Innovation in Complex Systems Industries: the Case of Flight Simulation

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The paper proposes that the notion of complex systems usefully describes a group of large scale, customized products and their associated supply industries. Examples include flight simulators (FSs), telecommunications exchanges, military systems, airplanes, chemical process plants and heavy electrical equipment. Complex systems, made up of many interconnected customized components, exhibit emerging properties through time as they respond to the evolving needs of large users. Taking the FS industry as a case history, the study identifies some of the basic rules governing innovation in this industry. These rules contrast sharply with those typically found in the 'conventional', market contest Schumpeterian model. Innovation in FS is coordinated by an institutional structure made up of suppliers, users, regulators, industry associations and professional bodies. In contrast with conventional market selection, new designs are negotiated prior to product development. Long-term stability among FS makers is observed, despite radical technological discontinuities, as industrial adjustment occurs via the exit and entry of specialist suppliers. There is no dominant design in the usual sense, nor do the conventional rules of volume competition and process-intensive innovation apply in FS. Competitive strategies remain focused upon design, engineering and prototype development, rather than incremental process innovation. Collaboration occurs among the innovation actors within institutions created by them to harness innovation and to allow new product markets to develop. Recognizing the limits of a single case, the paper suggests that other complex systems might exhibit similar processes for governing innovation and reducing risk and uncertainty in the absence of conventional Schumpeterian market mechanisms.

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1. *Introduction*

Some evolutionary scholars stress the heterogeneous nature of innovation and enduring inter-industry differences between structures, origins and processes of innovation (e.g. Pavitt and Rothwell, 1976). Pavitt (1990), for example, argues that distinct modes of innovation can be observed across four groups of sectors: (i) science-based; (ii) scale intensive, (iii) information intensive; and (iv) specialized supplier dominated. Hayes and Wheelwright (1984) distinguish five major groups of production innovation; project, job-shop, batch line flow, assembly line and continuous flow. Nelson and Rosenberg (1993) point to differences between complex systems (CSs), fine chemicals and bulk commodities such as steel.

By contrast, another influential body of work stresses similarities in the innovation process (Utterback and Abernathy, 1975; Abernathy and Clark, 1985; Clark, 1985; Utterback and Suarez, 1993). As Part I shows, this model argues that product and process technologies tend to follow life cycle patterns from birth to maturity. Firms compete by engaging in a technology race while consumers in the marketplace decide which innovations will be successful. For the purpose of this paper, this technology race/market contest approach is referred to as the 'conventional model'. The latter has influenced evolutionary theories of technical change as well as policy views on how the West should respond to the East Asian challenge in areas such as automobiles, semiconductors and consumer electronics.[1]

The paper argues that while the conventional model may apply to mass market commodity products it is highly unlikely to apply to another important group of products and industries, classified here as CSs.[2] As Part I argues, CSs account for a significant proportion of industrial output. In contrast with commodity goods, complex product systems are large item, customized, engineering intensive goods which are seldom, if ever, mass produced.[3] Examples include flight simulators, telecommunications exchanges, electrical power equipment, military systems, airplanes, helicopters, flexible manufacturing systems, chemical process plant, intelligent buildings and nuclear power equipment. In contrast with mass production industries,

[1] Policy studies include Womack *et al.* (1991) for automobiles and, more generally, Dertouzos *et al.* (1989). A critique of the method and data used in the original cross-industry study by Utterback and Abernathy (1985) is provided by Pavitt and Rothwell (1976). A general review of innovation models is provided by Forrest (1991).

[2] The theoretical section (Part I) draws heavily on Hobday (1994), which counterposes complex systems with mass production industries and argues for a research field in the area of CSs. A preliminary, working definition of CS products is proposed in Part I. Unless otherwise stated, the term CS refers to the product and the supply industry. The terms complex product system and complex product, used interchangeably, refer only to the product.

[3] The idea that a generic category of industrial products can be defined as CSs draws loosely upon complexity theory (Arthur, 1993, Lewin, 1993), the military systems literature (Walker *et al.*, 1988) and work on the measurement of the complexity of systems (Kline, 1990). Evolutionary scholars such as Nelson and Rosenberg (1993) mention CSs in passing, but neither define them nor analyse them as a distinct category for research purposes. Many individual CS industries are studied, but in isolation rather than as one of a generic group (e.g. Mowery and Rosenberg, 1982).

the West retains a general lead over Japan and other East Asian countries, although this cannot be taken for granted.[4]

As Part I argues, CSs can be defined partly by the number of customized, interconnected components and the amount of feedback between them. Typically, they exhibit emerging properties through time as they respond to the economic environment and the innovation demands of large users. CSs involve a high degree of precision and customization in design and production. They are invariably intermediate goods industries which supply large user firms rather than mass market consumers.[5] In contrast with large volume industries, CS industrial structures tend to be characterized by persistent bilateral oligopoly. Products are oriented to the needs of large sophisticated business users which depend on CSs for their survival, growth and profitability. Consequently, users involve themselves intimately in the innovation process.

While attention has been paid to the nature of innovation in individual CS industries, they are rarely treated as a distinct analytical category or compared with mass production industries. Therefore, the purpose of this paper is to examine, in detail, the logic of innovation in one complex industry—flight simulators (FSs)—and to contrast this with the conventional model. Further research is being conducted to compare the differences and similarities among a variety of CS industries.[6] To highlight its distinctive characteristics, the paper contrasts origins, processes and structures of FS innovation with those typically found in the conventional Schumpeterian model. The study shows how the key actors in the FS innovation process (manufacturers, users, regulators and professional groups) collaborate to resolve their competing innovating needs and negotiate with each other to arrive at specific innovation outcomes.[7] The study, carried out by a research

[4] In telecommunications, aerospace and military production, large Western firms face problems of bureaucratic inertia, slow growth and declining profitability. Japan is now competing in airplane subsystems, while Taiwan and South Korea have national strategies for entering the aerospace industry. The reasons why Japanese firms first concentrated on mass market industries and have yet to gain a competitive lead in large-scale, small-batch engineering industries is dealt with by Abegglen and Stalk (1985) Abegglen (1994) shows the spread of competitive mass production export industries from Japan to other parts of East Asia.

[5] However, not all intermediate (or business to business) industries are CSs. Some intermediate products are mass produced (e.g. ball bearings, metal boxes and dynamic random access memory semiconductors).

[6] The study is part of the programme of research by the Hydro-Quebec Chair in the Management of Technology in UQAM in Canada which aims to uncover and compare the logic of innovation in a variety of CS industries. In addition to FS, the following industries are being analysed: (i) nuclear power engineering; (ii) heavy electrical industrial products; (iii) aircraft design and building; (iv) software engineering projects; and (v) satellites and space stations. The present paper focuses on civilian FS, although links with the military were analysed during the research.

[7] FS manufacturers are the main focus of the study, although they form only one part of the FS innovation structure. The terms FS maker, integrator, manufacturer, developer and producer are used interchangeably in this paper to describe the primary suppliers of finished FS systems.

team over a two year period, involved more than 120 interviews with industry representatives in North America and Europe, continuous feedback through industrial working groups and two questionnaire surveys.

Part I contrasts the main elements of the conventional evolutionary model with those likely to be found in CS industries, offering a working definition of CS products and some preliminary ideas on how a taxonomy might be developed (Hobday, 1994). Part II summarizes the results of a detailed study on the international FS industry (Miller *et al.*, 1993). The structure, mechanisms and determinants of innovation are explored and related to the key transformation points in the industry's history. Contrary to the conventional model, despite radical technological discontinuities a persistent pattern of stability occurred among major FS suppliers, while significant upheavals and adjustments occurred in the supply chain. The paper explains this pattern and shows how an institutional superstructure was created by the main actors to coordinate and prosecute innovation, producing a self-organizing industrial system designed to cope with uncertainty and risk. Accepting the limits of a single case study, the conclusion summarizes the main findings and suggests that other CS industries are likely to devise analogous institutional mechanisms for facilitating innovation.

2. *Part I: Two Contrasting Models of Innovation*

The Conventional Market Contest Model of Innovation

The conventional model of industrial innovation is intimately linked to the production paradigm of mass market commodity goods. Firms and markets tend to clearly defined, recognizable entities. Large and small firms create markets and redefine industries by skilfully exploiting technical opportunities (Schumpeter, 1947). The creation and diffusion of new technologies are usually sequential activities: first, the R&D laboratory develops; then the market selects (Utterback and Abernathy, 1975).

The outcome of competitive contests are traceable to the competences, skills and complementary assets that the various rivals bring to the marketplace (Teece, 1986; Barney, 1991). If a firm succeeds in dominating a market, it is because its resources were superior to that of its competitors. Products, markets, industries and technologies undergo life cycles from fluid immaturity states to maturity (Kotler, 1976; Abernathy and Utterback, 1978). Cycles can cover long periods of gradual evolution, punctuated by short periods of disruptive change (Tushman and Anderson, 1986).

According to some, a central event in the evolutionary cycle is the standardization process whereby a particular product configuration (or dominant design) emerges to galvanize an entire market and to give direction to subsequent evolutionary trajectories (Utterback and Abernathy, 1975). At the early stage, the rate of product innovation is high, stimulated by market needs and a wave of new competing entrants. Product markets are ill-defined, products are unstandardized, processes are uncoordinated and user–supplier interactions shape the pattern of innovation. Eventually a dominant design is selected by the market, signalling an industrial shakeout. Small uncompetitive firms exit or are acquired by large companies. Eventually, a small number of firms come to dominate the industry by exploiting scale-intensive, incremental process improvements. As Utterback and Suarez (1993, pp. 2–3) put it, 'Eventually, we believe that the market reaches a point of stability in which there are only a few large firms having standardised or slightly differentiated products and relatively stable sales and market shares, until a major technological discontinuity occurs and starts a new cycle again'.[8]

In such markets, entry barriers vary according to the stage of the innovation cycle. Typically, at the early stages the main barriers are knowledge-based, whereas the barriers at the later stages are scale-based (Mueller and Tilton, 1976). Over time, there is a high turnover of firms in the industry. Entry precedes the dominant design and exit usually follows. Pioneers often fail to survive the harsh and shifting selection process of competitive contests (Olleros, 1986). With the emergence of radical new technologies, old competences can be destroyed, leading to industrial disruption and extinction for laggards in line with Schumpeter's notion of creative destruction (Tushman and Anderson, 1986).

