ELSEVIER

Research Policy 26 (1998) 689–710

research policy

Product complexity, innovation and industrial organisation

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Accepted 30 September 1997

Abstract

This paper highlights distinctive features of a neglected class of economic activity in the domain of innovation, namely the creation and development of high cost, complex products and systems (CoPS), asking how their nature might be expected to affect innovation and industrial organisation. It argues that because CoPS are highly customised, engineering-intensive goods which often require several producers to work together simultaneously, the dynamics of innovation in CoPS are likely to differ from mass produced commodity goods. To consider the argument, the paper describes some of the defining features of CoPS and counterpoises two ideal-type innovation schemes: a 'conventional' mass production innovation scheme, and an idealisation more suited to CoPS. Implications for innovation and industrial coordination are discussed, pointing to the project and the project-based organisation as natural CoPS organisational forms. While major differences between groups of CoPS are apparent, user involvement in innovation tends to be high and suppliers, regulators and professional bodies tend to work together with users ex-ante to negotiate new product designs, methods of production and post-delivery innovations. Markets are often bureaucratically administered and contestability is low in contrast to commodity goods which are characterised by arms-length market transactions. In relating the critical attributes of CoPS to industrial processes and organisational form, the paper emphasises the wide variety of possible innovation paths and points to the CoPS project, rather than the single firm, as a chief unit of analysis for innovation, management and competition analysis. © 1998 Elsevier Science B.V.

Keywords: Product complexity; Innovation; Industrial organisation

1. Introduction

The purpose of this paper is to draw attention to a neglected area of innovation study, namely the creation and development of high cost, complex products and systems (CoPS), asking how their nature might be expected to affect innovation and industrial organisation. The paper describes some of the key features of CoPS by drawing together ideas from studies of innovation, industrial sociology, software, project management, systems engineering, military systems and the history of technology. Because CoPS are high cost, customised goods, the dynamics of innovation and the nature of industrial coordination may well differ from other types of product, especially low cost, mass produced, commodity goods based on standard components. The paper suggests how and why the dynamics of CoPS innovation might differ from commodity goods, and looks at the

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0048-7333/98/$19.00
PII S0048-7333(97)00044-9

merits and disadvantages of treating CoPS as a distinct analytical category for research purposes.

As defined in Section 2, CoPS include high value products, capital goods, control systems, networks and civil engineering constructs. CoPS tend to be made in one-off projects (or small-batches) and the emphasis of production is on design, project management, systems engineering and systems integration. Examples include telecommunications exchanges, flight simulators, aircraft engines, avionics systems, train engines, air traffic control units, systems for electricity grids, offshore oil equipment, intelligent buildings and cellular phone network equipment.

Section 2 suggests that CoPS may well constitute a significant proportion of industrial output and the fixed capital formation upon which goods and services are produced and traded. Over the past two decades, many changes have occurred in CoPS development and use. Embedded software has transformed the physical composition and functioning of some CoPS and altered the ways projects are managed. Suppliers and users confront new risks due to a combination of technological, regulatory and market changes which together have transformed the innovation landscape of many CoPS industries.

To date, there has been little cross-sectoral comparative research on the nature and dynamics of CoPS innovation. As Section 3 argues, the emphasis of innovation research has been on mass produced commodity goods. This literature has had an important influence on conventional wisdom regarding patterns of innovation and industrial adjustment. With few exceptions, CoPS have been treated as special cases for innovation research. Consequently, understanding of CoPS has lagged behind the more visible, mass market, commodity-type industries, such as cars, semiconductors and consumer electronics. To show how innovation processes in CoPS might differ from those of mass produced simple goods, Section 3 contrasts two ideal-type innovation schemes: a 'conventional' innovation model based on standard components and a proposed CoPS scheme.

Section 4 touches on some of the implications for innovation and industrial coordination at the firm and project levels, suggesting that non-market mechanisms tend to play a significant part in CoPS coordination. Underlying some of the features of CoPS coordination is the need for multi-firm ex-ante agreement and negotiation on technical issues throughout the stages of design, development and manufacture. The need for administered cross-firm coordination is the consequence of both the nature of CoPS artifacts and the corresponding institutional features of CoPS markets.

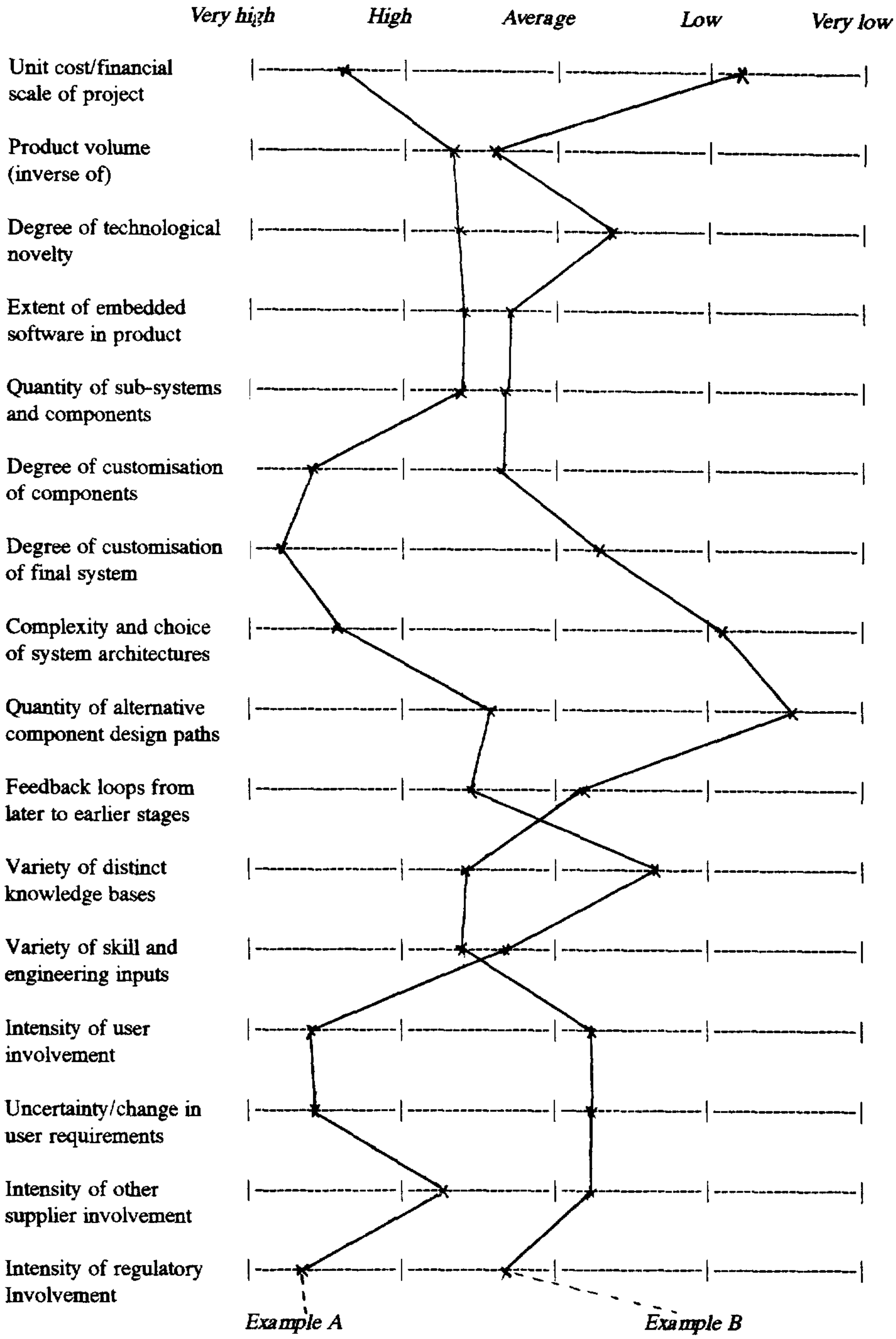
In Section 5, the paper suggests there is merit in pursuing cross-sectoral innovation research in CoPS and exploring further the contrast with mass produced goods. However, the differences between the various categories of CoPS in terms of product composition, production processes, industrial structures, company strategies and market characteristics, probably make non-trivial generalisations difficult.

