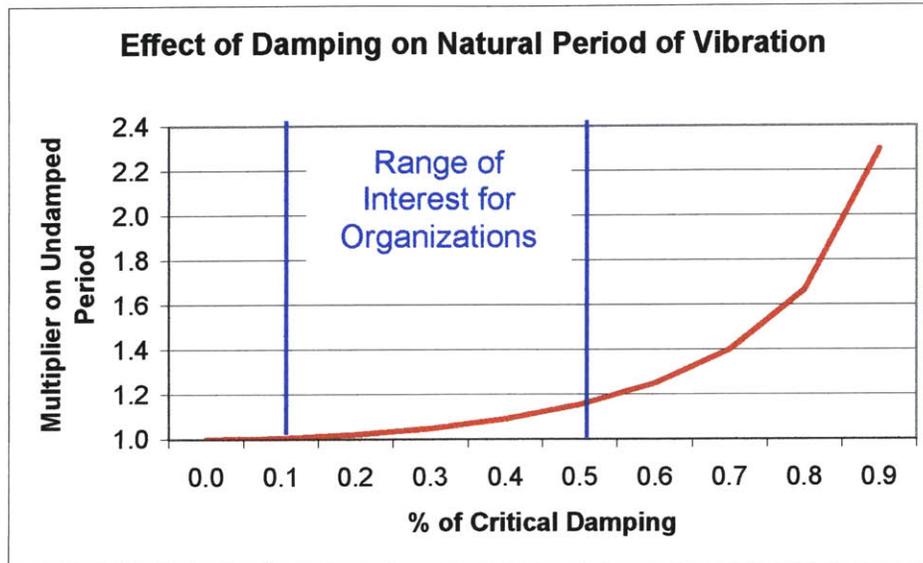
Although not derived here, the general form of the clockspeed formula that includes damping is shown in figure D2 below. Note that enterprise damping is expressed on a scale of 0 to 1 with 1 being known as “critical damping”. As discussed in chapter 3, typical values of damping in physical enterprises range from 0.01 to 0.10 , while typical values of damping in organizations lie in the range of 0.10 to 0.50.

Figure D2: *Damped* Formula for Clockspeed

$$T_n = 2\pi \sqrt{\frac{\text{Enterprise Inertia}}{\text{Enterprise Reactivity}}} \sqrt{1 - \text{Enterprise Damping}^2}$$

As can be seen from the equation above, the effects of damping are small and in fact negligible for values in the range of interest for human organizations. Figure D3 below shows how much the clockspeed slows down as the amount of damping increases. For the production-distribution enterprise studied in chapter 3 which had a damped clockspeed of approximately 26 weeks and approximately 30% damping, ignoring the effects of damping in the estimation of clockspeed would result in a clockspeed of 25 weeks – an “error” of less than 5%. For the purposes of enterprise design, the undamped approximation is satisfactory.

Figure D3: Relationship Between Damping and Clockspeed



In summary therefore, there are three ways to increase an enterprise's clockspeed (or velocity):