Complex Systems Industries: a Contrasting Paradigm?

It is difficult to define complex product systems, too early to elaborate a taxonomy or theory of innovation in CS industries and premature to claim that robust measurements of complexity exist.[9] In complexity theory (also known as the science of complexity), for example, there is no simple mathematical (or other) definition of a CS.[10] Indeed, by definition it should not be

[8] The study by Utterback and Suarez is based on seven industries: manual typewriters, automobiles, transistors, electronic calculators, semiconductors, television sets and television tubes, and parallel supercomputers. Note that, apart from supercomputers, these are all high volume, mass market-industries where incremental process improvements eventually play a large part in competitive performance. Their paper also touches on several other studies consistent with the conventional model.

[9] For an exploratory general taxonomy of a wide range of complex technical and social systems and comparative mathematical measurements see Kline (1990).

[10] The science of complexity is a relatively new branch of enquiry concerned with understanding dynamic, non-linear, CSs in society, biology, physics, economics and other walks of life (Lewin, 1993). No attempt is made in this paper to apply or relate complexity theory to the FS industry, although some

possible to easily or concisely describe the behaviour of such a system (Stewart, 1993). This section is therefore limited to offering a preliminary working definition of CSs in order to: (i) generate general propositions about the nature and processes of innovation in CS industries and to suggest how these might be expected to contrast with the standard mass production model; and (ii) to guide and inform the subsequent investigation into the FS industry.

The product characteristics of CS industries contrast sharply with mass production goods and imply distinctive forms of innovation and organization.[11] The preliminary definition, developed from a variety of sources discussed below, holds that complex product systems embody at least three general characteristics: first, they are made up of many interconnected, often customized, elements (including control units, sub-systems and components), usually organized in a hierarchical way; second, CSs exhibit non-linear and continuously emerging properties, whereby small changes in one part of the system can lead to large alterations in other parts of the system; and third, there is a high degree of user involvement in the innovation process, through which the needs of the economic environment feed directly into the innovation process (rather than through the market as in the standard model).[12] It is useful to elaborate on each of the three features in turn.

First, complex product systems embody a high degree of customization of the final product and its sub-systems and key components.[13] CSs are

ideas are used. Complexity theorists (e.g. Arthur, 1993) recognize the existence of complex products and industries, as do many others (e.g. Kline, 1990; Nelson and Rosenberg, 1993). As yet, however, there is little empirical or theoretical application of complexity theory to industrial innovation and evolutionary analysts seldom analyse or compare CSs as a distinct category.

[11] The definition is centred mostly on the product, rather than process or organization A fuller definition would account for the connections between the product, the manufacturing process and the organizational environment, as these may have a defining influence on the product. Although, as in the case of FS, process and organizational complexity can be very intense due to the need to synchronize actions and ensure the participation of key actors, a high degree of organizational complexity can also be found in many mass production industries (e.g. automobiles and wide screen televisions). An interesting issue, explored below for the case of FS, concerns the nature, structure, objectives and functions of organizational complexity in CSs, which may well contrast with those found in mass production industries.

[12] The obverse of this definition also defines a 'simple', mass producible product: (i) relatively few, mostly standardized components; (ii) relatively stable, predictable, linear properties; and (iii) user involvement largely mediated through arm's-length, market transactions. Simple products may also be 'non-linear' as new generations are developed. However, the impact of small design changes is likely to be relatively predictable compared with CSs.

[13] Not all components and sub-systems are customized, but many are. As in the examples of aircraft, telecommunications exchanges and FSs, products and their component inputs evolve to meet changing, often extremely demanding conditions. In a sense all products with more than one component part are systems. Complexity is therefore a matter of degree, as Walker *et al.* (1988, p. 29) point out. The degree of complexity is determined by scale, the variety of component and technology inputs, system control requirements, performance characteristics, the difficulties of integration and so on. The more complex a system, the wider the range of skills and capabilities needed to design, develop and manufacture the product. FS and aircraft developers, for instance, require craft, mechanical, electromechanical, precision engineering, machinery, software engineering, systems integration, materials, electromechanical interfacing and automated data exchange skills and knowhow.

invariably very high cost, series or batch produced or individually tailored for specific customers and/or markets. Much of the tacit skill and knowledge needed to produce CSs is embedded in people and is less fully codified than is typically the case in production systems for mass manufactured goods. Usually, these products embody many interconnections, sub-systems and numerous feedback loops. Often sub-systems (e.g. the software modules for public telecommunications exchanges or avionic systems for aircraft) can be extremely complicated, customized and high cost. The extent of feedback and interdependencies within the system means that small changes in one part of the system can lead to large changes in other parts, requiring more sophisticated control systems.

Hierarchy is an important facet of CSs and their component parts and materials. As Walker *et al.* (1988) show for military systems, products can be arranged and understood in terms of their hierarchy, extending from materials and components whose unit costs can be measured in cents or less to very large systems costing billions of dollars. Within the hierarchy of production of military systems such as Tornado, Trident and the European Fighter Aircraft, the outputs of each stage are the inputs of the next:

> as the hierarchical chain is climbed products become more complex, few in number, large in scale, and systemic in character. In parallel, design and production techniques tend to move from those associated with mass-production through series-and batch-production to unit production. Towards the top of the hierarchy, production involves the integration of disparate technologies, usually entailing large-scale project management and extensive national and international cooperation between enterprises. Thus the pyramid is also one of increasing organisational and managerial complexity' (Walter *et al.*, pp. 19–20).

Second, CS products tend to exhibit continuously emerging properties and, in particular, rising complexity through time, resulting from ever-increasing demands on performance, capacity and reliability.[14] For instance, the original turbojet engine designed in the 1930s by Frank Whittle was very simple, having only one moving part (the compressor–turbine combination). But, as Arthur (1993) points out, in order to overcome extreme stress, velocity, altitude and temperature demands, jet designers added more and more sub-systems. Yet more sub-assemblies were added to monitor and control the new sub-systems. A CS evolved as new functions were added to

[14] This does not rule out the possibility of an optimal level of complexity being achieved at any given time or, indeed, simplifying factors impinging on the product and its manufacture (e.g. the standardization of previously customized components). However, CSs such as flight simulators, aircraft and military systems do appear to have become larger, more costly, and more functionally and technically elaborate through time.

overcome limitations, to deal with exceptional circumstances and to adapt to an ever more demanding environment. Today's jet engines can embody more then 22,000 parts, many of which are customized. Similarly, modern telecommunications exchanges evolved to cope with ever larger telephone traffic requirements, spurring on new forms of modular software and semiconductor componentry.

Continuously emerging properties may also refer to a change in the form and structure of a system as it grows. Sahal (1985, pp. 62–63) argues that large systems cannot remain unchanged geometrically, functionally and materially as they grow. For example, some parts of a system may depend on volume (e.g. capacity for heat generation) whereas others may depend on area (e.g. capacity for heat dissipation). As a system grows in size, designers may have to offset the excess of volume by selectively increasing the dimensions of certain parts and constraining the growth of others. Equally, a change in the size of a system often requires changes in the material required for its construction, pointing to the emergent nature of CSs. For example, to produce the blades of large turbines for the jet engine, new nickel chromium super-heat-resistant alloys had to be developed. More generally, the growth of a CS is often accompanied by changes in its form and structure and the materials used.

Continuously emerging properties are intimately connected to the third characteristic of CSs: the high degree of direct user/buyer involvement in the innovation process. Users are heavily involved in complex products because they are dependent upon them for their business growth, profitability and survival. Outputs are often tailored to the needs of specific customers. Consequently, the buyers' involvement in R&D, design and production methods will often take place throughout the product's development and not just at the early stages, as in the conventional model. Users may be responsible for important post production innovations involving maintenance, upgrading, performance modifications and information feedback for future production and re-innovation (Rothwell and Gardiner, 1989). Unlike mass market buyers, CS user organizations learn and internalize much of the systems technology in order to be effective in their own business. In short, they have an important stake in the innovation process.

Close user–producer engagement enables buyers to feed their needs directly into the specification, design, development and manufacture of CSs, rather than through arms-length market-mediated transactions as in the standard model. In telecommunications, for example, large user organizations (e.g. AT&T) deeply influenced the innovation trajectory of exchange systems. Successful users are demanding and intelligent buyers, endowed with high levels of technological competence. Through the user, the environment feeds directly into not only into the product but also into the innovation path followed by the CS industry. Long-term, intimate user involvement in CSs is documented in the aircraft industry, the hovercraft industry, large scale agriculture machinery and chemical process plant contracting (Gardiner and Rothwell, 1985; Rothwell and Gardiner, 1989; Grieve and Ball, 1991).

Buyers expect, and are expected, to influence the design decisions of suppliers. Transactions are infrequent, large in value and long in duration. For instance, the design and implementation of a power network control system can last for 10 years (Hughes, 1983). Because high quality in design and production requires continuous feedback from users, engineering involves long-lasting, close interactions between buyers and sellers.

Over the past two decades, the diffusion of low-cost computer power and software engineering into the design, development and manufacture of CSs has assumed increasing importance. Embedded software has improved the control, flexibility and performance of many products, while systems integration and software engineering have become central to the mechanisms of innovation in many CSs. In modern FSs, new software techniques have given rise to concurrent engineering, enabling the parallel design and manufacture of the major parts of the system using predicted data and complex models. Concurrent engineering allows exact FS replicas to be delivered before a new aircraft is manufactured, so that pilots can be trained in advance of aircraft delivery, saving on costs and time. Parallel engineering dictates that many innovation decisions have to be coordinated and negotiated *ex ante* between producers, users, regulators and other interested parties. In aircraft, according to Mowery and Rosenberg (1982, pp. 103–135), much of the US$4–6 billion devoted to R&D for new commercial jets is spent on integrating together prototype machines, avionics, propulsion, and aerodynamic and other complex components. While software engineering may be transforming CSs integration, as yet very little is known about the causes and consequences of software diffusion, or the rates and patterns of change across CS industries.

