BOEING	SANTA FE INSTITUTE

A research partnership between Complexity Sciences and Business

Innovation, Sustainability and Growth of Human Social Organizations from Cities to Corporations.

Introduction:

The Boeing model for design and manufacture of the new airplane program is among the most ambitious and forward thinking program in existence. The approach includes a complex database of physical and functional characteristics, sub-system design/build plans, and other shared information that supports the broader project. In the same way that a new design criterion affects the mechanical properties and engineering knowledge domains for aircraft structures i.e., metals to composites, suppose university programs adopted courses that required emerging, interdependent relationships between physical product constraints and multidisciplinary, multicultural globally dispersed members of a design team? Specifically, teams of students are asked to complete a design assignment, but subgroups have independent contributions that impact the design plan and results of partnering groups. What if the design teams partnering with industry, were enrolled in two or more courses, or two or more departments? This academic – industry model is not a trivial task to achieve in a cooperative learning environment and particularly where grades are an important factor to consider. This concept, when overlaid against personal agency and social structure specifically, the user community, models and rules, could serve as a effective guide for constructing the framework for managing and capturing complex patterns of behavior.

SFI-Boeing Research Program:
The intent of this program is to build on the successful body of work that has already begun at SFI on developing a broad fundamental, quantitative, predictive theory of social organizations. A major component is to understand the role of innovation and adaptability in shaping the growth and sustainability of cities to corporations. Such a theoretical framework

is potentially very powerful for a company like Boeing in helping to recognize and understand that its growth, evolution and development have been constrained by general "laws" which may have important implications for its long-term survivability. Such laws reflect the general dynamical and structural properties of the multiple underlying networks of the organization itself as well as its relationship with the broader business community. This is manifested in generic scaling laws that indicate that organizations that participate in a business/economic ecology did not evolve, grow and adapt either "randomly" or in a planned controlled manner but were subject to dynamical laws. From a research perspective we view Boeing as a "case study" by providing data and significant support for the research. The project will be focused on understanding these big questions by seeking to reveal the underlying principles, constraints and dynamics independent of the details by which companies grow and evolve driven by innovation (their "coarse-grained behavior").

Summary of Research Objectives

We will develop a systematic research program that measures innovation in social organizations, from cities to corporations, and relates these metrics to other changes such as those in an organization’s economic output and size. From this synthesis we will develop a new quantitative, predictive theory of the structure, organization, dynamics and growth of social organizations from cities to firms. Our approach is based on the unprecedented integration of the largest datasets on cities and firms worldwide with transdisciplinary concepts of social organizations and complex systems coupled with the detailed knowledge of a specific industry and of Boeing, its leading company. Emphasis will be placed on understanding the interplay between innovation, wealth creation, and economies of scale as they are manifested in questions of growth, evolvability, adaptability and sustainability. Specifically, we will:

Objective 1: Establish metrics of innovation, economic growth and size of social organizations across scales using datasets from urban systems and corporations around the world and across times scales.

Objective 2: Establish the quantitative connection between the dynamics of innovation and growth of cities and firms. Study in detail the temporal evolution of Boeing’s Commercial Aircraft Division.

Objective 3: Discover and model mathematically the micro-scale processes and network structures resulting in scaling of economic productivity and innovation, including those leading to economies of scale and learning and increasing returns in innovation. Identify and analyze component processes within Boeing Commercial Aircraft Division that result in observed scaling relations and learning curves.

Objective 4: Develop a new synthesis of these findings in terms of a quantitative and predictive theory of the structure, organization, dynamics and growth of social organizations fueled by endogenous and exogenous innovation.

Objective 5: Use our empirical results and derived theoretical framework to suggest policy to promote sustained dynamics of innovation, productivity, and growth. Determine implications for education and training.

Background

Despite a growing wealth of quantitative data on human organizations we still do not understand in predictable and actionable ways, especially as regards policy decisions, what social, organizational and infrastructural factors promote innovation and accelerate discovery and economic growth. A central tenet of this proposal is that integrated studies of different kinds of social organizations across multiple size and time scales can provide crucial data and important insights for understanding the dominant factors involved in these processes.