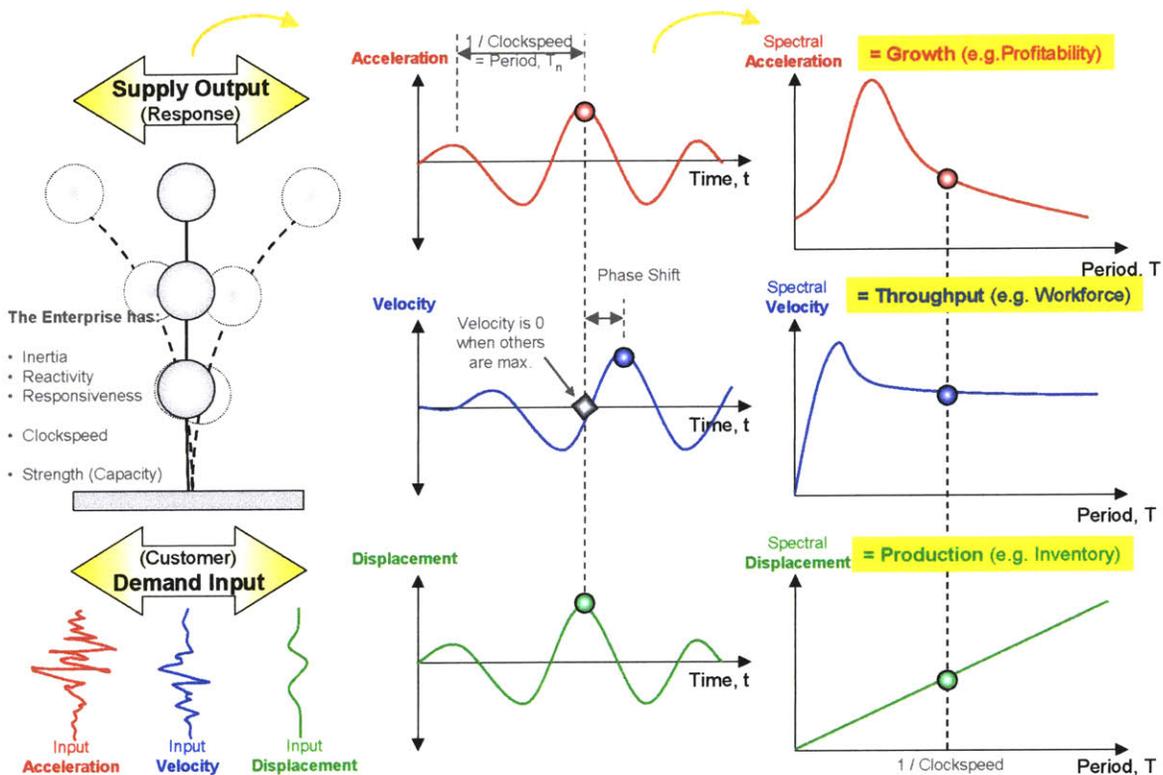
- Reduce the *Inertia*
- Increase the *Stiffness*
- Reduce the *Viscosity*

Of these three, Inertia and Stiffness have the most significant effect.

Appendix E: Enterprise Response Spectra

There are three different but related response spectra as shown in figure E1 below: acceleration, velocity and displacement.

Figure E1: Acceleration, Velocity and Displacement Response Spectra



Each quantity is related to another via the relationships shown in figure E2 below.

Figure E2: Response Relationships

$$A = \omega^2 D$$

$$V = \omega D$$

where:

A = Acceleration
V = Velocity
D = Displacement
 $\omega = 2\pi / T$

Appendix F: *Vensim* Industrial Dynamics Model

```
:MACRO: CLIP(x1,x2,y1,y2)
CLIP=IF THEN ELSE(x1>x2,y1,y2)
~      y1
```

```
:END OF MACRO:
```

```
*****
```

```
.Retail
```

```
*****~
```

```
UOR=INTEG(RRR-SSR,RRI*(DHR+DUR))
```

```
~      units
~      unfilled orders at retail
```

```
IAR=INTEG(SRR-SSR,AIR*RRI)
```

```
~      units
~      inventory actual at retail
```

```
STR=UOR/DFR
```

```
~      units/week
~      shipping rate to be tried at retail
```

```
NIR=IAR/DT
```

```
~      units/week
~      negative inventory limit rate at retail
```

```
SSR=CLIP(STR,NIR,NIR,STR)
```

```
~      units/week
~      shipments sent from retail
```

```
DFR=(MNR/IAR)+DHR
```

```
~      weeks
~      delay in filling orders at retail
```

```
MNR=DUR*IDR
```

```
~      unit*weeks
```

```
IDR=AIR*RSR
```

```
~      units
~      inventory desired at retail
```

```
RSR=INTEG((1/DRR)*(RRR-RSR),RRR)
```

```
~      units/week
~      requisitions smoothed at retail
```

```
PDR=RRR+(1/DIR)*(IDR-IAR+LDR-LAR+UOR-UNR)
```

```
~      units/week
~      purchasing rate decision at retail
```

```
LDR=RSR*DCR+RSR*DMR+RSR*DFD+RSR*DTR
```

```
~      units
~      pipeline orders desired in transit to supply retail
```

```
LAR=CPR+PMR+UOD+MTR
```