The nature of complex products has important implications for industrial organization and structure. Typically, CSs industries are bilateral oligopolies with a few large buyers facing a few large users. Buyers are not single individuals or families, as in the case of mass market durables, but large organizations with their own complex technical needs, as in the aircraft, military systems, telecommunications and FS industries. Usually producers (or systems integrators) face monopsonistic markets, highly politicized purchasing decisions, government regulators, sophisticated buyer/operators and long lead times in design and production. CSs tend to involve governments and/or regulators in the process of innovation for a variety of reasons, including safety (as in large scale human transportation systems and nuclear power plants), the need for international standards (as in communications systems), the monopolistic nature of several of these sectors (as in power generation equipment) and the importance of some CSs for the functioning of major parts of the economy. In many countries, the government owns, controls or closely oversees CS production, installation and operation in nuclear power equipment, telecommunications, aircraft and other CS sectors.

CS markets tend to be highly concentrated, the degree of contestability is constrained and purchases often depend on policies of governments and/or buyers towards nationally owned suppliers. In the UK, for example, the public telecommunications switching market, prior to the mid-1980s, was allocated to a small number of locally owned suppliers (mostly to GEC and Plessey). Since then, new policies of deregulation and liberalization have enabled one foreign supplier (Ericsson of Sweden) to capture a significant share of the market.

Typically, CSs cannot be mass produced, nor do they evolve into commodity products through time. Many mass market products appear to exhibit intense user–producer interaction and other CS characteristics at the early stage of their innovation cycle when the rate of product change is faster than the rate of process change. However, mass market industries eventually stabilize as tacit knowledge is formalized, markets expand, componentry is standardized and user–producer interaction is mediated through the market (as with automobiles, microcomputers and electronic consumer goods).[15] By contrast, CSs will tend not to reach the later stages of volume production and incremental process innovations of the conventional model, where competitive advantage and the rewards from innovation are centred (Teece, 1986). This follows because CSs tend to be large scale intermediate business-to-business goods rather than mass market products. CSs serve the needs of a small number of large industrial users and do not generally have mass market potential.

Treating CSs as an analytical category (or several categories) may have interesting implications for theory and policy. Regarding policy, when added together, CSs (including aerospace, military systems, telecommunications, nuclear power equipment and power stations) may represent a fairly large section of manufacturing output;[16] yet they appear to be an area in which East Asia has not made substantial competitive headway into Western markets. If true, this poses interesting questions as to why such a relatively

[15] See Langlois and Robertson (1989) for automobiles and Langlois (1992) for microcomputers.

[16] The US aerospace industry alone was estimated to be around US$150 billion in 1991 (*Aviation Week and Space Technology*, 18 March, 1991, p. 39).

poor export performance should be the case, given East Asia's remarkable competitive advance in commodity goods exports (Abegglen, 1994).

It may be the case that East Asian firms have intrinsic weaknesses in the area of large scale engineering and design-intensive products, such as CSs, and that their competences are more suited to commodity products such as cameras, automobiles and memory chips. Alternatively (or additionally), it may be that East Asian (particularly non-Japanese) firms are at an earlier stage of industrial development and that CS capabilities will be acquired through time. A further possible explanation could be that because CS markets are often highly politicized, risky, uncertain and sometimes uncontested, trade is relatively low (compared with simple goods) and market entry barriers for East Asian companies high. The fact that many Western CS producers straddle both military and civilian markets (e.g. aerospace, FS and telecommunications) and have close links with domestic governments and buyers may be another explanatory factor. Research could show whether any of these factors, a mixture of them or, indeed, other factors explain differences between the West and East Asia in competitive performance.

In theoretical terms, CSs appear to contrast sharply with the received wisdom of conventional life cycle, mass market innovation theory which holds centre stage in evolutionary analysis. This initial exploration suggests that it would be useful to go beyond general definitions to develop a taxonomy and a theory from which to explain CS innovation determinants, differences, similarities, mechanisms, dynamics and structures.

A taxonomy could embrace some of the dimensions which appear most relevant to CSs, but not so important to mass market goods. One such area is the degree of user involvement in the CS innovation process. In some CSs this may tail off at the point of production (e.g. in FSs), whereas in others it may carry through to de-commissioning (e.g. nuclear power equipment). Another issue which appears relevant is the degree of tacit knowledge in CS innovation. To what extent is CS development knowhow embodied in single individuals, groups and organizations, rather than codified in predictable production systems, as in mass manufacturers? Do the various CSs differ in this respect and, if so, why? It may be possible to devise measures of user engagement, tacitness and other apparently significant dimensions of CS innovation.[17]

A taxonomy might distinguish between complex stand-alone products (e.g. flight simulators and aircraft), traditional networks (e.g. electricity and

[17] Measurements could be devised for the degree of hierarchy, extent of customization, component numbers and variety, project durations and cost, skill and knowledge input diversity, software diffusion, parallel engineering, inter-company innovation interfaces and so on.

gas), information technology networks (e.g. local and wide area networks), complex capital goods (e.g. lithography equipment), plant (e.g. chemical and nuclear power), large scale transportation equipment (e.g. trains and ships) and infrastructures (e.g. intelligent buildings). The development of classification schemes for particular purposes could help guide theoretical work and policy analysis and highlight the essential properties of CSs upon which measurements of functions and efficiency could follow.

It may be that complex product groups are so different that the generic label 'CS' offers little to theory, policy and company strategy. Conversely, it could be that in comparison with mass manufactured goods, CSs are a robust and useful analytical umbrella category for a variety of purposes. For example, while most of the management and strategy literature focuses on the single firm (Whittington, 1994), a more appropriate (or additional) unit of analysis for technology management might be the functioning of the entire innovation structure, as argued above and shown below for the case of FS.[18] Without the efficient coordination of all of the innovation actors, and the interfaces between them, isolated improvements in management at the individual company level might have little effect on CS innovation efficiency and dynamism.

To sum up, the processes of innovation in CSs are likely to differ markedly from those of the conventional model because products are highly customized, large scale and engineering intensive, while production is usually single item or in small, tailored batches. Purchasing transactions are large in cost, few in number and long in duration. The latter, high volume, process intensive stages of the product life cycle may never occur in CSs. Thus competitive strategies are likely to centre upon the design and development 'stages' of the conventional product life cycle. In contrast with the conventional model, CS industries are typically bilateral oligopolies with a few large suppliers and a small number of sophisticated, demanding buyers. Buyers may well be involved throughout the process of innovation, cooperating in design, development, manufacture and post-production improvements and maintenance. In turn, this is likely to call forth a complicated institutional structure to govern and facilitate innovation, reduce risk and uncertainty and ensure *ex ante* agreements on innovation choices.

[18] To investige the technology management issues in three CS areas (FSs, wide area networks and infrastructure for digital mobile communications) a major research project is being conducted in the UK by a team from the University of Brighton (CENTRIM), the Science Policy Research Unit (SPRU) at Sussex University and the Open University Business School, with the co-operation of large international manufacturers in each area. One of the aims is to identify generic CS innovation management practices as well as those specific to the individual CS sectors.

3. *Part II: The Flight Simulation Industry: Innovation and Transformation*

Research Issues, Aims and Method

The FS sector provides an opportunity to explore some of the above arguments for the case of one CSs industry. The objective is to examine the structure, processes, determinants and sources of innovation in FS, to isolate the basic rules of innovation and to draw tentative implications for other CSs industries.[19] The study proceeded with a review of the literature and a preliminary identification of important research questions with industry executives. Data were then collected on the history and structure of the industry, the key innovation events, the main actors and their various contributions to FS innovation. Two industrial panels were set up to orient the study. Initial findings were presented to industry experts for feedback. A workshop on the evolution of simulator technology was held in Montreal, Canada.

Around 120 structured interviews were carried out in North America and Europe with senior officers from the following groups of FS organizations:

Simulation systems integrators/manufacturers	14
Sub-systems or components makers	15
Air carriers	8
Public regulators	5
National or international industry associations	9
Aircraft designers and builders	6
Research and military institutes	9
Flight training centres	4
Total	70

Questionnaires were sent to 70 senior industry executives (one from each organisation), to rank certain findings and to evaluate particular arguments. A separate questionnaire was answered by 35 small manufacturers of sub-systems and flight training devices. In total, 71 responses were obtained. This represented a large proportion of the FS sector population and no discernible, systematic bias was detected in the returns.

The questionnaires covered key events in the historical evolution of the flight simulation industry, including points of transformation of industrial structure (including the supply chain) and how integrator firms coped with technological uncertainty and complexity. The competitive strategies

[19] Although almost all interviewees were convinced that FS was an innovative, high performance industry, it is outside the scope of this paper to estimate how profitable or innovative FS was in relation to either alternative, less oligopolistic forms of organization or other industries.

of FS systems makers were identified and the nature of competition and cooperation among makers, users and parts suppliers was assessed. As well as ascertaining the nature and significance of design standards (or dominant designs) for the industry, the study also explored the role of government and regulation in the process of FS innovation. The full results of the study are presented in Miller *et al.* (1993). What follows is a summary of some of the main findings.

Introduction to FS

Simulators are devices used for pilot training. They replicate both aircraft behaviour and the flight environments in which precise tasks or manoeuvres are performed. FS was born when Ed Link patented a simple mechanical flight trainer in 1929. During World War II electronic analogue simulators were built to train pilots and reduce the number of accidents. Early commercialization began with Link, Miles and the Wright Brothers. In 1951 Redifon (now Rediffusion) built a Stratocruiser simulator for BOAC. BOAC and Lufthansa placed initial orders with CAE of Canada in the early 1960s.