2. Nature and scope of CoPS

2.1. Background and definition

The idea that a generic category of industrial products can be classified as CoPS draws on the military systems literature (Walker et al., 1988), work on the measurement of complexity of systems (Kline, 1990), scholars of large technical systems (Hughes, 1983), the project management literature (Shenhar, 1994) and studies of industrial organisation (Woodward, 1958). Evolutionary scholars such as Nelson and Rosenberg (1993) mention complex systems in passing, but neither define them nor ask whether there is merit in treating them as a distinct category. Individual CoPS industries such as aircraft are studied, but they are usually treated as special cases for innovation research (Mowery and Rosenberg, 1982).

For the purposes of this paper, CoPS are defined as high cost, engineering-intensive products, systems, networks and constructs. As discussed in Section 2.4 (Fig. 1), the term 'complex' is used to reflect the number of customised components, the breadth of knowledge and skills required and the degree of new knowledge involved in production, as well as other critical product dimensions. CoPS are supplied by a unit of production, be it a single firm, a production unit or a temporary project-based organisation involving many firms. CoPS are typically purchased by a single user (or a small number of



Notional examples: 'A' (air traffic control system) and 'B' a flight simulator.

Fig. 1. Some critical product dimensions of CoPS.

users), usually under one (sometimes more) formal contract within a recognisable, single project.

Within the classic framework of production processes (Woodward, 1958), ranging from project, small-batch, large batch, mass production to continuous process, CoPS are the high cost, high technology goods made in projects and small batches. [1] Some high cost, mature products would not be included (e.g., roadworks and simple building constructs), as they involve a narrow range of knowledge and skills and utilise mostly standard components and materials.

2.2. Hierarchy as a feature of CoPS

Although hierarchy is an intrinsic feature of all product architectures, component and system hierarchies can be very elaborate in CoPS. For example, the inputs to military systems extend from materials and components, whose unit costs can be measured in cents or less, to high cost components, to very large systems costing billions of dollars. Within the hierarchy of 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" (Walker et al., 1988, pp. 19–20).

Although from different research fields, authors such as Walker et al. (1988), Hughes (1983) and Shenhar (1994) agree that the extent of hierarchy can be helpful in defining types of products and systems. Hughes (1983), for example, groups products into assemblies, components systems and arrays. [2] According to Hughes, an assembly is usually a mass produced stand-alone product which performs a single function and does not form part of a wider system (e.g., a shaver, calculator or personal computer), unless it is connected by a network. By contrast, a component always performs a role in a larger system (e.g., a telephone exchange or an avionics unit). [3]

In its turn, a system is defined by three characteristics: components, a network structure and a mechanism of control. Systems are organised to perform a common goal (e.g., an aircraft, a business information system, or a weapon systems). Finally, an array or system of systems is a collection of distinct but interrelated systems, each performing independent tasks but which are organised to achieve a common goal (e.g., airports which consist of aircraft, terminals, runways, air traffic controls and baggage handling systems).

Within this classification, CoPS include high technology components and systems, but would exclude low-technology goods and most medium-technology goods, regardless of cost. Also, arrays comprised of combinations of systems would mostly be excluded from the definition, unless they were supplied under one definable project.

2.3. The project as a typical process of manufacture

The composition and nature of CoPS are closely associated with their process of manufacture (often a project). Indeed, the definition of one makes most

[1] One way or another, most of the goods produced in other production categories depend on CoPS (e.g., capital goods and computer systems). Many modern services (including mass transport, banking, communications and R&D) depend on CoPS.

[2] Shenhar (1994) independently provides a similar three-part grouping (an assembly, a system and an array), pointing to the degree of new knowledge (and therefore uncertainty) involved, ranging from super-high technology, high technology, medium technology and low technology. Miller and Cote (1987) (p. 11) operationalise the notion of 'high technology' using R&D intensity and proportions of scientists and engineers in the workforce. Here, the term high technology refers to the degree to which new knowledge is involved in production.

[3] In fact, there exists a grey area between assembly and component. For example, a personal computer could be an assembly or component depending on its use.

sense in relation to the other. In this paper, the chief units of analysis for innovation are: (a) the project; and (b) its output (or product) and the links between them. [4] The project represents a clearly defined CoPS supply task undertaken within a certain timescale and given resources with the specific needs of one or more customers in mind. The CoPS project is a temporary coalition of organisations which usually cuts across the boundaries of single supplier firms. CoPS projects normally involve a series of phases including pre-production bidding, conceptual and detailed design, fabrication, delivery and installation, post-production innovation, maintenance, servicing and sometimes, de-commissioning.

Within the project management field, CoPS can be viewed as a sub-set of projects concerned with the development, manufacture and delivery of CoPS. Projects, in general, span all types of industry and services and many different tasks. Only recently has the project management literature begun to isolate the differences between various types of projects. Usually, projects tend not to be desegregated and are treated as fundamentally similar: 'a project is a project is a project'. [5]

2.4. Critical product dimensions of CoPS

2.4.1. Indicators of complexity

To analyse further the nature of CoPS, Fig. 1 lists many of the critical factors which define the character of a product and its 'complexity', along a range of dimensions independent of particular sectors or industries. [6] These dimensions, which together provide a rough approximation of product complexity, help conceptualise how various aspects of complexity relate to innovation. Important indicators of product complexity already noted include the quantity of tailored components and sub-systems, the hierarchical manner in which they are integrated together and the degree of technological novelty of the CoPS in question. Fig. 1 extends the number of critical product dimensions adding, for example, the variety of knowledge bases included in the CoPS.

The listing provides a selection of product features which directly contribute to difficulties of managing production and innovation by adding uncertainty and risk. Other important product dimensions may be neutral with respect to coordination and risk (e.g., whether the product is stand-alone, as in the case of an aircraft, or networked as in the case of a business information system). The extent of use of software and information technology (IT) may also be an important feature of particular products (e.g., new IT design tools, or bidding or project management systems), but may be neutral with respect to coordination (in some cases IT may assist, in others hinder project progress).

It is important to emphasise that complexity, hierarchy and other critical features are a matter of degree. Most CoPS, by definition, embody a fair degree of complexity and risk in at least some respects. However, taken together, the critical di-

[4] This focus on the supply side differs from the approach used by historians of 'large technical systems' such as Hughes (1983), Mayntz and Hughes (1988) and Summerton (1995) who analyse the historical evolution of networks and systems. Large technical system are, in fact, made up of individual CoPS (and other inputs) and deeply influence the innovation trajectories of CoPS (Davies, 1995, 1996).

[5] Pinto and Covin (1989) (p. 49) cited in Shenhar, 1994 (p. 1308). For a collection of project management papers see Cleland and King (1988). Within the project management field, Shenhar (1993, 1994) attempts to show how project coordination relates to the scope and novelty of the product. Pinto and Covin (1989) examine the differences between construction and R&D projects.