~ units
~ pipeline orders actually in transit to retail

UNR=RSR*(DHR+DUR)
~ units
~ normal unfilled orders at retail

CPR=INTEG(PDR-PSR,DCR*RR1)
~ units
~ clerical in-process orders at retail

PSR=DELAY3(PDR,DCR)
~ units/week
~ purchase orders sent from retail

PMR=INTEG(PSR-RRD,DMR*RR1)
~ units
~ purchase orders in mail from retail

RRD=DELAY3(PSR,DMR)
~ units/week
~ requisitions received at distributor

MTR=INTEG(SSD-SRR,DTR*RR1)
~ units
~ material in transit to retail

SRR=DELAY3(SSD,DTR)
~ units/week
~ shipments received at retail

.Retail.Noise

*****~

Implements the noise input from Section 15.7.3, not found
in Appendix B

NSE=SAMPLE IF TRUE(
Time-INTEGGER(Time)<TIME STEP,NSN,NSN)
~ units/week
~ sampled noise input

NSH=
0
~ units/week [-100,100,10]
~ noise amplitude

NSN=
NSH*RANDOM NORMAL(-6,6,0,1,seed)
~ units/week
~ normally distributed noise

seed=
7459
~ dmnl
~ random number seed for noise

.Distributor

*****~

UOD=INTEG(RRD-SSD,RRI*(DHD+DUD))
~ units
~ unfilled orders at distributor

IAD=INTEG(SRD-SSD,AID*RRI)
~ units
~ inventory actual at distributor

STD=UOD/DFD
~ units/week
~ shipping rate to be tried at distributor

NID=IAD/DT
~ units/week
~ negative inventory limit rate at distributor

SSD=CLIP(STD,NID,NID,STD)
~ units/week
~ shipments sent from distributor

DFD=(MOD/IAD)+DHD
~ weeks
~ delay in filling orders at distributor

MOD=DUD*IDD
~ unit*weeks

IDD=AID*RSD
~ units
~ inventory desired at distributor

RSD=INTEG((1/DRD)*(RRD-RSD),RRI)
~ units/week
~ requisitions smoothed at distributor

PDD=RRD+(1/DID)*(IDD-IAD+LDD-LAD+UOD-UND)
~ units/week
~ purchasing rate decision at distributor

LDD=RSD*DCD+RSD*DMD+RSD*DFF+RSD*DTD
~ units
~ pipeline orders desired in transit to supply distributor