From the early 1950s to the mid-1960s (prior to digital computing) a long period of experimentation took place, but there was little in the way of landmark innovations. Analogue computers improved gradually, as did the hydraulics and visuals. During this period the industry began a slow take-off.

During the late-1960s digital mainframe computers took over from analogue ones, leading to a rapid improvement in the fidelity, speed and capacity of FSs. However, up until the late-1970s pilots were mostly trained in airplanes. Simulators were viewed as a complement to live training rather than a substitute for it. Some training credits were granted by the regulators, but the process of certification was ill-defined and informal. Simulator technology was perceived as inadequate for manoeuvres such as take-off, landing and missed approach. Increasingly, though, the needs of more powerful jet aircraft encouraged a focus on problems such as air turbulence, recovery manoeuvres and landing and take-off procedures so that costly and dangerous live training in aircraft could be minimized.

Steady advances in computer and visual technologies took place during the early-1970s, expanding the use of simulators and leading to standards of fidelity and training credits. By this time, only training manoeuvres involving ground handling were still made in airplanes. In the mid-1970s cybernetic models and actuators could be used to simulate risky manoeuvres, including landings. The goal of zero-flight-time (full pilot training in a simulator) began to be discussed and the industry set about organizing the institutional mechanisms by which the goal could be achieved.

In the late 1970s the Federal Aviation Administration in the USA, the Ministry of Transport in Canada and other national regulators agreed on procedures for zero-flight-time training. Between 1977 and 1980 simulation rules were established for training the licensing of FSs. Further discussions culminated in the Advanced Simulation Plan of 1980 which categorized FSs into three groups and approved FS credits against flight time. Air navigation bodies defined standards and certified simulators for training. FS training time began to be formally logged and used as a measure of pilot experience. Pilots were retrained at regular intervals, particularly when a new aircraft was being introduced.

During the early-1980s advances in digital technology led to computer-generated imagery which could produce daylight, dusk and night-time scenes. Six-degrees-of-freedom hydraulic motion systems were developed to run on software. Velocity was simulated by a variety of techniques (including moving the visual screen up and down), giving the illusion of constant real time flight. As a result of these improvements and the Advanced Simulation Plan, sales began to increase rapidly in the early-1980s.

Today, a hierarchy of simulation systems are used for training. Full-flight simulators (FFSs) are full-size replicas of specific aircraft cockpits. They combine mathematical models and original flight data to simulate the behaviour of the aircraft and record pilots' responses to changing conditions. Given the cost of commercial flight time, pilot training and re-training is carried out in FFSs. There are four grades of FFS, the highest being used for zero-flight-time training.

In addition to FFSs, there are seven levels of flight training devices (FTDs) ranging from one (simple) to seven (highly complex). Unlike FFSs, high-level FTDs are not usually equipped with motion or visual systems. They can carry out around 50–60% of the training now performed on FFSs. FTDs are often used for training in specific operations such as flight management. Other computer-based training devices are used for familiarizing pilots with normal and emergency ground and air procedures and to introduce pilots to flight equipment and manoeuvres. A typical training programme includes 50 hours in a FFS, 50 hours in FTDs, 60 hours in computer-based trainers and a few hours of live training.

According to our interviews, a FFS can cost US$16–20 million each. This is made up of visuals (US$4–5 million), simulation (US$6–7 million) and avionics and flight management systems (US$6–7 million). A high level FTD (level 6) costs around US$3 million. Although very few official data on the total market exist, the size of the civilian FFS market can be estimated from the following unit sales data (assuming an average selling price of US$18 million): 40 in 1986 (US$720 million), 20 in 1987 (US$360 million),

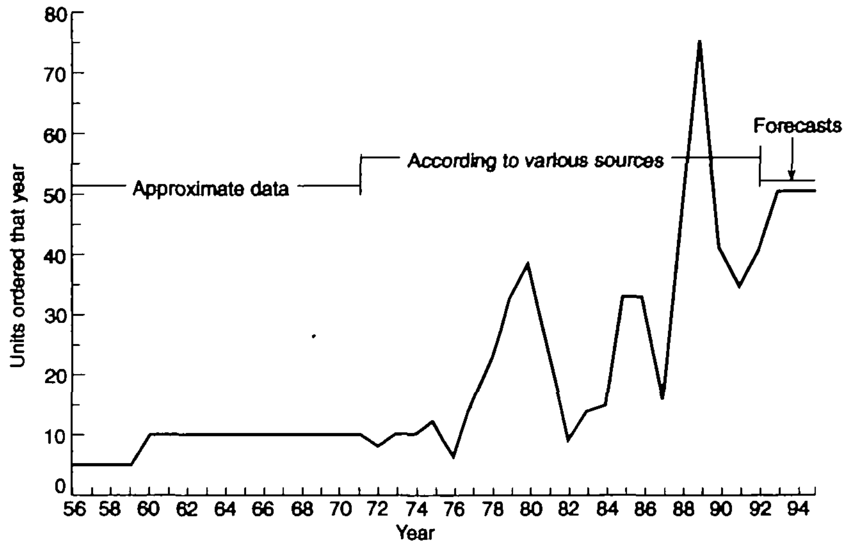

FIGURE 1. Yearly sales of FFSs, (civil sector). *Source*: Industry data/authors interviews.

42 in 1988 (US$756 million), 45 in 1989 (US$810 million), 41 in 1990 (US$738 million) and an estimated 30 in 1991 (US$540 million) (*Flight International*, 3–9 April 1991, p. 25). To these figures should be added sales of FTDs (around 25 were sold in 1990), computer based training systems, related services and maintenance. Military flight simulation is estimated to be around three to four times the value of the civilian sector. Most major suppliers compete in both sectors. All in all, the total market is fairly small (around US$1 billion per annum for civilian FS and a further US$3–4 billion for military) for an international industry, but large enough to sustain a small number of medium-sized manufactures.[20]

At the present time, training in simulators has largely substituted for training in aircraft. Simulators are now capable of fully developing pilots' skills. They contribute to flight safety by allowing pilots to carry out complicated and dangerous manoeuvres. They also produce large savings for the airlines. It costs around $5000 per hour to operate a Boeing 747-400 aircraft, compared with only $500 per hour to run a simulator (one aircraft with six crews requires around 150 hours of training per annum).[21]

As Figure 1 shows, sales of simulators grew at a steady pace up until the late-1970s. With digital computing and zero-flight-time training, FSs of all

[20] In 1990, before the market downturn, Rediffusion employed around 2900 people and Link-Miles around 1330 (plus a further 700 or so within the Thomson-CSF FS Group) (*Flight International*, 3–9 April 1991, pp. 24–25). Both have subsequently reduced their staff. Industry structure is discussed below.

[21] Figures refer to operating costs and do not include fixed costs. If the latter are included, the comparative cost of simulation is far less than real flight. Unfortunately estimates were not available for fixed costs.

TABLE 1. Price of simulators in real terms

Simulator	Year	Constant price (millions US$)
Airbus 300	1972	12.8
Airbus 300	1979	12.9
Airbus 310	1981	10.3
Airbus 300–600	1983	11.5
Airbus 320	1992	12.3

Source: Author's estimates/interviews.

kinds were rapidly adopted by airlines and training schools. This led to an increase in FFS installations from around 150 in 1980 to nearly 600 in 1992.

To meet performance demands, the complexity of FSs has greatly increased over the last 30 years. The simulator for the Boeing 737-300 had only two electronic central processing units (CPUs), while the FSs for the Boeing 767-300 and 747-400 both had 63 CPUs. The quantity and sophistication of subsystems and software has risen to meet the needs of modern aircraft training. Iteration rates (the speed at which the FS responds to pilots' decisions) have increased by an order of magnitude since 1965. Largely as a result of declining computer costs, real prices of simulators have remained at about the same level since the early-1970s. Table 1 shows the price of simulators in constant dollars for the Airbus 300 series. These and other simulators have become increasingly complex, reliable and faithful to the actual aircraft.

The Structure and Process of Innovation in FS

Although the conventional model pays little attention to the role of institutions in innovation, economist such as Richardson (1972), Arena (1983) and Dosi (1988) point to the shaping affect of meso-systems and institutions. The innovation parameters of the FS industry can be described by a technology superstructure and infrastructure made up of various groups of actors. As Figure 2 shows, FS integrators make up the core of the producer sector. The innovation superstructure represents the 'market' for FS: air carriers, regulators and professional bodies. Air carriers purchase the equipment, while regulators and professional bodies set the standards which must be met. The innovation infrastructure comprises the specialist suppliers and the aircraft builders who supply a large proportion of the hardware, software and flight data necessary for FS production.

The FS producer sector comprises around 115 firms (Table 2), including integrators of FFSs and high level FTDs, suppliers of simple systems and

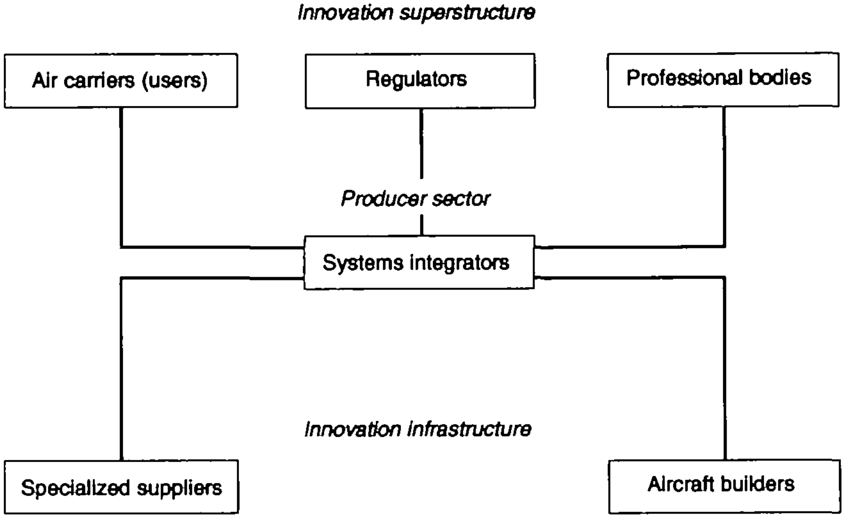

FIGURE 2. Innovation structure in FS.

specialist suppliers of components, software, sub-systems and services (the supply chain). Of the 14 integrators of FSs, eight build mostly FFSs while the other six make lower grade FTDs. A further 12 integrators make generic training devices and simple computer based systems.