[6] Fig. 1 makes no attempt to provide measurements of the scales of high to low. Although the scales are somewhat arbitrary and some rely on subjective judgement, they do help illustrate the range of factors involved. Also note that the terms 'complex' and 'complexity' (dictionary definition) are used as shorthand to describe the combined affect of several critical product dimensions. Similarly, the terms 'simple' and 'simpler' goods, used elsewhere in the paper, are used as shorthand to describe low cost, mass produced goods based on standard components. Not all of the dimensions in Fig. 1 necessarily confer complexity (e.g., unit cost), but most do. For example, the number of components, their degree of customisation and the range of distinct knowledge sets embodied, all contribute to the complexity of overall and detailed design. In particular, such dimensions influence the design complexity of the interfaces between components and sub-systems (as well as the overall product architecture), particularly when there are feedback loops from later to earlier stages in the production process.

mensions provide both an indication of the degree and nature of the complexity of specific products, and suggest the difficulties of the coordination task. Fig. 1 may also be used to provide a complexity profile, as in the example of A (an air traffic control system) and B (a flight simulator). In principle, the scores for A and B could be derived in relation to each other, a notional benchmark or against a previously produced CoPS of a similar kind. It is probably wise not to make too sharp a distinction between product and project in the assessment. The two CoPS features are inextricably entwined, the product shaping the nature and quality of the project and vice versa. Equally, it is also wise to view CoPS in relation to the market in which they are embedded, as the quality of their attributes can only be understood in the light of the demands of the marketplace. As discussed in Section 4, market structure (e.g., duopoly) and exigencies of regulation and user involvement will shape many of the parameters and choices within a particular project.

2.4.2. *Product architectures*

Touching on some more of the key dimensions, Henderson and Clark (1990) show the importance of the interconnections between components and subsystems in the evolution of product architectures. Decisions about the ways in which components are integrated together to form a coherent whole (or 'architectural decisions') require knowledge about the components' core design concepts, how these concepts are implemented in practice and the ways in which the core components are integrated and linked to each other. The quantity of possible alternative system architectures can pose significant coordination problems for CoPS suppliers, especially when system integrators, users and regulators have to agree ex-ante on the path of innovation (Miller et al., 1995). Certain normal architectures can be stabilised within standard designs, influencing the capabilities and strategies of suppliers. The larger the number of tailored components and sub-systems, the more difficult the architectural choices will tend to be. With many organisations sharing architectural decisions, elaborate long term institutional arrangements, involving suppliers, major users and regulators may be called into place (Arena, 1983; Dosi, 1988; Richardson, 1972). For very large systems, the option of internally coordinating all the required capabilities within one firm may be unavailable due to inadequate managerial span of control (Penrose, 1959).

2.4.3. *Design paths and feedback loops*

Equally, within the architecture of CoPS, many alternative design routes for particular components may exist (Iansiti and Khanna, 1995) and what appears to be incremental evolution at the system performance level can mask substantial discontinuities at the component level. As Metcalfe and de Liso (1995) (p. 21) point out, in such cases, focusing devices are needed to cope with the danger of 'combinatorial explosion': impossibly large numbers of alternative design paths for firms to make any realistic estimates of how to proceed. In CoPS, the problem of narrowing design choice can be daunting, especially under conditions of rapid technological change, unclear user requirements and multiple, customised components.

To make coordination matters more complex, there may be substantial feedback loops from later to earlier production stages which require alterations to overall system architectures or to the design of specific components. Such feedback loops are commonly found in military systems where elaborate procedures are imposed by purchasers, such as the US Department of Defense and the UK Ministry of Defence, to monitor and control changes to specifications which occur during product development (Chambers, 1986; Lake, 1992). Engineers in such sectors acknowledge the need to proceed through stages of product development with incomplete information, changing user requirements and emerging (unpredictable) system properties (Boardman, 1990). The ability to master these processes (and their risks) can confer competitive advantage on particular suppliers.

In order to decide upon system architectures and component design paths, particular forms of interfirm collaboration are often required in CoPS. As many authors show, technological coordination across firms is an essential part of managing innovation, regardless of product type (Vernon, 1960; Lundvall, 1988; Hamel et al., 1989). In CoPS, as Section 4 argues, the institutional structures within which CoPS firms are embedded function to realise markets, create projects and agree innovation paths in the absence of 'normal' market selection mechanisms. However, even with a clear view of user needs and design options, collaborative projects often fail in one respect or another (Pinto and Prescott, 1988; Shenhar et al., 1994).

2.4.4. *Breadth of knowledge and skills*

Other related dimensions of product complexity include the variety of distinct knowledge and skill bases which need to be integrated into the final product. In modern aircraft, for example, a wide variety of skills embracing new materials, software technologies, fluid mechanics and communications systems need to be mastered (Vincenti, 1990). The need for elaborate systems integration can expand the variety of skill and engineering inputs far beyond the competencies of even the largest individual producers and dictate that they work closely with specialist firms to produce the final system. In some cases, project completion depends critically on knowledge embodied in key individuals and groups, recognised for their abilities.

2.4.5. *Coordination across units*

Another factor which tests the ingenuity of CoPS producers is the intensity of user involvement and the user's own understanding of final requirements. Sometimes, a user is unclear precisely what needs to be (or indeed can be) supplied. Or the user may make changes to requirements as the project unfolds. Similarly, the intensity of other supplier involvement can further complicate coordination difficulties. *Ceteris paribus*, the larger the number of firms involved in product definition, design and manufacture, the more complex the coordination task. The degree to which the managerial span of control is outside the prime contractor's reach influences the extent to which innovation has to be negotiated between the parties concerned, rather than directed by a leading contractor.

In addition, the intensity of regulatory involvement can shape the path of CoPS innovation. Regulation may be needed for safety purposes (e.g., as in aircraft and buildings), interfacing standards (e.g., as in telecommunications) and other reasons. In some industries, regulators take an intense interest in new products, approving design innovations, verifying production methods and adding new criteria to system validation and accreditation.

2.4.6. *Embedded software*

In Fig. 1, the extent of embedded software in the product (a sub-set of the degree of technological novelty) is considered important enough for a separate line entry, given the way embedded software has transformed many CoPS. Embedded software has become a core integrative activity, spurred on by low-cost computer power which has improved the control and performance of many systems (e.g., flight simulators, military systems, telecommunications exchanges, air traffic control systems, aircraft engines and avionics).

The coordination of embedded software within and between firms has proved to be an uncertain, risk-intensive activity (Humphrey, 1989; Paulk, 1993; Buxton and Malcolm, 1991). Most observers acknowledge the difficulties of ensuring software-intensive projects are completed within budget and on time (Charette, 1989; Lyytinen et al., 1995; Boehm, 1991). Indeed, there is now sufficient evidence to argue that embedded software is a stumbling block in the execution of many large CoPS projects, leading to delays, cancellations and cost overruns (Gibbs, 1994; Peltu, 1992; Littlewood and Strigini, 1992). Needless to say, in large CoPS where many firms are involved, the software coordination problem becomes more intense.

2.4.7. *Product profiles*

Fig. 1 can be used to develop a product profile of a particular CoPS, along a number of dimensions, as in the case of examples A and B. [7] Overall, a heavy bias towards the left hand side of Fig. 1 indicates a CoPS of very high coordination complexity and risk (e.g., a new space project, involving the development of new materials and information systems). Some very large projects (e.g., the Channel Tunnel) may call into being a temporary industrial structure involving hundreds of firms for the purposes of the

[7] Not all dimensions are equally related to difficulties of coordination. For example, as noted in Section 2.4.6, the degree of embedded software has proved to be a serious risk, regardless of other factors.

project, to be scaled down or terminated once complete. Conversely, a scoring towards the right hand side might indicate a batch produced, stand-alone system with relatively little technological novelty and low risk, such as repeat orders for civil flight simulators. However, even the latter are likely to pose more innovation coordination difficulties than say, a bicycle, which is based on standard components and fewer knowledge inputs.