LAD=CPD+PMD+UOF+MTD
~ units
~ pipeline orders actually in transit to distributor

UND=RSD*(DHD+DUD)
~ units
~ normal unfilled orders at distributor

CPD=INTEG(PDD-PSD,DCD*RRI)
~ units
~ clerical in-process orders at distributor

PSD=DELAY3(PDD,DCD)
~ units/week
~ purchase orders sent from distributor

PMD=INTEG(PSD-RRF,DMD*RRI)
~ units
~ purchase orders in mail from distributor

RRF=DELAY3(PSD,DMD)
~ units/week
~ requisitions received at factory

MTD=INTEG(SSF-SRD,DTD*RRI)
~ units
~ material in transit to distributor

SRD=DELAY3(SSF,DTD)
~ units/week
~ shipments received at distributor

.Factory
*****~

UOF=INTEG(RRF-SSF,RRI*(DHF+DUF))
~ units
~ unfilled orders at factory

IAF=INTEG(SRF-SSF,AIF*RRI)
~ units
~ inventory actual at factory

STF=UOF/DFF
~ units/week
~ shipping rate to be tried at factory

NIF=IAF/DT
~ units/week
~ negative inventory limit rate at factory

SSF=CLIP(STF,NIF,NIF,STF)
~ units/week
~ shipments sent from factory

DFF=(MPF/IAF)+DHF
~ weeks
~ delay in filling orders at factory

MPF=DUF*IDF
~ weeks*unit

IDF=AIF*RSF

~ units
~ inventory desired at factory

RSF=INTEG((1/DRF)*(RRF-RSF),RRI)
~ units/week
~ requisitions smoothed at factory

MWF=RRF+(1/DIF)*(IDF-IAF+LDF-LAF+UOF-UNF)
~ units/week
~ manufacturing rate wanted at factory

MDF=CLIP(MWF,ALF,ALF,MWF)
~ units/week
~ manufacturing decision rate at factory

LDF=RSF*(DCF+DPF)
~ units
~ pipeline orders desired in transit to supply factory

LAF=CPF+OPF
~ units
~ pipeline orders actually in transit to factory

UNF=RSF*(DHF+DUF)
~ units
~ normal unfilled orders at factory

CPF=INTEG(MDF-MOF,DCF*RRI)
~ units
~ clerical in-process orders at factory

MOF=DELAY3(MDF,DCF)
~ units/week
~ manufacturing orders into factory

OPF=INTEG(MOF-SRF,DPF*RRI)
~ units
~ orders in production at factory

SRF=DELAY3(MOF,DPF)
~ units/week
~ shipments received at factory

~.Parameters
*****~

AID=6
~ weeks
~ desired inventory coverage at distributor

AIF=4
~ weeks
~ desired inventory coverage at factory

AIR=8

~ weeks
 ~ desired inventory coverage at retail
 ALF=1000*RR1
 ~ units/week
 ~ manufacturing capacity limit at factory
 DCD=2
 ~ weeks
 ~ delay in clerical order processing at distributor
 DCF=1
 ~ weeks
 ~ delay in clerical order processing at factory
 DCR=3
 ~ weeks
 ~ delay in clerical order processing at retail
 DHD=1
 ~ week
 ~ delay due to minimum handling time at distributor
 DHF=1
 ~ week
 ~ delay due to minimum handling time at factory
 DHR=1
 ~ week
 ~ delay due to minimum handling time at retail
 DID=4
 ~ weeks
 ~ delay in inventory (and pipeline) adjustment at distributor
 DIF=4
 ~ weeks
 ~ delay in inventory (and pipeline) adjustment at factory
 DIR=4
 ~ weeks
 ~ delay in inventory (and pipeline) adjustment at retail
 DMD=0.5
 ~ week
 ~ delay in order mailing from distributor
 DMR=0.5
 ~ week
 ~ delay in order mailing from retail
 DRD=8
 ~ weeks
 ~ delay in smoothing requisitions at distributor
 DRF=8

~ weeks
 ~ delay in smoothing requisitions at factory

 DRR=8
 ~ weeks
 ~ delay in smoothing requisitions at retail

 DPF=6
 ~ weeks
 ~ delay in production lead time at factory

 DTD=2
 ~ weeks
 ~ delay in transportation of goods to distributor

 DTR=1
 ~ week
 ~ delay in transportation of goods to retail

 DUD=0.6
 ~ week
 ~ delay in unfilled orders due to out-of-stock items with normal inventory \ at distributor

 DUF=1
 ~ week
 ~ delay in unfilled orders due to out-of-stock items with normal inventory \ at factory

 DUR=0.4
 ~ week
 ~ delay in unfilled orders due to out-of-stock items with normal inventory \ at retail