As shown above, these groups are highly interactive, competent, yet independent parties with partly competing innovation interests. It is helpful to examine the functioning of each of the six categories in turn: (i) FS systems developers; (ii) the FS supply chain; (iii) aircraft builders; (iv) air carriers; (v) regulators; and (vi) professional bodies and industry associations.

The first group, FS systems integrators, are applied engineering firms which build simulators to the requirements of buyers, regulators and aircraft builders. They add value through systems capabilities, software/hardware integration, the modelling of aircraft behaviour and the application of training methodologies. Most systems developers are vertically integrated to some extent. In the early electromechanical days, up to 70% of the FS hardware was manufactured in-house. Since the onset of digital computing, outside firms supply up to 70% of the systems integrators' components. Some integrators still produce components for image generation, motion systems and visual systems.[22] Most rely on a combination of in-house technical skills and outside specialized suppliers.

[22] Link-Miles, for example, attempted to design their own computers based on distributed micro-processing architectures but soon realized that this was a mistake (interview, 1992). Today they rely on industry specialists for microprocessor designs. Although Link-Miles now concentrates on systems integration it still produces a range of medium-cost visual systems and other inputs.

TABLE 2. The Flight Simulator Industry (1992)

Systems developers of FFSs and FTDs	14
Integrations of generic training devices	12
Specialized suppliers	89
Computers	13
Instruments	10
Motion systems	5
Visual systems (High and low value)	20
Training analyses	12
Software houses	10
Upgrading of simulators	10
Others	9
Overall total	115

Source: Authors compilations from ITEC, *Aviation Week*.

Competition in the FFS sector is strong and the industry is highly concentrated. Three firms have dominated the market since the 1960s: Rediffusion, CAE and Link-Miles. In the early 1990s, Rediffusion in the UK (owned first by Hughes of the USA and later by Thomson) and CAE of Canada (which owned Singer-Link in the USA) were the largest suppliers of FFSs. In 1990 CAE sold 17 FFSs while Rediffusion sold ten (out of the total world sales of 41). Thomson-CSF of France (which owned Link-Miles in the UK) sold four FFSs in 1990. Rediffusion and CAE built simulators for most major aircraft types (e.g. 747-400 and MD-11), whereas Thomson-CSF concentrated on the A320 Airbus series. Rediffusion claimed to have 31% of the installed base of civil FSs worldwide and around 30% of annual sales (in 1991). Other minor suppliers include Flightsafety International, Microflite Simulation, Reflectone (owned by British Aerospace) and Aeronautical Systems Designers.

FS makers are required to master at least four technical fields: (i) the skills to integrate interdependent hardware and software components (motion, visual, computer and cockpit) into a coherent whole (the simulator); (ii) the know-how to use and develop the mathematical simulations which replicate the behaviour of the aircraft (as well as the actions of pilots and crew); (iii) the detailed knowledge of client requirements for training, checking and quality programmes which involves theoretical work as well as teaching methods; and (iv) a knowledge of rules and regulations (notably the acceptance test guides) which specify the requirements for simulator approval. Simulator makers must understand the aerodynamics of the aircraft and the behaviour of pilots during normal and emergency manoeuvres in order to develop complex software models to emulate flight contingencies such as landing with only one motor. They also need to understand the cognitive, emotional and physical responses of pilots.

The process of buying a simulator demands an intense interaction and synchronization among the players in Figure 2 and contrasts starkly with the market mediated transactions of the conventional model, where user demands are articulated through relatively swift, numerous, arms length purchasing decisions. Typically, air carriers contact FS makers to ask for bids. The bidding process lasts a few months and involves major development choices. The FS is designed to meet the buyer's needs as well as the regulators' expectations. On average, the process of design and integration lasts two years and involves close cooperation between the air carrier, the aircraft builder and the simulator manufacturer. Simulators are customized to the requirements of each aircraft. Even within a type of aircraft, such as the 747-400 series, each airplane (and each FS) is different. FSs may need to replicate different motors, avionics and cockpit displays; air carriers demand specialized training programmes with tailored instructor stations, recovery scenarios and so on. Once delivered to the air carrier, the simulator is tested by the regulator for certification.

The second group, the FS supply chain, is made up of around 89 large and small specialist technology suppliers (Table 2). Major sub-system suppliers, such as Evans and Sutherland (E&S), work closely with FS makers on new innovations. For example, E&S, a pioneer in image generation, has a long-standing relationship with Rediffusion and other leading FS producers. E&S works with integrators to ensure its technology can integrate with other parts of the FS. Sub-system firms also collaborate closely with other FS input suppliers. The leading workstation supplier for low-end FSs, Silicon Graphics, works with the producers of software tools for FS (e.g. Gemini) and with CAE to supply specialized image processing systems and real time computing technology.

Aircraft builders, the third group, form another part of the innovation infrastructure. They produce aerodynamic simulators for aircraft, but tend not to build FSs because of the cost, specialist skills and barriers to entry in simulation. Aircraft makers are, however, central to the FS development process. They not only sell the aerodynamic models, experimental flight data and, sometimes, cockpit avionics to FS makers, but also work closely with FS engineers, suggesting ideas for training manoeuvres and other FS tasks.

The transfer of experimental flight data from aircraft builders to FSs is overseen by the International Air Transport Association. Roughly two years ahead of a new aircraft delivery, systems developers buy the mathematical models which describe the aerodynamics behaviours of the aircraft. The data package can cost around US$800 000 and has to be approved by the regulators so that training can commence ahead of aircraft delivery.

Air carriers, the fourth group, are part of the innovation superstructure in FS. As clients, they purchase FSs according to aircraft replacement cycles, expected flight market growth and financial resources. On average, each set of 15 airplanes requires one simulator. Air carriers have to train pilots according to their own standards and those of the regulators. They expect simulators to be fully customized to fit their training requirements and to be certified shortly after delivery. Air carriers run pilot training centres and develop training methods and programmes. As they develop new demands and new expertise they inform systems developers about their future needs. Innovative designs suggested by systems developers are usually subjected to analyses by air carriers for their approval.

Preference of air carriers for particular FS integrators is partly based on regional and historical factors. For instance, simulators for the European Airbus are mostly built by Thomson-CSF of France or, less frequently, by CAE. Simulators for Boeing and McDonnell Douglas are built by both CAE and Rediffusion, while Thomson-CSF is attempting to sell simulators to Boeing. Although substantial overlap and competition exists, to some extent the contestability of the market is determined by the purchasing decisions of large buyers, which in turn can be influenced by national government policy.

Regulators, the fifth group, form another part of the innovation superstructure. The Federal Aviation Administration of the US, the Civil Aviation Authority of the UK and the Ministry of Transport of Canada are recognized as leaders. Regulators demand that standards are met in return for certifying both the training programmes and the FSs used in them. Regulators indicate the real flight time credits allowable through FS training. They insist that simulators are faithful to the aircraft so that safety standards can be improved. Regulators are willing to change regulations to encompass new innovations, if such changes improve safety. They also recommend innovations which may improve safety standards in the medium- to long-term.

Formal industry associations and professional bodies, group six, have an important stake in the innovation process. Industry associations include the Air Transport Association in the US and the International Air Transport Association. Important professional bodies include the Royal Aeronautical Society in London and the American Institute for Astronautics and Aeronautics. By organizing working groups to produce new standards for the industry, the professional bodies, especially the Royal Aeronautical Society, have emerged as the unofficial global meeting places of the technical community.

To sum up, the need to coordinate innovation in FS called forth a complex institutional superstructure. New technology proposals are channelled through professional bodies such as the Royal Aeronautical Society. Acceptance test guides are established by regulators who then specify approval requirements and validate tests during and after the development of an FS. After contracting, trust and reciprocity are necessary between buyers and sellers. Because many uncertainties have to be resolved during the process of innovation in FSs, they cannot be purchased as arm's length market transactions as in the standard model. Instead, intense relational transactions develop, allowing for constant information exchange and regular interaction between industry participants. Continuity of relationships is valued and respected, and helps define the competence of partners. Innovation in FS unfolds within a set of governing institutions where, as discussed below, cooperation and competition co-exist.

Innovation and Industrial Transformation

Industry representatives identified four major groups of factors which influenced the industry's evolution over the past 40 years: (i) institutional rule changes; (ii) technological changes; (iii) competitive strategies; and (iv) exogenous market events. Questionnaire respondents were asked to rank each group in terms of relative importance. Within each group, FS executives were asked to identify the most significant sub-factors effecting the evolution of the industry since the 1950s. Table 3 shows the response of the FS community.

Interestingly, technological innovation was not viewed by industry experts as the most important inducer of industrial transformation. Technology was seen as a facilitator; a necessary but insufficient condition for change. Regulatory/institutional turning points were viewed as the most important events by industry experts. Without these, new technology breakthroughs could not have been exploited by the industry.