For example, the study of population agglomerations such as cities [1-12] has revealed many important features of the nexus between population scale, innovation and growth. The privileged role that cities have played in the development of science and technology, and more broadly, in the generation of inventions and innovations has been well documented by historians, urbanists, geographers, anthropologists and regional economists. Sociological and economic studies of urban dynamics reveal that the agglomeration of people induces both *economies of scale* in services and *increasing returns to scale* in rates of wealth creation and innovation [3,10,12,13]. This means that as more people come together, the rate of economic and intellectual productivity *per capita* tends to increase in a way that we have recently shown follows self-similar statistics [12,13]. These quantitative regularities suggest that there are universal dynamics at play in human societies that are accelerated by bringing more people together. In this sense cities are just one very natural mechanism for reaping the benefits of high social connectivity between very different people conceiving and solving problems in a diversity of ways.

Similar processes are also at play in other social organizations, such as corporations, even though they are much less well understood. Here and throughout this proposal we will use the generic terms *firm* and *corporation* to refer to organizations ranging from universities and non-profit organizations to for-profit companies. Corporations display an even broader set of variability than cities. Different corporations are dedicated to a myriad of different products, services, and markets, and their dynamics and organization must reflect some of these contingencies. Nevertheless, much has been written about qualitative universal characteristics of firms, whereby economic success is connected to growth and, in turn, to the development of more explicit organizations of management, control, and of innovation.

A large qualitative body of literature has described the lifecycle of corporations, decision-making in organizations, and their general features of organization [14-16] as gathered through historical and case study methods. Analogies to other systems, specifically to biological organisms, are also common metaphors for the study of social organizations [17]. This foundational literature describing the complexity of modern organization has been valuable in framing questions for further large-scale quantitative studies. The main objective of the research proposed here is to establish functional quantitative metrics of innovation, economic productivity and size of human social organizations and connect and understand them by developing a quantitative theoretical framework that captures and predicts universal features of how organizations grow, innovate, age and die. The change in size (growth) of a city or firm is necessarily predicated on the availability of resources, through increases in its economic productivity. New resources in turn come from new ideas, either in the form of technologies or organizational forms. Thus, innovation is necessary for increases in economic output and this in turn permits increases in the organization's size. A larger size permits certain economies of scale, better matching of resources and, at least in principle, a larger number of potential innovators. These interdependencies can create virtuous cycles of innovation, wealth creation and growth.

Performance curves in social organizations. An important component of a firm's performance is the progress in individual technologies. However, the link between scaling relationships in technological performance and macro-level scaling relationships in firm-wide performance remains poorly understood. A major part of this project will be to decompose technological change and investigate the effects on broader metrics of firm performance. Technological performance can be measured via *performance curves*. The costs of many goods have been shown to decrease in a regular way with increasing cumulative production [27-39]. This phenomenon was first observed by Wright in a pioneering study of aircraft manufacturing in 1943. In his study Wright found that the cost/unit of a technology *L* (aircraft), and the cumulative number of units produced *n* are related as a power law of the form $c(n) = c_0 n^{\alpha}$, where L_0 is a constant setting the initial cost and α is a scaling exponent.

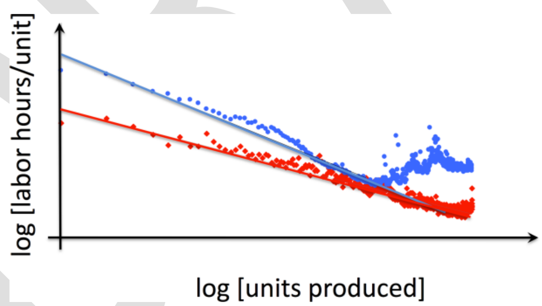


Figure 1: Performance curves in manufacturing. A) The cost (labor hours) of airplane manufacture at Boeing versus number of units produced (units suppressed due to the proprietary nature of data). Model A (blue points) shows initial faster learning with α=0.67 (solid blue line), while model B (red points) has α=0.39 (solid red line). Late in the history of model A's production labor hours/unit increased sharply due to the reconfiguration of the original aircraft.