.Test

*****~

RRR=RRI+RCR
 ~ units/week
 ~ requisitions received at retail

RCR=
 STP+SNE
 {Note: the following term adds the noise in Section 15.7.3, which is not included in the model listing in Appendix B}
 +NSE
 ~ units/week
 ~ requisition change at retail

STP=STEP(STH,STT)
 ~ units/week
 ~ step test input

SNE=SIH*SIN(2*PI*Time/PER)
 ~ units/week

```

~      sinusoidal test input

PER=52
~      weeks [0,400,10]
~      period

RRI=1000
~      units/week
~      retail requisitions, initial rate

SIH=0
~      units/week [-100,100,10]
~      sinusoidal input amplitude

STH=0
~      units/week [-100,100,10]

STT=4
~      week [0,52,1]
~      step input time

PI=3.14159
~      dmnl

```

```

*****
      .Supplementary
*****~

```

```

TIS=IAR+IAD+IAF
~      units
~      total system inventory
~      :SUPPLEMENTARY

```

```

*****
      .Control
*****~

```

Simulation Control Paramaters

```

DT= TIME STEP
~      week
~      delta time (same as time step)

```

```

FINAL TIME = 100
~      week
~      The final time for the simulation.

```

```

INITIAL TIME = 0
~      week
~      The initial time for the simulation.

```

```

SAVEPER =
  TIME STEP
~      week
~      The frequency with which output is stored.

```

```

TIME STEP = 0.05

```

~ week
~ The time step for the simulation.

Appendix G: *Vensim* Commodity Dynamics Model

Average Life of Capacity=

200
~ months

Capacity in Transit= INTEG (

+Transit Initiation Rate-Transit Completion Rate,
Transit Delay*(Desired Production Capacity-Production Capacity)
/(Transit Delay+Transit Initiation Delay))
~ Units/Month

Capacity Utilization Factor=

Capacity Utilization Lookup(Desired to Actual Capacity Ratio)
~ dmnl

Capacity Utilization Lookup(

[(0,0)-(2,2)],(0,1),(0.25,1),(0.5,1),(0.75,1),(1,1),(1.25,1),(1.5,1),(1.75,1),(2,1))
~ dmnl

Commodity Price=

Commodity Price Lookup(Relative Inventory Coverage)
~ \$/unit

Commodity Price Lookup(

[(0,0)-(2,100)],(0,100),(0.25,95.5),(0.5,87),(0.75,72.5),(1,50),(1.25,27),(1.5,15),(\n1.75,7.5),(2,0))
~ \$/unit

Consumer Population=

200
~ people

Consumption Adjustment Delay=

3
~ Month

Consumption Rate=

Consumer Population*Per Capita Consumption*Test Input
~ Units/Month

Depreciation Rate=

Production Capacity/Average Life of Capacity
~ (Units/Month)/Month

Desired Capacity Lookup(

[(0,0)-(100,2000)],(0,0),(20,10),(40,50),(60,1150),(80,1500),(100,1600))
~ Units/Month

Desired Inventory Coverage=

10
~ months

Desired Production Capacity=

Desired Capacity Lookup(Expected Price)

~ Units/Month

Desired to Actual Capacity Ratio=
Desired Production Capacity/Production Capacity
~ dmnl

Equilibrium Per Capita Consumption=
Per Capita Consumption Lookup(Commodity Price)
~ Units/Month/person

Expected Cons Adjustment Delay=
100
~ months

Expected Consumption Change Rate=
(Consumption Rate-Expected Consumption Rate)/Expected Cons Adjustment Delay
~ (Units/Month)/Month

Expected Consumption Rate= INTEG (
Expected Consumption Change Rate,
591)
~ Units/Month

Expected Price= INTEG (
Expected Price Change Rate,
50.22)
~ \$/unit

Expected Price Adjustment Delay=
3
~ months

Expected Price Change Rate=
(Commodity Price-Expected Price)/Expected Price Adjustment Delay
~ (\$/unit)/Month