The most important regulatory event was the advanced simulation plan of 1980, discussed below. This made zero-flight-time training possible, leading to market growth and a governance structure able to cope with rapid technological innovation. Prior to the advanced simulation plan, the certification of simulators by regulators was uneven and informal. In the mid-1970s air carriers pushed for objective standards and a system to enable simulation to substitute for live training. The idea of the advanced simulation plan originated with users (airlines) which convinced the regulators that all training manoeuvres, including landing, could be carried out in simulators. Eventually, joint government/industry experiments were set up under

TABLE 3. Ranking of Change-inducing Factors Affecting the Flight Simulation Industry Since the 1950s*

1. Institutional/regulatory
   - Advanced Simulation Plan (1980)
   - Classification of FTDs (Early-1990s)
   - Advanced Qualification Programme (Early-1990s)
2. Technical
   - Shift to digital computing (Late-1960s)
   - Motion-Systems 6 degrees of freedom (Early-1970s)
   - Computer generated imagery (Early-1980s)
   - Glass cockpit aircraft (Mid-1980s)
   - Reduced instruction set computing (RISC) (Early-1990s)
3. External market events
   - Kick-off orders by innovative carriers (Early-1960s)
   - Entries of independent tranining centres (Early-1980s)
4. Internal competitive events
   - Consolidation of mergers (Late-1980s)
   - Entry by acquisitions of major players (Early-1990s)

* No attempt was made to compare the sub-factors for relative importance.

the Federal Aviation Administration and the Air Transport Association to assess the technical and training issues and subsequently the idea was accepted.

Two other less important regulatory events were the classification of FTDs and the advanced qualification programme. The advanced qualification programme categorized FFSs and FTDs according to levels of complexity and allowed air carriers to design their own training programmes using combinations of FFSs, FTDs and computer-based training devices. For some functions, FTDs emerged as an alternative to FFSs. The cost advantages of substituting FFS training with FTD training appealed to the air carriers and led to development and take off of FTDs in the early-1990s.

The dominant technical event was the shift from analogue to digital computing. This substantially increased the power and speed of FS operations per unit cost and paved the way for second-order innovations in computer-generated imagery, glass cockpit avionics, RISC architectures, software modelling, flight performance predictions, concurrent engineering and workstation-based FTDs. Another technological event was the perfection of six-degrees-of-freedom motion systems in the early-1970s.

The most significant market event was the start-up orders from leading carriers in the early-1960s which gave birth to the modern industry. Another boost to the industry was the independent training centres which entered in the early 1980s (e.g Flight Safety International) to offer FS services to smaller airlines and the military.

The key competitive turning point was the wave of mergers and acquisitions in the late-1980s. Thomson-CSF acquired Burtek in the USA and Link-Miles in the UK, while CAE acquired Singer-Link in the USA. Hughes acquired Honeywell Simulations in the USA and Rediffusion in the UK (the latter was sold to Thomson-CSF in 1994). The acquisition of established FS players by aircraft manufacturers signalled further market concentration.

To sum up, the most significant transformation events in FS were regulatory and institutional. Technological change was a facilitating factor, necessary but insufficient for industrial evolution in FS. Intriguingly, the least important factor cited by respondents was the entry and exit of FS integrators. This contrasts sharply with the conventional model, where industrial adjustment among producers is centrally connected to innovation.

Innovation, industrial stability and adjustment

As noted in Part I, in the conventional Schumpeterian model, radical technological discontinuity leads to creative industrial disruption. Subsequent process and product innovations shape observed patterns of exit and entry (Tushman and Anderson, 1986; Utterback and Suarez, 1993). These elements of the conventional model do not fit the FS industry, nor are they likely to apply to other CSs industries (Hobday, 1994).

In contrast with the conventional model, the FS supply industry exhibits a high degree of stability through time, despite dramatic technological discontinuities and other upheavals. Most of the competitors which entered the industry in its formative stage are still active, either as independent firms or as autonomous divisions of larger firms.

Figure 3 shows the total number of systems developers in 1992 was 14, down from a peak of 18 in 1985–1986. Since the 1950s, the FS industry has been dominated by three major firms: CAE (including Singer-Link), Rediffusion and Thomson-CSF (including Link-Miles). Our historical research showed that only three major entries took place over a 25 year period. As far as exit is concerned, only two systems developers left the industry over a period of 25 years (Miller *et al.*, 1993).[23]

According to industry participants, barriers to entry and exit explain the stability of a tight oligopoly in the FS supply industry.[24] The cumulative

[23] The factors which explain stability and continuity in FS may also apply to other CS industries such as telecommunications exchanges. Both industries were subjected to similar waves of apparently 'competence destroying' technological change (the diffusion of digital semiconductor-based technology) in accordance with Tushman and Anderson (1986). However, despite these changes, in telecommunications (as in FS) many of the old 'electromechanical oligopolies' (e.g. Siemens, Ericsson and Alcatel) survived and remain major players in the digital exchange competition.

[24] As discussed below, major industrial adjustments occurred in the supply chain, rather than among equipment producers.

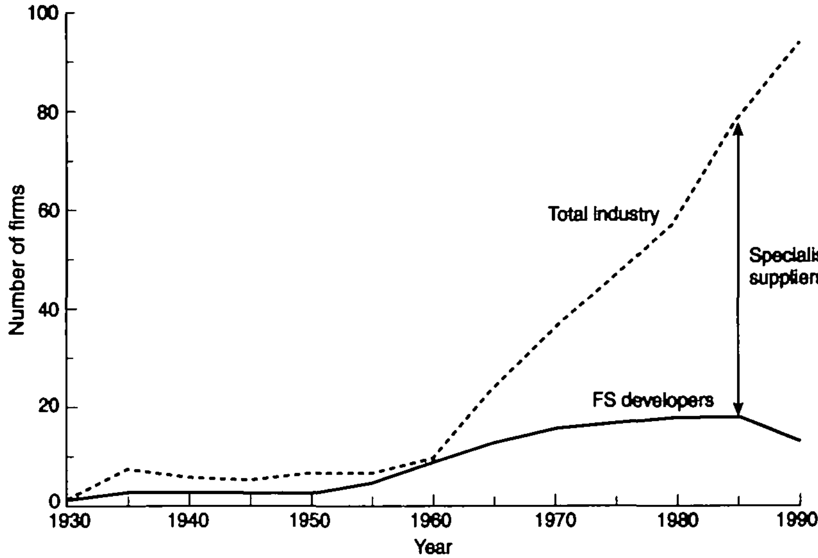

FIGURE 3. Stability among systems developers and rapid growth of suppliers.

learning advantages of early movers is a major barrier to exit and entry. The learning of complex FS technologies requires a considerable amount of specialized knowledge. Learning-by-doing is one source of competence building. System developers undertake over 30% of their R&D as part of specific simulator sales contracts. Additional sales lead to self-reinforcing learning effects, which consolidate success and widen the knowhow gap between incumbents and potential newcomers. Potential entrants are deterred by the high cost of bidding, not to mention the further costs of systems development. FS integrators find it difficult to leave the industry or to diversify to other sectors because many of their skills and assets are of little value outside the narrow confines of the FS industry.[25]

As shown above, successful FS makers have to accumulate specialist knowledge in at least four distinct inter-related areas. Early competitors developed proprietary models of the behaviour of planes (landing gear, wind shear and so on), pilots' cognitive reactions (e.g. in training manoeuvres) and numerical databases (e.g. the digitalization of satellite and aerial photographs). In addition, producers have developed the knowhow to blend these

[25] This feature applies to telecommunications exchanges and computer manufacturing where digital technology seemed to favour cross entry as a result of technological convergence. However, IBM invested heavily in telecommunications but later retrenched into its core computing business. Likewise, telecommunications firms such as Ericsson of Sweden invested in computing equipment but later withdrew after sustaining heavy losses. Today, the conventional wisdom in the information technology business is centred on core competence rather than ideas of convergence.

areas of knowledge into a functioning system. Consequently, the cumulative number of simulators built is an accepted industry proxy for accumulated engineering expertise. Even large competent firms such as Boeing Aircraft, with expertise in aerodynamic engineering simulations, choose not to try and compete in FSs, relying instead on CAE and Rediffusion.

Market reputation for quality and performance is another highly significant barrier to entry. The main criteria by which buyers chose FS makers are demonstrated capabilities in: (i) designing and building simulators; (ii) delivering them on time; and (iii) obtaining certification by regulators. Users expect high levels of competence from system developers and they exclude those considered not competent from the bidding process. Even firms in closely related areas are rarely invited to bid for new orders (e.g. aerospace firms and makers of FTDs).

Successful firms enhance their reputations and gain recognition from new clients within the consensus building institutions. Since technical working groups define the parameters of what is acceptable, they became a vehicle for incumbents to display competence. Systems developers are often ranked in reputation and credibility according to their contributions to collective debates. Like learning effects, reputational effects are cumulative in character.

Financial barriers to entry are also significant. Developing the technical competence to build simulators requires time, experience and large investments. The cost of entry deters new entrants, even those with deep pockets. Cyclical variations in sales and profitability add to the financial risk and uncertainty involved.

Systems integrators are viewed as valuable assets by the FS sector as a whole. Even in the face of financial difficulties they rarely exit. They either survive or are absorbed by competitors or related companies. In the late-1980s there were major takeovers of this kind. The systems firms survived partly because they were valued as repositories of competencies and linkages for the sector as a whole.

In contrast to the stability among FS integrators, the data show a constant and dynamic adjustment among firms in the specialist supply chain. In order to facilitate innovation, new suppliers regularly enter and exit the supply chain. The total number of specialist suppliers grew steadily from around 10 in the early-1960s to 89 in 1992 (Tables 2 and 4). Specialists are often small firms, created by technical entrepreneurs. Some firms enter from related sectors to supply computer and visual systems, motion equipment, cockpit instruments and avionics, software, training analyses, maintenance and other services. In 1992 two-thirds of the specialist firms had assets of less than US$1 million, and 95% of them sold some proportion of their output inter-

TABLE 4. Supply Chain Adjustment to Technological Evolution and Discontinuities

Type of firm	Number of firms	Mean year of entry
Computer systems for simulation technology	13	1965
Computer graphics and image generation	10	1980
Training analysis and consulting	12	1978
Cockpit instruments and electronics	10	1963
Training devices	12	1982
Complex visual systems	10	1987
Software	10	1982

Source: Questionnaire returns, industry data and interviews

nationally (interview data). Around half of them were so specialized that they saw no major competitor in their particular niche.