The systematic decrease in cost with increasing production defines a performance curve – a general term which includes learning curves for an individual firm, or experience curves covering an entire industry. These performance curves have been measured at different scales, from entire industries and cumulative production across the globe to individual factories. An unpublished preliminary example of a learning curve that we have recently derived from aircraft assembly data from Boeing is shown in Figure 3. This clearly manifests increasing performance with the increase in number of each type of aircraft manufactured. Although these performance curves are consistent with power law behavior, there are significant deviations, especially in the later production of model A. These curves can therefore also be viewed as diagnostics of changing performance, revealing for example significant perturbations on the organizational structure or manufacturing strategy of the particular product.

An important part of this proposal is to study such performance curves in great detail, especially as they pertain to Boeing aircraft production, including all component costs that constitute airplanes as modular structures. In this way we will bridge scales from the economics of small components, to aircraft assembly, generations of aircraft models and the aggregate performance of Boeing Commercial Aircraft.

Hypotheses for the origin of scaling laws for innovation and wealth creation.

We have shown that there is strong empirical evidence for approximate power law scaling for multiple metrics representing innovation and wealth creation in social organizations (cities and corporations) as functions of size. We have also previously shown that both economies of scale and increasing returns promote growth, albeit with very different long-term asymptotic behavior. These realizations lead to the proposal of a series of social and economic “microscopic” mechanisms [41-43] that can lead to the observed aggregate laws of returns. The unifying logic of these mechanisms is their exploration of the nature of knowledge and information as public goods, i.e. resources that can be accessed without cost, unlike physical commodities or energy. Possible mechanisms leading to aggregate scaling are:

The first phase of this quantitative study will commence by analyzing Boeing as a complex adaptive system but with a view to start building a broad fundamental, quantitative, predictive theory of social organizations, with the help of the successful body of work that has already begun at SFI. A major component is to understand the role of innovation and adaptability in shaping the growth and sustainability of cities to corporations. Why Boeing? Boeing itself is largely a structure facilitating and integrating the flow of information through the complex organization network consisting from its many divisions and its multi-tiered multi-national suppliers chains. Boeing’s outstanding longevity (has thrived for 100 years while others failed), outstanding complexity, high propensity for innovation and the availability of the data recommend the company as the perfect case study, from which in the future a bridge can be build towards developing some universal laws of sustainability. The study will attempt to identify the reasons for the system’s longevity, to quantifiably measure its robustness to perturbations and to define the strategy for its optimization and sustainability as a complex network. The study will attempt to look at this complex network’s topology and at the dynamics of the information flow across the network, studying the impact this dynamics has on technologies and speed of innovation within the company. The study will look at the efficiency of the company’s internal communication and especially try to determine the ways of the optimization of the information flow from the bottom up, with the goal to increase the speed of innovation and economic productivity. The study will attempt to answer some specific questions, such as for example: how the number of internal patents has been growing with the growth of the company's size? Can out of this data some dynamic laws be derived and what are the strategic implications and innovation expectations for a company of a certain size? The study will especially focus on those areas of the system's landscape where the knowledge spillover occur and will especially try to determine in quantifiable terms the rates of technological improvement due to the knowledge transform. The analyses of the data on learning curves, design structure matrices and patents (preferably all of the above for several different models) could be very useful in further investigating questions surrounding how technology characteristics (such as modularity) affect rates of technological improvement.

Thru SFI we can leveraging the complexity approach to explore the problem space, i.e., frame the "Nature of the Problem" What are the issues underlying the complexity of organization and natural systems? The objectives of the research proposal below are to understand the underlying issues that cause us to perceive a system to be complex, and formulate a set of fundamental research questions whose pursuit would be appropriate for joint sponsorship, with for example the NSF, given its charter to support fundamental research. The broad community that participated in the workshop as well as the subsequent presentations could define the overarching fundamental research questions. This would validate our SD assumptions and enable strategic prioritization of and measurement criteria for partner resources.