Inventory= INTEG (
+Production Rate-Consumption Rate,
5900)
~ Units

Inventory Coverage=
Inventory/Expected Consumption Rate
~ months

Noise=
0
~ dmnl

Per Capita Consumption= INTEG (
Per Capita Consumption Change Rate,
2.96)
~ Units/Month/person

Per Capita Consumption Change Rate=
(Equilibrium Per Capita Consumption-Per Capita Consumption)/Consumption Adjustment Delay

~ (Units/Month/person)/Month

Per Capita Consumption Lookup(
[(0,0)-(100,10)],(0,7),(20,6.5),(40,5),(60,1),(80,0.3),(100,0))
~ Units/person/Month

Production Capacity= INTEG (
+Transit Completion Rate-Depreciation Rate,
591)
~ Units/Month

Production Delay=
6
~ months

Production Initiation Rate=
Production Capacity*Capacity Utilization Factor
~ Units/Month

Production Rate=
DELAY3(Production Initiation Rate, Production Delay)*PUF
~ Units/Month

PUF=
PUF Lookup(Desired to Actual Capacity Ratio)
~ dmnl

PUF Lookup(
[(0,0)-(2,2)],(0,1),(0.25,1),(0.5,1),(0.75,1),(1,1),(1.25,1),(1.5,1),(1.75,1),(2,1))
~ dmnl

Relative Inventory Coverage=
Inventory Coverage/Desired Inventory Coverage
~ dmnl

StepSize=
0.15
~ dmnl

Test Input=
1+STEP(StepSize,0)-STEP(StepSize,10)+Noise
~ dmnl

Transit Completion Rate=
DELAY3(Transit Initiation Rate, Transit Delay)
~ (Units/Month)/Month

Transit Delay=
4
~ months

Transit Initiation Delay=
3
~ months

Transit Initiation Rate=

(Desired Production Capacity-Production Capacity-Capacity in Transit)
/Transit Initiation Delay
~ (Units/Month)/Month

.Control

*****~

Simulation Control Paramaters

FINAL TIME = 200

~ Month

~ The final time for the simulation.

INITIAL TIME = 0

~ Month

~ The initial time for the simulation.

SAVEPER =

TIME STEP

~ Month

~ The frequency with which output is stored.