Although 'simpler' goods (discussed in Section 3) exhibit fewer design and architectural options, some may score fairly highly on particular dimensions (e.g., design complexity), especially at the early stages of the product life cycle (e.g., microcomputer or a car). However, most goods based on standard components are likely to be less complex in terms of most key dimensions in Fig. 1. Generally, there are fewer customised components, fewer suppliers, less regulatory constraints and a smaller variety of knowledge and skill inputs. Simpler goods can benefit from a greater degree of learning from prior generations of product, and the codification of process knowhow due to volume production. In CoPS, process learning within products and between product generations is more haphazard due to the difficulties of transferring knowledge from one project to another, changing user needs and the customisation of component inputs.

Most mass produced goods will tend to exhibit low scores against most of the critical dimensions above. Many simple goods would fall to (or off) the right of Fig. 1 and would, no doubt, need to account for other key innovation features not so important to CoPS (e.g., process control, product–process interfacing and design for manufacture). In the case of more complex mass produced goods (e.g., the car), some critical dimensions might be higher than in some CoPS, but on average, simple goods pose less coordination difficulties because overall product complexity is less intense and there are fewer organisations involved.

2.4.8. *Implications for experimentation*

An important implication of system cost and complexity is the high cost of experimentation. Unlike simpler products, it may be extremely costly or impossible to build prototypes for design, production or market experimentation purposes (e.g., in civil construction). Here, computer-based process representation tools can ameliorate, but not dispense with, the design problem involved (Nightingale, 1997). Typically, the larger the project, the more the investment, experience and knowledge required at the early stages of production, including overall and detailed design, the choice of components and materials and the structure and management of the project. Mistakes at the early stage can be extremely costly and hard to rectify. From an engineering perspective, the one-off nature of many CoPS, means that it is difficult to systematically capture and recall previous design and development experiences. The larger the project and the more systemic and complex the product, the more important tacit knowledge is likely to be in CoPS project design and execution. In some cases (e.g., passenger airports), overall concept knowledge may reside in a small number of well-known individuals worldwide. In other cases, there may be only a handful of engineering teams capable of designing and building new versions of complex products (e.g., in flight simulation, Miller et al., 1995). Because of the inability to experiment and because of feedback loops from later to earlier stages, step-by-step continuous learning during CoPS projects is likely to be central to their design, production and installation (Lindblom, 1959).

2.5. *Possible CoPS candidates*

Table 1 presents a selection of potential CoPS candidates in order to illustrate their range and variety. They include sub-systems, such as avionics parts used in aircraft, as well as complete aircraft. [8] Some of the CoPS in Table 1 overlap with low technology products. For example, some standard civil engineering projects (e.g., roads and construction) may involve little new knowledge or uncertainty. However, many modern civil engineering projects require the application of novel technologies and skills. A mod-

[8] The alphabetical listing is somewhat unsatisfactory. As some systems are components of others, it would be useful to have sectoral groupings. Depending on the particular purposes, one could classify CoPS according to standard industrial classification (SIC) schemes, standard product classifications (used in trade statistics), technological function (e.g., control units and communications systems), the degree of complexity and economic importance.

Table 1
Candidate examples of complex product and systems (CoPS)[a]

Air-traffic control systems
Aircraft engines
Aircraft carriers
Armoured fighting vehicles
Avionics equipment
Baggage handling systems
Banking automation systems
Base stations for mobile comms
Battleships
Bridges
Bulk carriers (ships)
Business information networks
Chemical plant
Clean rooms for semiconductors
Combined cycle gas turbines
Cruise liners
Dams
Docks and harbours
Electricity network control systems
Electronic commerce systems (e.g., Internet systems)
Electronic retail networks
Flexible manufacturing systems
Flight simulators
Frigates
Ground to air missile control units
Helicopters
High speed trains
Hovercraft
Integrated mail processing systems
Integrated tram systems
Intelligent buildings
Intelligent warehouses
Jet fighters
Mainframe computers
Maritime communication systems
Mine hunters (and other large military ships)
Missile systems
Nuclear decommissioning systems
Nuclear fusion research facilities
Nuclear power plant
Nuclear waste storage facilities
Ocean drilling vessels
Offshore oil production platforms
Oil refining equipment
Oil tankers
Passenger aircraft
Port loading/unloading systems
Process control systems for oil refining
Production systems (automated)
Racing power boats
Radio towers (large)
Refuelling aircraft and systems
Remote nuclear decommissioning units
Racing cars (e.g., Formula 1)
Rail signalling/control systems
Road systems/flyovers
Road traffic management systems
Robotics equipment
Roller coaster equipment
Runways for aircraft
Satellite systems
Semiconductor fabrication equipment
Sewage treatment plant
Space launch vehicles
Space observatories
Space stations
Strategic bombers
Submarines
Supercomputers
Superserver networks
Synchrotron particle accelerators
Tanks (e.g., main battle)
Tank communication systems (battlefield and tactical)
Telecommunications exchanges
Telecommunication network management systems
Telecommunication repeater systems
Training jets
Rail transit systems
Water filtration/purification plant
Water supply systems
Wide area networks
Yachts (e.g., 12-m racing)

[a]Includes networks, sub-systems, and constructs (e.g., intelligent buildings). Selected examples only (in alphabetical order).

ern transit system, for example, may involve computer simulated bridge design, advanced structural engineering, an understanding of the latest materials technology, geotechnics, fire engineering and environmental assessment skills. Many building projects (e.g., airport terminals, sports facilities and corporate headquarters) incorporate highly sophisticated IT systems and new materials (Gann, 1993).

A cursory glance at Table 1 suggests that CoPS could represent a significant proportion of industrial output. The US aerospace industry alone was estimated to be around US$150 billion in 1991, more than twice as large as the world semiconductor industry at that time (Aviation Week and Space Technology, 1991, p. 39). UK committed expenditures on 25 defence projects, excluding the exceptionally large

Eurofighter and Trident projects, amounted to £32 billion (Guardian, 1996, p. 6).

In recent years, the innovation environment for many CoPS has changed profoundly. Technological, policy and financial changes have forced the pace of innovation in areas such as aircraft and air traffic control systems. [9] Market growth and the internationalisation of firms has progressed apace as has privatisation and new forms of regulation. New mechanisms of financing and deal structuring have made ever larger projects possible in the UK and elsewhere. [10] The deregulation of sectors such as telecommunications, aerospace, nuclear power and electricity in several countries has increased the demands for new CoPS in network upgrading, while large new investments in Eastern Europe and East Asia have changed the market prospects facing suppliers.

3. CoPS vs. mass production

3.1. Two ideal innovation types

In order to explore further the contrast between CoPS and simpler products and to draw out possible implications for coordination, this section counterpoises two ideal innovation types: [11] a mass production 'conventional' model with a proposed CoPS/project scheme. The term conventional is used because the original model of Utterback and Abernathy (1975) has had a profound influence on evolutionary theories of innovation and management and strategy thinking (Utterback and Suarez, 1993; Womack et al., 1991; Tushman and O'Reilly, 1997; Klepper, 1996). Of course, as discussed in Section 3.2, many take exception to the conventional view, stressing variety and discretion in matters of innovation structure, process and strategy. For the purposes of this paper, the contrast between CoPS and the conventional model is a useful tool to describe ideal type innovation processes which helps point to possible hypotheses about industrial coordination and innovation.

3.2. The conventional view of innovation

A stark version of the conventional view is summarised in the right hand side of Table 2. The conventional model, which focuses on stages through which product and process technologies tend to pass within industries, stresses similarities in the innovation process, arguing that product and process technologies tend to follow life cycle patterns from birth to maturity (Utterback and Abernathy, 1975; Abernathy and Clark, 1985; Clark, 1985; Utterback and Suarez, 1993; Klepper, 1996). Firms are assumed to compete in a technology race while consumers decide which products will be successful through arms length market transactions. Many would not agree with the conventional view. Other innovation analysts point to the heterogeneous nature of innovation and long lasting inter-industry differences between origins and processes of innovation (e.g., Pavitt and Rothwell, 1976; Freeman, 1994; Pavitt, 1990; Nelson and Rosenberg, 1993; Woodward, 1958).