The Boeing Company: a microscopic study of the origins of scaling and performance curves

Boeing is the world's leading aerospace company and the largest manufacturer of commercial jetliners and military aircraft combined. Additionally, Boeing designs and manufactures rotorcraft, electronic and defense systems, missiles, satellites, launch vehicles and advanced information and communication systems. As a major service provider to NASA, Boeing operates the Space Shuttle and International Space Station. The company also provides numerous military and commercial airline support services. Boeing has customers in over 90 nations and is one of the largest U.S. exporters in terms of sales. Boeing has a tradition dating back to 1916 of aerospace leadership and innovation, including but not exclusively creating new, more efficient members of its commercial airplane family. Headquartered in Chicago, Boeing employs more than 158,000 people across the United States and in 70 countries. This represents one of the most diverse, talented and innovative workforces anywhere. More than 90,000 people hold college degrees – including nearly 29,000 advanced degrees – in virtually every business and technical field from approximately 2,700 colleges and universities worldwide. It also leverages the talents of hundreds of thousands more skilled people working for Boeing suppliers worldwide. Boeing is organized into two business units: Boeing Commercial Airplanes and Boeing Integrated Defense Systems. Supporting these units is Boeing Engineering, Operations & Technology, which helps develop, acquire, apply and protect innovative technologies and processes.

Our analysis will focus on Boeing Commercial Airplanes Division. Boeing has been a leading manufacturer of commercial jetliners for more than 40 years. Presently, Boeing's main commercial aircraft (and on which we have detailed cost data) are the 737, 747, 767 and 777 and the Boeing Business Jet. New product development efforts are focused on the Boeing 787 *Dreamliner*, and the 747-8. The company has nearly 12,000 commercial jetliners in service, roughly 75 percent of the world fleet.

Boeing challenges related to innovation and growth. Because of its obvious breadth and long history Boeing represents an extraordinary opportunity as a case study for understanding the underlying mechanisms of growth and innovation that give rise to scaling and learning aggregate laws. A fundamental challenge to the sustainability of all social organizations is adaptability and evolvability. This is manifested in Boeing by the sequence of aircraft models that the company has manufactured through the years and the organizational and engineering challenges that it has had to face. For example, the production of current generation aircraft has substantially changed from previous models, requiring a working knowledge of new materials and a novel organizational model, heavily dependent on the relationships with many partners worldwide.

New airplane products depart from previous airplane programs in three fundamental ways:

1. *Advanced composite materials* such as carbon fiber reinforced plastics are being applied to many aircraft structures to improve performance and save weight.
2. *Design* accomplished using new *Product Lifecycle Management* methodologies, a comprehensive new software package which incorporates product concept, design, manufacturing information, and after market support using 3D data.
3. A new global *shared-value shared-risk* business model where Boeing's role is primarily that of Systems Integrator, and responsibility for all phases of production is shared with partners.

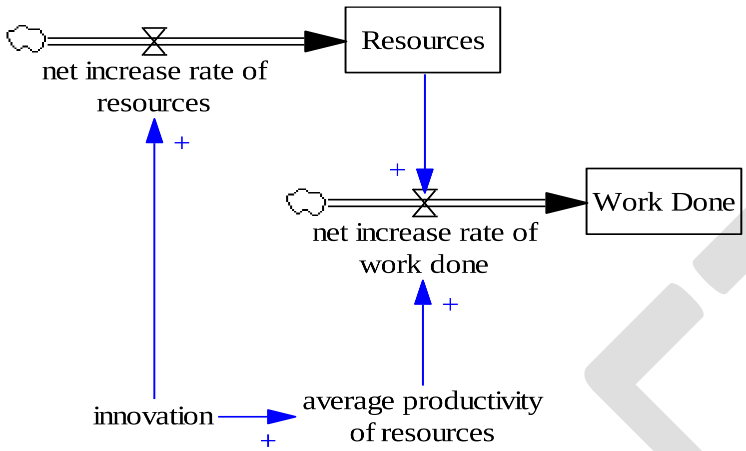
These changes in technology and organization are typical of those faced by any major company. They provide an enormous opportunity to increase growth and productivity. By taking greater advantage of economies of scale and working with partners to improve their performance and efficiency, a company such as Boeing can be more competitive in the market and improve the value it provides to the customers.

It is essential to understand innovation and adaptation in corporations in order to develop methods that overcome network and organizational constraints. For Boeing, possible policy actions include attempts to accelerate internal efficiencies and assist those managed by its partners to achieve the same high performance standards. This includes the dissemination of timely and accurate information, and other processes, tools, education and support that can maintain high levels of innovation and value creation.