TIME STEP = 0.5

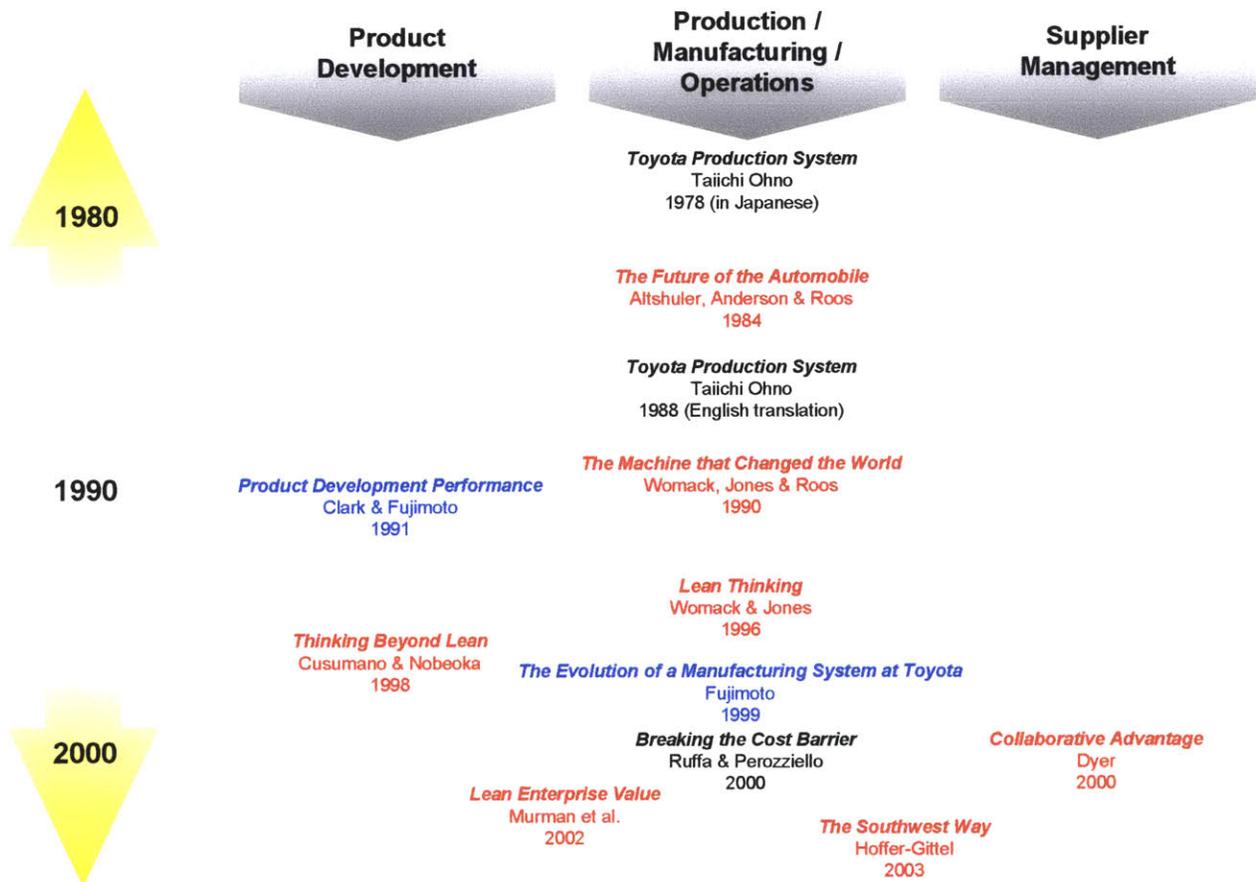
~ Month

~ The time step for the simulation.

Appendix H: Research Chronology of Lean

A chronology of research on Lean is broken down into functions and is shown below in figure G1. The body of literature began in 1978 with a description of the Toyota Production System by its architect, Taiichi Ohno. As can be seen, subsequent to this work (and its 1988 translation) the vast majority of the research was undertaken in the automobile industry as part of MIT's *International Motor Vehicle Program*. Much of this focused (though not exclusively) on manufacturing. In addition, research at the Harvard Business School (shown in blue) covered the Japanese automotive industry, and had more of a focus on the product development side.

Figure G1: Research Chronology of Lean



About the Author

Ted Piepenbrock conducted this research as a Fellow of MIT's *Leaders for Manufacturing* program, a dual masters degree program in the *Sloan* School of Management, the School of Engineering and sponsored by a consortium of leading global manufacturing companies. In addition, he conducted this work as a research assistant of the *Lean Aerospace Initiative*, a consortium of public and private sector agencies and firms dedicated to the improvement of the aerospace industry.

Prior to MIT, he was an associate director of *Ove Arup & Partners*, one of the world's premier engineering/architecture firms located in London where he had spent the best part of the 1990s designing some of the world's tallest buildings and longest bridges. As a specialist in structural dynamics and earthquake engineering for more than 10 years, he traveled over one million miles to more than 20 countries and was occasionally spotted commentating on international television and newsprint like *CNN* and the *BBC*. His passions eventually took him from "the business of building" to "the building of business" where he had a fantastic time at *McKinsey & Company* designing high-performance production systems.

Upon completion of this thesis, he went on to continue to develop this research in a dual, concurrent PhD program at the *MIT Sloan School of Management* and the *MIT Engineering Systems Division*.