Although not made explicit, the conventional model is intimately linked to the production paradigm of mass market commodity goods. The single firm is a chief unit of analysis for competitive purposes, rather than the project as in CoPS. Firms and markets tend to be clearly defined entities. Large and small firms compete to create markets and redefine industries by skilfully exploiting technical opportunities (Schumpeter, 1947). The creation and diffusion of new technologies are usually viewed as separate, if not sequential activities: the R&D lab develops and the market selects (Utterback and Abernathy,

[9] A single air traffic control (ATC) facility (one of three new ones) installed in the UK near Fareham in 1996 cost £350 million. It experienced serious delays and cost overruns (Financial Times, 1994, p. 10). In Europe, there are 31 different systems in 51 ATC centres using 22 different operating systems in need of upgrading and rationalisation (Foresight, 1995, p. 65).

[10] The Channel Tunnel, which cost well over £11 billion (more than twice the original estimate), was made possible by more than 200 funding banks, coordinated by 18 instructing banks (Economist, 1994, p. 42; Lemley, 1992, p. 23).

[11] Although ideal types are not intended to be accurate descriptions of the real world, they can be useful yardsticks for helping to compare real world observations and are often deduced from rough approximations of empirical data (Cawson, 1986, pp. 31–32; Doty and Glick, 1994, pp. 230–251). The two innovation types correspond to end points on a scale, standing in logical contrast to each other. Actual cases will tend to fall between the two poles or somewhat outside the continuum.

Table 2
CoPS vs. mass production industries (two ideal types)

	CoPs project organisation	Commodity products, functional organisation[a]
Product characteristics	Complex component interfaces	Simple interfaces
	Multi-functional	Single function
	High unit cost	Low unit cost
	Product cycles last decades	Short product life cycles
	Many skill/knowledge inputs	Fewer skill/knowledge inputs
	(Many) tailored components	Standardised components
	Upstream, capital goods	Downstream consumption goods
	Hierarchical/systemic	Simple architectures
Production characteristics	Project/small batch	High volume, large batch
	Systems integration	Design for manufacture
	Scale-intensive, mass production not relevant	Incremental process, cost control central
Innovation processes	User–producer driven	Supplier-driven
	Highly flexible, craft based	Formalised, codified
	Innovation and diffusion collapsed	Innovation and diffusion separate
	Innovation paths agreed ex-ante among suppliers, users etc.	Innovation path mediated by market selection
	People-embodied knowledge	Machinery embodied knowhow
Competitive strategies and innovation coordination	Focus on product design and development	Focus on economies of scale/cost minimisation
	Organic	Mechanistic
	Systems integration competencies	Volume production competencies
	Management of multi-firm alliances in temporary projects	Focus on single firm (e.g., lean production, TQM,MRP II)
Industrial coordination and evolution	Elaborate networks	Large firm/supply chain structure
	Project-based multi-firm alliances	Single firm as mass producer
	Temporary multi-firm alliances for innovation and production	Alliances usually for R&D or asset exchange
	Long-term stability at integrator level	Dominant design signals industry shakeout
Market characteristics	Duopolistic structure	Many buyers and sellers
	Few large transactions	Large numbers of transactions
	Business to business	Business to consumer
	Administered markets	Regular market mechanisms
	Institutionalised/politicised	Traded
	Heavily regulated/controlled	Minimal regulation
	Negotiated prices	Market prices
	Partially contested	Highly competitive

[a]Note that flexible specialisation (Piore and Sabel, 1984) is a sub-set of simple product/mass production industries in this formulation. Here, flexible specialisation is an advanced form of mass production.

1975). Similarly, innovation is usually treated as separate from diffusion: innovation occurs and diffusion follows.

According to Utterback and Abernathy (1975), a central event in the innovation process occurs when a dominant design emerges to galvanise an entire market and to give direction to subsequent evolutionary trajectories. 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 unstandardised, 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 and a small number of firms ultimately 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." [12]

According to the conventional view, entry and exit vary according to the stage of the innovation cycle. Typically, there is a high turnover of firms in the industry. Entry precedes the dominant design and exit usually follows. According to Tushman and Anderson (1986), with the emergence of radical new technologies, old competencies can be destroyed leading to company failure and industrial disruption in line with Schumpeter's notion of creative destruction.

3.3. A contrast with CoPS

The left hand side of Table 2 summarises the ideal type version of CoPS innovation, contrasting product life cycles, processes of manufacture, industrial coordination, corporate strategies and market features. CoPS are never mass produced, product life cycles can extend over decades and decisions to invest may take months or years. In some cases, innovation proceeds long after the delivery of the product, as new features are added and systems are upgraded and modified.

In the extreme case depicted in Table 2, CoPS contrast sharply with mass produced goods. At the product level, CoPS are made up of many customised, interconnected control units, sub-systems and components. By contrast, a 'simple', mass producible product has relatively few, mostly standardised components. [13] Therefore, the degree of CoPS system hierarchy is high, architectures are complex and designs frequently tailored for specific customers and markets (Hayes and Wheelwright, 1984). Sub-systems (e.g., the avionic systems for aircraft) themselves can be complex, customised and high cost (Mowery and Rosenberg, 1982).

System complexity can be very high and can increase from one generation to another due to ever-rising demands on performance, capacity and reliability. Although simplifying factors may impinge on products and processes (e.g., the modularisation or standardisation of previously customised components), through time, many CoPS become larger, more costly and more functionally and technically elaborate as in the case of the turbojet engine designed in the 1930s by Frank Whittle. The original design 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, control units and components. Today's jet engines can embody more than 22,000 parts, many of which are customised.

As a consequence of system complexity, new product development in CoPS requires a deep understanding of the limits and possibilities of system architecture, the capabilities of partner suppliers and the needs of highly demanding professional users. Once installed, the CoPS may continue on its path of innovation over many years, with changes being made to control features, sub-systems and performance characteristics.

In their design and development, in contrast with simple goods, CoPS exhibit emergent and unpredictable properties. [14] The extent of feedback be-

[12] The latter study is based on seven industries: manual typewriters, automobiles, transistors, integrated circuits, electronic calculators, television sets and picture tubes, and parallel supercomputers. Apart from supercomputers, these are all mass market products where incremental process improvements eventually play a large part in competitive performance

[13] A passenger car, for example, is made up of many parts and components but, unlike in a CoPS, these are highly standardised, enabling the final product to be mass produced in large volumes at low unit cost.

[14] With simpler products, the impact of small design changes is likely to be relatively predictable due to constraints dictated by the standardisation of components and sub-system interfaces and the need to design with mass production in mind.

tween one stage and the next means that small changes in one part of the system can lead to larger changes in other parts. Equally, from generation to generation, small changes in one part of a system's design can require the addition of sophisticated control systems and, sometimes, new materials. Emergent, unpredictable properties may also refer to major changes in the form, structure and material requirements of a system as it grows in size (Sahal, 1985).

As a result of these properties, product life cycles and innovation paths do not follow those predicted in the conventional model. In CoPS, mass production does not take place and the suppliers' chief task is one of project management, design, development and systems integration. Although some mass produced goods exhibit intense user–producer design interaction at the early stage of the innovation cycle, this eventually stabilises as markets expand and components are standardised. After this, user–producer interaction is mediated through the market as in the case of automobiles (Langlois and Robertson, 1989), microcomputers (Langlois, 1992) and electronic consumer goods.