Potential Research objectives and goals:

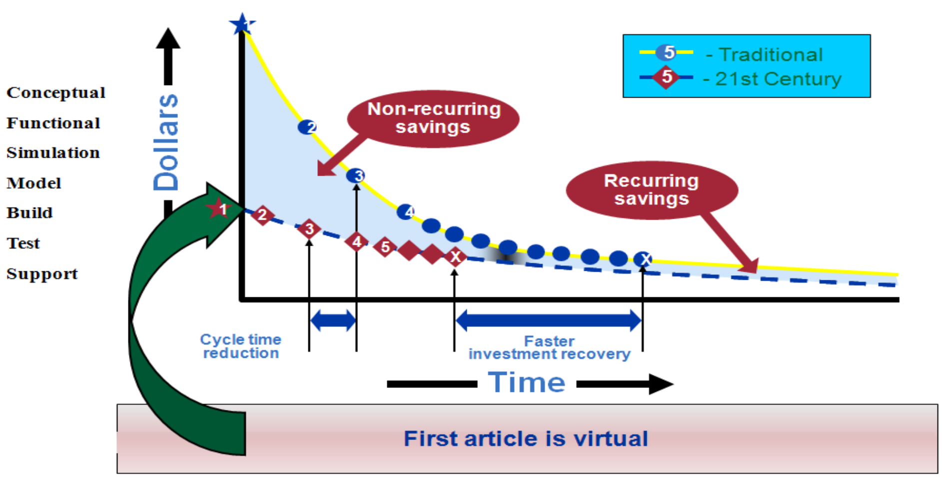
- Can one construct a general theory of social organizations that is quantitative and predictive? Are there “universal” scaling laws that reveal underlying principles?• Are there average idealized social organizations? Did they evolve under “natural selection” in a “free market” environment via competition?
- What is the nature of their hierarchies and generic network structure? Are there universality classes of networks? Is there an optimal maximum (or minimum) size?
- How robust is this heterogeneous social system? What is the capacity for dynamic adaptation? What policies and procedures enable adaptation, how do they propagate through the social network?
- What is the effect of internal – external policy decisions, technology and global pressures change? How do these decisions support the goal oriented behaviors of social agents? (Contagion phenomena)
- What computational models can we employ to better understand an innovation culture, as a complex adaptive system?
- What are the commonalities among adaptive agents (leadership, and extended global workforce)? Can we distill these behaviors into prototypical adaptive behaviors; can we leverage this insight to shift lifelong learning strategies? Can we identify the level of sophistication and enabling conditions?
- Social Niche Construction: the new business model fundamentally altered the internal agent behavior through exposure to global external agents and cultures. Can we model this new operational mode and understand how to leverage the combined intellectual capital generated from this diverse perspective?
- Social worlds: This new model presents a opportunity to shape – influence global behaviors by shifting the balance of local and regional control. How is this accomplished by agents within this global environment? How does this decentralized – centralized balance occur, how does this impact agent behavior i.e., heuristic business modeling for the benefit of the collective system goals?
- Social agents receive or acquire knowledge; the information is leveraged against a schema, processes and acted on. Within the social network, how do agents access information, what is the level of fidelity, how do they direct their acts toward optimizing the solution space?
- How can societies evaluate the tangible and intangible returns from investments in innovation and global business and economic modeling, and to predict the likely returns from future investments within tolerable margins of error and with attention to the full spectrum of potential consequences
- How do learning communities attempt to capitalize on the potential synergy between diverse groups of people to address multiple, diverse aims. A good example of this phenomenon is the learning cities initiative (West 2002, Yarnit 2000) which seeks to build city wide learning communities which both improve citizen learning and economic regeneration.

Productivity and Learning curves:
Worker output in airplane manufacturing (Wright, 1936) linked to technology adoption and learning curve, as measured by productivity efficiencies.



- Education – learning system, adaptive learning strategies and pedagogies

Production verses Learning Curve and Knowledge spillovers:



Project Participants:

- Luis Bettencourt, SFI External Professor
- Geoffrey West, SFI President and Distinguished Professor
- Jessika Trancik, SFI Postdoctoral Fellow
- Michael Richey, The Boeing Company
- Mohammad Mojtahedzadeh, The Boeing Company
- Rick Stephens, The Boeing Company
- Elane V. Scott, Birth2Work