Entries and exits occur frequently in the supply chain as new technical trajectories expose existing specialists to the risk of obsolescence. With each new technological wave, entries accelerate, some firms exit and others re-orient their activities to survive. For example, innovations in computer-generated imagery and low cost visuals led to a dozen recent entries. Suppliers of specialist mainframe computer systems (e.g. Gould/Encore), which entered in the mid-1960s, are currently in the process of exiting or scaling down substantially due to the adoption of low-cost microprocessor-based (RISC) technology. New entrants such as Silicon Graphics and Motorola are rapidly gaining shares in the computer graphics and image generation sectors, displacing traditional suppliers.

Table 4 shows the average year of entry for each group of specialists. A group of cockpit instruments suppliers entered in the early-1960s, closely followed by mainframe computer systems suppliers. A dozen or so training analysis and consultancy firms entered in the late-1970s. Groups of software firms, computer graphics suppliers and training device makers entered in the early-1980s in response to the industry take-off. Later in the 1980s 10 or so suppliers of complex visual systems entered.

In summary, industrial adjustment occurred historically in the supply chain rather than among the equipment manufacturers as proposed in the conventional model. Cumulative barriers to entry and exit enabled manufacturers to survive radical upheavals. In other CSs industries (e.g. telecommunications and aircraft manufacturing) similar factors may well produce an analogous pattern of industrial adjustment.

Institutional Coordination of Innovation and Dominant Designs

Contrasts with the conventional model. In the conventional model, innovations are subject to selection by user–producer interaction in the early stage and then by arm's length market choices, as buyers evaluate the merits of the competing products of rival firms. By contrast, FS innovations involves a high degree of cooperation among FS integrators, regulators and other players throughout the innovation process. Arm's length market choices play little or no part in the selection of FS product innovations, nor are they likely to in other CSs goods. Arriving at a common product standard (or dominant design) requires the *ex ante* pooled expertise of FS integrators, air carriers, systems developers, aircraft builders, regulators and international coordinating bodies. Each party has its own specific interests in the design, but each has a general interest in promoting technological improvements. In the absence of a conventional market selection mechanism, an elaborate set of institutions has evolved to coordinate and promote innovation in FS.

Crafting a responsive collaborative framework. In FS, technological opportunities and threats were insufficient conditions for the diffusion of innovations. The research showed that the institutional structures and processes taken for granted in today's industry did not simply occur or arise out of market transactions. On the contrary, they were initiated and crafted by a small number of key individuals widely recognized across the industry as entrepreneurial leaders, not only in the field of technical innovation but also in the areas of regulation, standards and consensus building. Each successive wave of technological change was associated with one or more industry champions, including Edward Booth (Federal Aviation Administration), Captain Ray Jones (Royal Aeronautical Society), Brian Hamson (CAE), Vince de Paulo (American Airlines), Hans Dieter Hass (Lufthansa) and M. Bess (Air France). Drawn from a variety of groups in the innovation structure, these individual were entrusted by their organizations to bring about progress in the national and international decision-making institutions, for the benefit of the entire FS industry.

The crafting of appropriate institutions able to respond to new technological opportunities resulted in a robust and enduring system, the emergence of new FS markets and the diffusion of innovations. Through specific institutional mechanisms, the FS community was able to discuss, test and coordinate successive changes in technology and new approaches to training.

Competing innovation interests. Within the institutions, competing innovation interests were reconciled so that *ex ante* agreements on new innovations could be arrived at. The primary innovation interest of integrators and their suppliers was to promote sales through improvements in quality and performance and reductions in cost. By innovating in accordance with users' expectations, suppliers gain or maintain market share and generate enough sales to recoup their R&D investments. Suppliers therefore only innovate with a reasonable probability of certification in mind.

By contrast, the primary interest of air carriers was to promote innovations which would reduce the cost and improve the effectiveness of training while maintaining safety standards. Like suppliers, air carriers also needed to know that new FSs or other training devices would be certified. Carriers had an additional interest in avoiding innovations which might depreciate prior investments in FSs and training programs.

Regulators were responsible to government bodies for ensuring that innovations did not jeopardize flight safety, which defined their stake in the innovation process. Yet they held the primary responsibility for approving any changes in the modes of FS design, classification and certification. On the one hand, an overly zealous regulatory system would block technological progress and raise costs. On the other hand, a lax system would lead to poor quality training and worsen FS reliability and flight safety.

Aircraft builders also held specific innovation interests. Central to the innovation process, they had to generate experimental flight data and aerodynamic models for the simulation systems developers to take up and use. Builders were pressurized by the powerful air carriers to develop and deliver high quality data packages on time. For these services they received significant payments. Any lapse in performance could bring abut a swift and punitive response from the air carriers.

In short, innovation in FS involved a division of responsibilities and a variety of complementary, sometimes competing, motivations and interests. Over the past 30 years or so, the FS industry created institutional mechanisms to identify and coordinate the diffusion of both radical and incremental innovations.

Mechanisms for institutional coordination. Within the institutions a collective strategy for the *ex ante* targeting of innovation emerged. To deal with increasing FS complexity, the industry evolved a self-organizing structure which is able to adapt and respond to technological and economic events. In the 1970s the regulators were invisible to the FS makers. Simulator manufacturers were discouraged from dealing directly with regulators. Airlines regulated themselves, overseen by relatively passive regulators. During the 1980s new technologies and the need for fast responses to complex problems brought the regulators into close iterative contact with the FS makers and other parties.

The FS industry coordinates innovation by forming: (i) *ad hoc* working groups for incremental innovations; and (ii) long-term networks for major innovations. Incremental innovations occur in the normal course of building specific simulators. For instance, a novel instructor station may be added by an *ad hoc* network consisting of the integrator, the air carrier and the regulator. Air carriers may request modifications or encourage new designs (e.g. a new visual system) from the simulation system developer within a working group. Working groups are both cooperative and competitive events. Supply firms use them to display their competencies to buyers (air carriers) and regulators. Reputation and technical credibility are demonstrated during the institutional rule setting in working groups. Displays of below-par skills affect a firm negatively, while shows of skill and competence can benefit a company's sales.

Working groups are organized by industry associations and professional bodies to produce standards and agree on new designs. As discussed earlier, the main organizers include the Air Transport Association, International Air Transport Association, Federal Aviation Administration, Civil Aviation Authority, Royal Aeronautical Society and American Institute for Astronautics and Aeronautics. The latter two professional bodies in the UK and the USA have become the global meeting places of the FS technical community. For instance, the recent working group on the certification and standardization of simulators worldwide was both initiated and hosted by the Royal Aeronautical Society. Eventually, its recommendations will be accepted officially by most national regulators.

In the study groups the interested parties negotiate new innovative goals. If successful, regulators accept these goals and certify the simulators accordingly. This framework enables FS makers to invest in forward R&D with some degree of probability of approval and use by air carriers. The system acts as an *ex ante* focusing device for longer-time R&D and, according to industrialists, prevents underinvestment in new technology.

Study groups diffuse technological innovations and new industry practises after debates and studies. One example was the Advanced Simulation Plan. Studies by working groups argued that complex pilot manoeuvres could be carried out in simulators. This view was accepted and approved by the Federal Aviation Administration and other national regulators in 1980. The Advanced Simulation Plan became standard practise among air carriers, leading to the take-off of the FS market during the 1980s. A second example was the Advanced Qualification Programme. The Federal Aviation Administration and the Air Transport Association met in July 1987 to discuss the revision of performance validation parameters. A study group was made up of systems developers, airplane builders, regulatory bodies and training centres. In 1989 a draft report was completed enabling FTDs to be certified alongside FFSs for training purposes. This allowed air carriers to design their own training programs using combinations of FFSs and FTDs and led to the take-off of the FTD market.

A third example was the introduction of software-based, concurrent engineering. In the mid-1980s a major airline insisted that aircraft builders deliver data packages to FS integrators, so that FSs could be built prior to the delivery of new airplanes. This allowed the airline to train its pilots entirely on simulators, saving on costs and time. The development of concurrent engineering practises in FS involved close interactions between integrators and other parties, structured by formally agreed rules.

For concurrent engineering to take-off, aircraft builders had to provide predicted data, logical structures and mathematical models well in advance of aircraft manufacture. Simulator makers had to interact with aircraft makers to understand both the data and the aerodynamic models for the engines and flight management systems. Regulators had to verify the quality of the data packages and develop temporary certification procedures (prior to the availability of actual experimental flight data). Committees had to be established under the International Air Transport Association to formalize data exchanges and outline standard procedures for any contract to purchase airplanes and/or simulators.

Today, regulators play a pro-active part in the innovation process. For example, the Federal Aviation Administration provides guidance to manufacturers on new generations of simulators to ensure higher safety (or lower costs at equivalent safety). Regulators encourage innovation by allowing air carriers to gain training credit hours and by certifying that simulators meet performance criteria prior to aircraft manufacture. They legitimize FSs by testifying that they are faithful to the behaviour of a specific aircraft. They also encourage innovations in the design and use of training equipment.

Although regulators are part of the innovation process, most have limited resources. They therefore remain informed by participating in the joint study groups. A few, such as the Federal Aviation Administration and the Civil Aviation Authority, have the resources to become involved in the engineering detail of the technology. These regulators take the lead in promoting best practise. Other national regulators tend to follow.

According to the questionnaire returns, the three main functions of the working groups are: (i) to target innovative efforts; (ii) to ensure that major innovations are appropriate to all parties before introduction; and (iii) to involve the regulator early in the process. Interviewees were asked to rank the relative influences of the various parties to the introduction and coordination of radical innovations. FS suppliers were ranked only third, after air carriers and regulators, reflecting the importance of the latter two groups. International bodies, industry associations and training organizations were jointly ranked fourth, while sub-systems developers came fifth.