This raises the question of whether CoPS are really any different from simpler products or merely a reflection of the extent of the market. After all, as Adam Smith pointed out, the division of labour is limited by the extent of the market and therefore demand is the key to understanding innovation and production processes. In this light, it is the (limited) nature of demand which dictates that complex one-offs are simply products which are truncated at the early stage of the product life cycle. However, this interpretation is unsatisfactory for understanding the dynamics of CoPS innovation. Unit demand may well not be very high for complete systems but market value may be extremely high (e.g., passenger aircraft or ships). While normal production process learning may be difficult in CoPS, there may well be scope for learning economies between product generations and at the components level, where demand may be very high. From a strategic viewpoint, CoPS suppliers may be able to gain advantage by altering design architectures to increase the scope for high volume component use in CoPS. At the level of design, CoPS producers do not have to account for high volume production as a key design constraint. Therefore, their design rules and decision procedures probably differ substantially from those followed in mass produced, simpler goods where design-for-mass-manufacture is all important (Pugh, 1991; Ullrich and Eppinger, 1995). Another interesting issue is the way in which some CoPS industries give rise to mass produced goods (e.g., mainframe computers to personal computers) and how incumbents (e.g., IBM and Amdahl) cope with the differences required in facing commodity, mass production markets. The latter two companies had substantial difficulties in adjusting from tailored CoPS mainframes to the commodity PC market.

With many CoPS there is a high degree of user involvement through which business needs feed directly into the innovation process (rather than through the market as in the standard model). As Table 2 notes, throughout the product's life cycle, the users' involvement in R&D, design, production and subsequent innovations distinguishes CoPS from simple goods, where direct buyer involvement occurs (if at all) at the early stages. Users may be responsible for maintenance, upgrading, performance modifications, de-commissioning and feeding back information to suppliers users during production (Rothwell and Gardiner, 1989; Gann, 1993). Innovation and diffusion may overlap considerably and cannot be neatly separated, as in mass produced goods (Leonard-Barton, 1988; Fleck, 1988).

4. Implications for coordination and management

4.1. Nature of CoPS networks

Although the degree of product cost and complexity is likely to effect production and innovation processes, it should be noted that ideal-type comparisons tend to stereotype both CoPS and mass production issues. There are likely to be sharp differences not only between CoPS (e.g., nuclear plant and aircraft), but also between mass produced goods (such as cars and semiconductors). Bearing these caveats in mind, this section considers implications of product cost/complexity for the CoPS coordination issues noted in Table 2, touching on the project, the project-based firm, the CoPS network and typical industrial structures. [15] Often, the issue of coordination is posed as a dichotomy between market allocation mechanisms and hierarchy, the boundary between the firm and market determined by relative costs (Coase, 1937; Williamson, 1971). Richardson (1972) (p. 887) observed that beyond conscious planning within firms and the spontaneous operation of price mechanisms, there exists a wide continuum ranging from commodity-type market transactions, to an intermediate area of linkages based on goodwill, through to complex inter-locking clusters, groups and alliances where cooperation is fully and often formally developed. Vernon (1960) made a similar point, arguing that firms cluster together to change inputs rapidly, to overcome uncertainty, to communicate closely and thereby generate external economies.

Typically, CoPS projects are embedded within production networks where alliances are formally developed to structure and coordinate innovation. CoPS tend to be individually developed, tailored and produced in projects (or made in small batches) for particular customers. Transactions are infrequent, large in value and long in duration. For instance, the design and implementation of a power network control system can last 10 yr (Hughes, 1983). Because high quality requires continuous feedback from users, project management, systems engineering and design involves long-lasting, close interactions between buyers and sellers.

In very high cost CoPS, markets tend to be duopolistic and highly bureaucratised, involving elaborate price formulas, negotiated for each single transaction. Governments and regulators often become involved, regulating and politicising individual transactions (e.g., the purchase of a military system). Governments become involved in the coordination of CoPS for a number of reasons. These include safety (as in large scale human transportation systems and nuclear power plants), the need for international standards (as in telecommunications systems), the need to prevent monopolistic abuse, and other strategic and military reasons.

Sometimes there appears to be considerable long-term stability in CoPS networks, especially at the level of systems integrators (e.g., in telecommunications and military systems) despite radical technological change and contrary to the predictions of the conventional model (Tushman and Anderson, 1986). In some cases, stability among integrators stands in contrast to the considerable industrial adjustment occurring among the specialist companies in the supply network, as illustrated in flight simulators and mainframe computers (Miller et al., 1995; Iansiti and Khanna, 1995).

Often, the degree of market contestability is low, as purchases depend on the policies of governments or nationally-owned purchasers (e.g., utilities) towards locally-owned and foreign suppliers. In the UK, for example, prior to the mid-1980s, the public telecommunications switching market was reserved for a small number of locally-owned suppliers (mostly GEC and Plessey), rather like the defence market. Since then, attempts at liberalisation have enabled some foreign suppliers (e.g., Ericsson of Sweden) to capture shares of the market. In many other countries, governments own, control or closely oversee CoPS production and operation in sectors such as nuclear power, telecommunications and aircraft.

In lower cost CoPS, non-market mechanisms are often evident, for example in bidding procedures and price negotiations by committee. In higher cost CoPS, markets are often highly politicised and regulated and are sometimes not contested, or only partially contested, as in the case of some US military systems. This contrasts with the conventional model where many buyers and sellers compete and adjust via entry and exit, signalled by the emergence of dominant designs. The more complex and higher cost the product, the more coordination is likely to be based on fewer, more irregular market transactions, non-market pricing, biased purchasing policies and administered, regulated competition.

4.2. Determinants of technical advance

The issue of product cost and complexity in CoPS has several implications for evolutionary theories of

[15] In his seminal article, Richardson (1972) (p. 896) argues that "theories of industrial organisation should not try and do too much". Arguments designed to prove the inevitability, or indeed, the superiority of particular forms of coordination are bound to confront contradictory arrangements within and between sectors and countries. In particular, he argues that "some ex-ante matching of plans is to be found in all markets in which firms place orders in advance" (p. 896).

technical change and for understanding the determinants of technical advance. For instance, in some cases the selection environment is highly bureaucratised and politicised, involving suppliers in close negotiations with users over protracted periods. In such cases, the selection environment includes suppliers and is entwined with what is selected, both at the firm and product levels. A strong technical performance on the part of individual suppliers is likely to be rewarded over time, *ceteris paribus*, with more orders, prime contractorships, a greater share of the market and a more dominant position in the CoPS network. However, national preference for local suppliers, low contestability and high barriers to entry may allow poor performers to dominate particular markets despite long-term poor technical performance.

Regarding incentives to conduct R&D, to the extent that users play a direct role in funding R&D and shaping paths of innovation, they are likely to provide incentives for R&D. In some cases, unlike commodity goods, users will get directly involved in R&D and product design leading to 'user push' or 'demand driven' innovation, as has occurred in passenger aircraft and telecommunications exchanges. Incentives may be determined by a conscious sharing of risks between suppliers and users, subject to change according to government and user purchasing policies. For example in the UK, in military, construction and other sectors, the Government has attempted to stimulate private finance initiatives, shifting the risk from Government to the private sector. By contrast, R&D for consumer goods is determined more by the strategies of major suppliers and their perceptions of consumer taste, registered by market purchasing signals.

4.3. The project as a coordination mechanism

Within CoPS networks, the project is a primary form of coordination. The project, a temporary organisational form, is a focusing device which enables different types of supplier firms, users, regulators and professional bodies to agree the fine detail of CoPS development and production. The CoPS project is responsible for realising the market, for coordinating decisions across firms, for enabling buyer involvement and for allocating technical and financial resources. The project exists to communicate design and architectural knowledge and to combine the distinctive resources, knowhow and skills of many suppliers. The nature, cost and complexity of the CoPS in question is likely to shape the form of the project and the approach to the task at hand. The resources of the participants need to be combined, through time in a controlled manner with production tasks focusing on project management and systems integration.

In the case of very large engineering constructs, entire project-based industrial structures are sometimes called into being by financiers, systems integrators, government bodies, sub-contractors and other stakeholders for the sole purpose of creating and implementing the CoPS project. The Channel Tunnel, for example, entailed a massive task of financial, managerial and technological coordination involving hundreds of contractors, at least 208 lending banks and around 14,500 employees at its peak (Lemley, 1992, p. 14 and 23).

A fairly typical small scale military CoPS (in this case, a training device for the UK air defence system), is described in Fig. 2. [16] A commissioning agent made up of a senior committee of civil servants and industrialists initiated the project which was funded by the customer (two branches of the MoD). [17] The project was managed by a systems integrator (Company A) who also provided some of the equipment and much of the architectural design. A project manager from company A coordinated the governing project committee which shared information, took major decisions and allocated tasks to smaller groups. The scope for direct project management was low as agreements on design choices, equipment and costs had to be negotiated. Major decisions needed the agreement of all major organi-

[16] Similar project structures are found in other military projects, but there is a great deal of variety and discretion even within the military sector. Some projects become very large. For example, the European Space Program's Ariane project involved at least 44 contracting firms and many other organisations (Shachar and Zuscovitch, 1990). Boehm and Ross (1989) provide not dissimilar descriptions of complex software projects.

[17] Note that the customer was distinct from the user (the British Army).

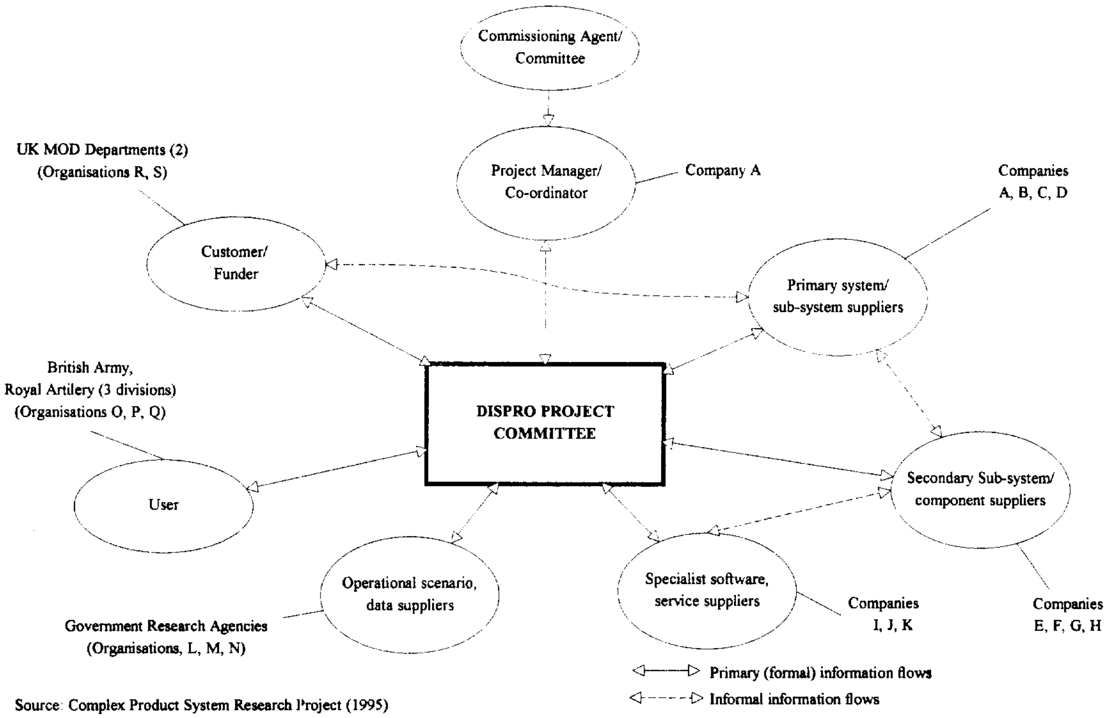


Fig. 2. Structure of military project DISPRO (Distributed Interactive Simulator Project).

sations, including the user, the customer and, sometimes, specialist sub-contractors (firms IJK).

Fig. 2 shows the various types of supplier groups, divided into primary (firms A to D), secondary system suppliers (E to H), specialist suppliers (I to K) and data supply organisations linked to the user (L to N). In civilian flight simulation projects, there is more of a role for regulators and professional bodies. In military projects, such functions are carried out by groups linked to the customer and user (organisations O to S).

4.4. The project-based organisation

Within CoPS supply networks, firms organise structures and strategies around the needs of projects, which often cut across conventional industrial boundaries. Larger project-based organisations are likely to embody typical functional departments which provide technical, human and financial resources for project bidding, management, systems engineering and so on. There are many different categories of CoPS project-based organisations, ranging from large prime contractors, which specialise in project management and systems integration, to tiny specialised sub-contractors which supply tailored components, software or services. Any one project may combine these groups in a variety of roles, with the same firm acting as prime contractor in some projects and sub-contractor in others.

Individual firm structures and business processes are likely to be shaped by the changing profile of CoPS projects, especially their size, complexity and duration. Some project-based firms (e.g., in construction) are likely to derive most of their income from large projects over which they exercise little span of control (Gann, 1993). In other cases, firms may direct and control particular projects, largely from within the firm. Some firms may engage in a mix of CoPS projects and batch or mass production, combining project-based and functional organisational forms. While the possible permutations of intra-organisational form are many, most CoPS suppliers will be tested and influenced by the exigencies of project management, systems integration and multi-firm collaboration.

Because production is of a one-off kind, oriented to meet the needs of individual customers, the project management task is quite different from the mass production task. As Woodward (1958) (p. 23) put it in her research into UK companies in the early-1950s:

"those responsible for marketing had to sell, not a product, but the idea that their firm was able to produce what the customer required. The product was developed after the order had been secured, the design being, in many cases, modified to suit the requirements of the customer. In mass production firms, the sequence is quite different: "product development came first, then production, and finally marketing."

Although some CoPS producers develop generic products (or platforms for new products) in advance of securing orders, a significant degree of customisation is usually required in CoPS.

Through its influence on projects, the CoPS will influence the character of coordination within firms. CoPS prime contractors, usually systems integrators, require distinctive managerial competencies capable of bidding for, defining and engineering large scale systems. In aircraft, according to Mowery and Rosenberg (1982) (pp. 103–135) much of the US$4 billion to US$6 billion devoted to R&D for commercial jets was spent on integrating together prototype machines, avionics, propulsion and other aerodynamic components. In addition to their internal tasks, systems integrators often have to coordinate the innovation activities of the supply network made up of small firms, major users, large partner companies, regulators, standards bodies and government departments.

For efficiency in CoPS projects, it is likely that a responsive, step-by-step, crafted management is needed to deal with uncertainty and feedback loops (Lindblom, 1959; Sapolsky, 1972; Mintzberg, 1989), rather than the more deterministic approach advocated by some (Porter, 1980; Hammer and Champy, 1993). The intricate demands of CoPS lend themselves to the organic approach put forward by Burns and Stalker (1961) rather than mechanistic, hierarchical management styles.

CoPS coordination is very much effected by the breadth of technologies required. The more elaborate a CoPS, the wider the range of skills and capabilities needed for bidding, design, development and manufacture. Flight simulator producers, for instance, require a range of craft skills as well as knowhow in mechanical, electromechanical, precision and software engineering competencies. They have also to master aspects of systems integration, materials, electro–mechanical interfacing, automated data exchange, human–computer interaction and pilot training needs. Much of the required knowledge is embodied in key individuals and cannot easily be codified.