The nature of dominant designs in FS. Widely shared, stable conceptions emerge on how best to design and make a simulator capable of emulating a specific aircraft and meeting the training needs of pilots. However, unlike the dominant design of the traditional model, the FS standard is agreed *ex ante* by users and other parties and not trial-tested in the marketplace. In contrast with the conventional dominant design, the FS standard does not signify an industry shakeout, nor does it signal the onset of volume production and incremental, process-led improvements as proposed by Abernathy and Utterback (1978). In FSs a dominant design signifies: (i) an agreed approach among competitors and users to product and process; (ii) the dominance and stability of this approach for several years; and (iii) a path or trajectory for subsequent innovations.

These essential features may well apply to dominant designs in other CS industries. In contrast with the conventional model, the rate of product innovation remains higher than process innovation over the duration of any particular standard in many CSs, where new demands constantly flow from users to producers. As a result, the latter, mass market stages of the conventional 'innovation cycle' are never reached and output volumes remain small.

Commonality in FS design is usually defined at the level of sub-system. For example, for the past decade, industry wisdom stated that computer hardware will be digital, displays will be computer-based, motion systems will use software-driven hydraulic components and integration will rely on simulation models. Since the adoption of the Advanced Simulation Plan, only incremental changes have been made to the 1980 standard FFS approach. These widely accepted parameters defined the design trajectory of FFSs.

However, radical new trajectories do emerge from time to time to challenge the dominant designs of FSs. Most recently, high level FTDs based on RISC workstations have threatened the dominant design of the FFS. The final outcome of this contest has yet to be seen. However, most industrialists believe that for some time to come, FFSs will be used in combination with FTDs, and that FFSs cannot yet be dispensed with for many training activities.

The irrelevance of the volume production stages of the product life cycle in CSs does not mean that production methods are unimportant for competitiveness. On the contrary, in FS (as in aerospace, military systems and telecommunications) firms compete partly by the efficiency of their internal production organization, especially with respect to software engineering. With very low volume outputs (say up to five simulators), software development is organized on a customized unit basis. Successful firms learn to develop the specialized skills needed to manage very low volumes effectively. With more than five units, firms tend to organize software within a functionally separated, matrix structure in order to improve efficiency by making tasks routine as far as possible. Firms also try to gain synergies across projects and from one generation of system to another. Input/output software is sometimes common across projects, as are data buses and fly-by-wire systems. In some cases the same basic software tools can be utilized for both civilian and military systems. Thus, production competitiveness concentrates on efficiency within what would be described as the early stages of the conventional model, mainly design and prototype development.[26]

Competition and collaboration in FS innovation. In the conventional model of innovation, cooperation and competition among rivals are usually viewed as mutually exclusive. Cooperation, it is argued, may lead to price fixing and other collusive behaviour patterns. However, in FS competitive and collaborative strategies have always co-existed, both being necessary complements of each other. Rivals collaborate to set rules and to develop anticipatory standards in the early stage of an innovation, with each other, with users and with regulators. Once the rules are set the industry is fiercely competitive in contested areas.

Regarding competitive strategies, FS suppliers gain advantage by building competences, technical credibility and expertise in training analysis, cognitive decision-making, mathematical modelling, systems integration and software engineering. According to industry participants, learning (and the accumulation of knowledge) is the most important element of competitive strategy. Second is a firm's reputation for technical expertise. Third is on-time delivery. Fourth is the credibility gained by participating in working groups.[27]

FS suppliers also have a strong motive for collaboration. For the market to develop, integrators need their innovations to be accepted by the users and regulators. This requires a coherent institutional framework. Similarly, users and regulators need to ensure safety standards are met. When radical innovations are proposed, integrators cooperate horizontally to set standards,

[26] These early stages correspond to the project and job-shop ways of organizing production described by Hayes and Wheelwright (1984). In their terms, the conventional model would be a special case termed assembly line process organization.

[27] See Miller *et al* (1993) for details of the determinants of competitive advantage in FS.

reduce uncertainty, enable the market to develop and allow learning among suppliers and users. Without agreement, a market might not develop at all. Users might not be able to benefit from technological advance while suppliers might find the rules of competition confusing.

In the case of minor innovations (e.g. CAE's recent visual system 'Maxview', which has begun to displace Rediffusion's 'Wide' system), suppliers compete directly in the market once the regulators have approved the design. Thus, in the case of minor product innovations, collaboration occurs vertically between suppliers and users and regulators, rather than horizontally among suppliers. User–producer collaboration of this kind occurs throughout the innovation process, resulting in long-term relations with aircraft users, FS makers, regulators and professional bodies.

According to FS integrators, the most important area of cooperation is their long-term relationships with innovative air carriers. This includes both the development of specific simulators and joint research activities for future FSs. Collaboration in working groups is viewed as the chief means for resolving technological and regulatory issues. Other significant collaboration strategies include long-term alliances with aircraft builders and cooperation between FS makers and specialist suppliers.

Exclusive long-term relations between air carriers and FS suppliers are viewed with suspicion by the industry. FS firms claim they prefer market flexibility and the stimulus of several demanding buyers. For their part, most air carriers wish to avoid being locked in and prefer the option of choosing between FS suppliers. Manufacturing and development alliances between civilian simulation integrators are rare in FS and no major examples could be found in this research. However, some horizontal partnerships were identified in the military field (e.g. Link-Miles has collaborated with British Aerospace, Rediffusion and other FS makers in the European Fighter Aircraft and other projects). Such collaborations are frequently the result of political/military pressures.

4. *Conclusion*

This paper has argued that an important group of products and industries could be classified as CSs and that the processes, structures and dynamics of innovation in CSs could be expected to contrast sharply with those found in the conventional Schumpeterian model. It has explored in detail the historical patterns of innovation and industrial transformation in FS, as one example of a CS industry. The innovation processes in FS were consistent with the general propositions concerning CS industries. However, it is not possible to generalize from a single case study and further research is underway to explore and compare patterns of innovation in other CS sectors.[28]

FS was found to be an example of a self-organizing, enduring, industrial system able to innovate in response to the needs of the external environment and large users in particular. In contrast with the arm's length market transactions of the conventional model, FS designs were negotiated *ex ante* by the main innovation agents, within an innovation structure designed to cope with uncertainty and risk. Unlike the mass market goods of the conventional model, FS products did not follow typical life cycle patterns but constantly evolved to meet the requirements of demanding users, regulators and professional bodies. In the absence of conventional market focusing devices and inducements, other CS industries might well require analogous structures for enabling innovation and allowing users to engage directly in the innovation process.

Technological opportunities and threats were necessary but insufficient conditions for the diffusion of innovations in FS. Also essential were the institutional structures which facilitated innovation and allowed new markets to develop. Governing institutions in FS were initiated and crafted by a small number of key individuals, representing suppliers, regulators, standards bodies and users. Over the years, a robust and elaborate innovation structure, now taken for granted, evolved through which the FS community was able to discuss, test and coordinate incremental and radical innovations, agree new approaches to training and generate new product markets.

The study showed that the innovation structure in FS was made up of a governing superstructure of active and capable users, powerful regulators, industry associations and professional bodies. The supply infrastructure was made up of FS integrators, large aircraft manufacturers and a chain of suppliers which produced FS components, subsystems, software and services. Each group of actors defended its own interest in the innovation process and outcome, but understood the need for collective agreement. Over the decades, successive innovations were negotiated between the various actors resulting in new FS markets and the exploitation of technological change.

Since the industry's inception, a remarkable degree of long-term stability among FS suppliers was observed, despite radical technological discontinuities and the predictions of the conventional model. Stability was due, in part, to the cumulative, long-term barriers to entry and exit facing FS makers. Such stability might also apply to other CSs industries where integrators are valued repositories of competence, knowledge and linkage. In contrast with

[28] Hobday (1994) indicates how a taxonomy and theory of CSs might be developed for the purposes of corporate strategy and government policy. Notes 6 and 18 mention two major CS research projects, both of which compare different categories of complex products.

the conventional view, exit and entry took place among specialist suppliers rather than among FS manufacturers. Through time, as specialist firms responded to technological advance, the supply chain restructured to meet changing conditions.

Agreed approaches to FS design and manufacture emerged but these differed markedly from the conventional dominant design. Product standards signified neither an industry shakeout nor a shift to competition based on process-intensive innovation. Indeed, the latter volume production stages of the conventional model were irrelevant to FS, as they probably are to other CS products. As a result, strategies for FS manufacture focused on design, prototype development and small batch production.

Competition and collaboration co-existed in FS. Horizontal collaboration between FS makers occurred in the setting of standards and agreeing the introduction of innovations. Once agreed, firms competed on price, quality, performance and delivery. Vertical collaboration occurred between FS suppliers and users throughout the innovation process. Depending on the final FS product for their business needs, users played an active part in design and development. The form of collaboration in FS had both advantages and disadvantages. Without it, suppliers, users and regulators would have suffered greater uncertainty and risk, markets might not have developed and innovations might not have diffused. With it, there existed the danger of collusion among suppliers, non-contested markets, the growth of bureaucracy and 'cosiness' between suppliers and users.

Thus, in contrast with the conventional model, innovative performance in FS depended not solely or primarily on the capabilities, skills and strategies of any single supplier, but rather on the efficient functioning of the entire innovation structure. In FS, competitiveness and efficiency depended on effective regulation, inter-corporate collaboration and communications, and the skills of the various working groups in sharing knowledge and reaching agreements.

It is possible that other CSs industries will exhibit similar institutional structures in order to coordinate innovation, reduce uncertainty and permit markets to develop in the absence of the conventional Schumpeterian mechanisms. This is due to the evolving nature of complex products, the industrial structures in which they tend to be embedded, and the need for active participation of users. In areas such as telecommunications exchanges, nuclear power plant and military systems, as in FS, governments and regulators have a stake in the innovation process for reasons of safety and the need for national and international standards. Other CS industries may also be undergoing upheavals as a result of advances in software engineering and systems integration. Further comparative sectoral research is underway to illustrate the logic of innovation in a variety of CSs and to provide a clearer understanding of the determinants of competitive performance in CSs industries.

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