4.5. The central role of the user

In contrast to commodity goods, the CoPS user tends to be a large organisation with a considerable interest in the outcome of each project. The user is the primary organisation through which the needs of the business environment feed into the CoPS innovation process, rather than through arms-length market transactions as in the conventional model. Users, sometimes owners and operators, frequently collaborate with suppliers in R&D and production as well as maintenance, upgrading and re-design, for example in aircraft, hovercraft, chemical process plants and electricity network control systems (Gardiner and Rothwell, 1985; Rothwell and Gardiner, 1989; Grieve and Ball, 1991; Hughes, 1983). Many CoPS are business-to-business, capital goods, tailored to the needs of specific customers. Sometimes users depend upon CoPS for their business profitability and survival. [18]

Unlike mass market buyers, CoPS users often need to learn and internalise systems design skills and architectural knowledge in order to be effective in their own business. Intimate user–producer links allow buyers to feed their needs directly into the specification, design, development and manufacture

[18] Although most CoPS are business-to-business goods, not all business-to-business products are CoPS. Some business-to-business goods are mass produced (e.g., ball bearings, metal boxes and dynamic random access memory semiconductors), while others are fairly simple and lack direct user involvement.

of CoPS. In telecommunications, for example, large user organisations (e.g., AT&T) influenced the innovation trajectory of public exchange systems. Successful users can be demanding and intelligent buyers, endowed with high levels of technological competence. The depth of user involvement and its influence at various stages of the innovation process is one of the critical dimensions of CoPS. In some, user involvement may tail off at the point of production (e.g., in flight simulators) whereas in others, it may carry on through to de-commissioning (e.g., nuclear power equipment).

4.6. Implications for management theory and practice

Because the chief unit of analysis for corporate strategy and competition is normally the single firm, consideration of CoPS adds a new twist to traditional management theories. [19] In CoPS, firms create markets in networks and exploit their advantages within multi-firm projects. Therefore, collaboration in, bidding for, and executing projects are core competencies for CoPS producers. Deliberate, often innovative, strategies for inter-firm coordination are demanded by the nature of the task. One of the chief functions of the prime contractor is to coordinate human and physical resources across firms to good effect. This capability to deliver effective ex-ante coordination across a web of producers, users and regulators is important to the long term success of project-based firms.

Typically, the CoPS supplier will require particular management skills and strategies centred far more around bidding, design and development than production economies of scale as in the case of mass produced goods. The management of projects has to deal with uncertainty over emerging properties and changes in user specifications. As a result, the capability to deal with a variety of feedback loops, in different ways, at various stages of project execution is essential to project-based firms (Morris and Hough, 1987; Morris, 1994).

Although CoPS may not be mass-produced, batch production and use of standard parts can lead to substantial production learning economies. In the case of aircraft, the recent strategy of Rolls Royce, British Aerospace and others is to increase the use of commercial, off-the-shelf modules, simplify production, increase the scale of output of components, realise learning economies and thereby reduce costs. Despite such trends, customisation techniques, systems integration and project management skills remain at the heart of aircraft supplier competencies.

Notwithstanding component standardisation strategies, the disbanding of teams at project completion is likely to have negative implications for production learning and organisational learning in general. In the functional organisation, firms are able to learn by gathering data on routines and improving group practices (Garvin, 1993; Stata, 1989). However, because CoPS projects are temporary and products highly customised, there will be less scope for routinised learning. The difficulties in capturing and sharing knowledge from one project to another may hinder routinised learning and compromise productivity improvements.

Increasingly, systems integrators require project management competencies for dealing with complex scheduling and engineering tasks, especially in software-intensive projects. However, many standard management tools, including Materials Requirements Planning (MRP), statistical process control and lean production were developed to suit mass production tasks and often have the single firm in mind, rather than the multi-firm project. As such, these tools may be inappropriate or require substantial modification for use in CoPS.

Above all, because the chief unit of competition is the project rather than the single firm, with large CoPS, isolated improvements at the individual firm level can only have limited impact on project performance and competitiveness. To be most effective, the latter requires the optimisation of the total project network, rather than any one supplier. Such problems strain conventional management wisdom to its limit.

[19] Most of the renowned writers on strategy and management, focus quite properly on the single firm (e.g., Chandler, 1962, 1990; Cyert and March, 1963; Drucker, 1977; Porter, 1980, 1985; Mintzberg, 1989; Rumelt, 1974; MacCrimmon, 1993; Simon, 1993; Peters, 1987; Teece and Pisano, 1994; Hamel and Prahalad, 1994; Hammer and Champy, 1993). Although there is now a large body of literature on networks, this has yet to address itself to the issue of product complexity.

5. Conclusion

The paper argued that the nature of a product (especially its complexity and cost) will play an important part in shaping innovation processes, organisational forms and industrial coordination. In the case of high cost, complex products, systems and networks, the project and the project-based firm are natural forms of organisation. In contrast with simpler goods which lend themselves to functionally-based mass production, CoPS tend to be produced in projects or small batches, tailored for individual users. Under these conditions, the chief unit of analysis for competition purposes is the multi-firm project, not just the individual firm. With many larger CoPS, competition occurs among rival coalitions of firms at the bidding stage of projects. Selection often takes place in bureaucratically administered and politicised markets, rather than in the arms-length market transactions of the conventional model.

Perhaps the most salient image of CoPS is that of many organisations working together to realise markets, carry out production and agree innovation decisions ex-ante and during production, rather than in the conventional arms-length market setting. Project-based organisations can be very elaborate due to the need to synchronise actions and ensure the close collaboration of production partners.

The comparison between CoPS and mass produced commodity goods should not be pushed too far. Indeed, the paper argued that, as with patterns of industrial coordination, there exists a continuum of product complexity from the very simple, through various intermediate levels, through to extremely high cost, exceedingly complex artifacts and systems. Some of the constituent dimensions of product complexity were discussed, including technological novelty, customisation of components, product architecture and hierarchy, alternative design paths and the variety of knowledge and skill bases required for production. *Ceteris paribus*, the higher the degree of overall cost and complexity, the higher the likelihood of information uncertainty, risk and feedback loops from later to earlier stages in the production process. Equally, the higher the degree of cost, complexity and uncertainty, the more difficult the task of coordination and project management.

Although attention has been paid to many individual CoPS, they are rarely treated as a distinct analytical category for research purposes and, consequently, there exists little cross-sectoral research into CoPS innovation and coordination. It seems likely that major organisational differences occur between different classes of CoPS, according to sector, function and the particular types of system (e.g., whether they are networked or stand-alone). It would also appear that large, software-intensive CoPS exhibit a great deal of uncertainty and risk and strong feedback loops from later to earlier stages, adding to the difficulties of coordination.

While the mass production vs. CoPS contrast is over-simplistic, it drew attention to the issue of product complexity and coordination and generated ideas which might deepen our general understanding of innovation processes. There could well be merit in comparing the functioning of different kinds of project-based organisations and their respective roles in CoPS innovation networks. It might also be informative to ask how and why innovation differs in the various classes of CoPS. Future comparative research promises to provide further insights into the ways in which product characteristics shape organisational form, innovation and industrial coordination.

Acknowledgements

This paper was prepared within the Complex Product Systems Innovation Centre, supported by the UK Economic and Social Research Council. It follows on from work conducted under the EPSRC Technology Management Initiative (grant GR/K/31756). The author would like to thank Andrew Davies, Chris Freeman, David Gann, Tim Brady, Keith Pavitt, Paul Gardiner, Martin Bell, Howard Rush, Roger Miller, William Walker, Mike Gibbons and Sylvan Katz for comments and advice. Two anonymous referees are also thanked for their comments and criticisms on an earlier draft. The normal disclaimers apply.

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