

The Role of Technical Standards in Co-ordinating the Division of Labour in Complex System Industries

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1 Introduction

The idea of complex products and systems has featured in a number of recent studies (Miller, Hobday et al. 1995; Rycroft and Cash 1999; Hobday et al. 2000). A central aim of these studies has been to identify the specific managerial, technological, and organisational issues that arise when engineering-intensive design processes are required to create systemic products or other complex artefacts such as civil engineering projects or sophisticated producer goods. Some of these studies use a specific term of art, CoPS (complex products and systems), to refer to a subset of these design-intensive activities that involve relatively small production ‘runs’ of unique design.

The organisational arrangements necessary for the creation of CoPS are a focus of recent research. It is recognised, for example, that the division of labour involved in CoPS often involves multiple technologies and competences that must be effectively integrated. This division of labour often spans organisational boundaries and, in the words of one recent study, will ‘depend heavily on continuously adaptive organizational networks that know how to do more than any individual can understand in detail’ (Rycroft and Cash 1999, 3), wording that mirrors, at an organisational level, Polanyi’s (1962, 87-95) discussion of the tacit components of *personal* knowledge. Issues of how knowledge is accumulated, modified, and applied in these organisational networks have become central features of the research agenda for understanding innovation.

Correspondingly, for authors in this literature (e.g. Prencipe and Paoli 1999; Davies and Brady 2000; Hobday et al. 2000), the arrangements for design and production of a given artefact are a more telling indication of whether it should be regarded as a CoPS than a physical examination of the number of components incorporated in the artefact. In effect, the issue is not the definition of the physical complexity of the product. Instead, it is the difficulty of ‘integrating’ the components of the system, which, in turn, is shaped by what knowledge is required for integration and how this knowledge is acquired, retained, and applied to the integration process.

This chapter considers one type of knowledge underlying the system integration process, the problem of creating technical interface standards, particularly in areas of technology where digital electronics are involved. Technical interface standards are the collection of explicit rules that permit components and sub-systems to be assembled in larger systems and hence are also called technical compatibility standards (Greenstein and David 1990). This usage of the term ‘standards’ is distinct from, but often related to, two other uses of the word ‘standards.’ ‘Reference standards’ are the explicit rules that are used to characterise the physical properties of raw materials or artefacts and often play a background or foundational role in defining the building blocks for compatibility standards (e.g. the definition of a unit of electrical resistance, the ohm, involves reference standards). ‘Quality standards’ are explicit rules that further elaborate and combine reference standards to address health, safety, or other desired attributes of the materials and artefacts used in industrial processes or the resulting manufactured outputs. Although reference and quality standards accompany the processes of defining and using compatibility standards that are discussed in this chapter, their specific role is not examined.

Technical compatibility standards are determined through various public and private processes of consultation and ‘published’ by standards organisations (referred to as *de jure* standards), through processes of market leadership (*de facto* standards), and through processes of design and problem solving within organisations or between organisations that lead to ‘privately held’ technical compatibility standards. This last class of standards has not previously been analysed within the standardisation literature and will be referred to in this chapter as ‘local standards.’ The standardisation literature (e.g. Farrell and Saloner 1988, David and Greenstein 1990, Hawkins et al. 1995), has, to date, included considerations of the technical deliberation processes necessary to reach ‘arms length’ agreement in standards setting processes organisations (private and public) and the economic issues arising from the production of the quasi-public or public good represented by standards. Quasi-public goods, those available to members of a ‘consortium’ or similar closed group, are characteristic of various ‘proprietary’ standards. These ‘proprietary’ standards include those that are unpublicised and used internally as a means of co-ordinating and dividing labour among different organisations, defined as ‘local’ standards in this chapter. At the most basic level of economic analysis, technical compatibility

standards provide a means of re-using and hence economising on engineering design costs.

Before outlining the main arguments of this chapter, it is useful to briefly indicate the relevance of technical compatibility standards to the issues associated with CoPS. Technical compatibility standards are often discussed in relation to mass-production and the large-scale re-use of standards engineering efforts. CoPS, by contrast, are often identified as not involving mass-produced products and systems. What relevance do standards have for CoPS?

In the case of both CoPS and ‘complex’ mass-produced products the level of design costs is relatively high. The distinction between them arises from the level of output of similar or identical artefacts expected for the two types of products. In the case of ‘complex’ mass-produced products, a large scale of output provides a means of amortising design costs and the principal economic issue is whether market demand will support high levels of output. For mass-produced artefacts, failure to achieve market objectives will result in the abandonment of the product design and serious damage to the originating company. Because of competition between such products, the market for mass-produced products is likely to involve the emergence of a single ‘dominant design’ (Utterback 1996) which is commercially successful, i.e. it amortises design costs and yields at least a normal rate of return on invested capital. When a dominant design involves a collection of components and sub-systems, it is likely that technical compatibility standards will be developed to provide a means of co-ordinating vertical supplier chains. In this context, technical compatibility standards are closely linked to a massive scale of output and to convergence on a dominant design.

In the case of CoPS, the size of the product market is much smaller and the range of possible substitutes much narrower. This may be the consequence either of market or technological conditions. Market conditions for some types of CoPS, for example, civil engineering projects, naturally limit the quantity output; the Thames, Schuylkill, or other rivers of 100 to 200 miles in length only require a limited number of bridges and these are likely to be built (and rebuilt) infrequently. For a variety of producer goods, it is technological conditions that influence the total output; maintaining a

competitive position requires introducing technological improvements as they become available. Moreover, complex goods are subject to continuous problem solving and debugging activities, some of which compel major ‘model’ changes curtailing the ‘production run’ of previous designs. In effect, dominant designs for CoPS may fail to emerge because technological change continually ‘breaks open’ incumbent designs.

Unlike mass-produced products, CoPS artefacts are likely to be sold on the basis of pre-negotiated prices with potential buyers or on the basis of continuing relationships with particular customers. Like mass-produced products, however, CoPS may incur engineering costs that require a higher level of market success than can be assured from ‘pre-order’ processes. In addition, many of the most sophisticated CoPS products, including civil engineering projects, are based upon bidding procedures that involve ‘all or nothing’ contests between rival companies.

To summarise, the engineering costs of both mass-produced products and CoPS are relatively high. In the case of mass-produced products, a principal objective is to amortise these costs by producing large quantities without incurring further design costs, a process that often leads to the emergence of a dominant design and a series of standards associated with that design that facilitate the co-ordination of supplier networks and vertical chains of supply. In the case of CoPS, high design costs are persistent, either because of a small potential market for a particular model or because models are frequently altered to embody technological improvements. Regardless of whether the product is mass-produced or is a CoPS, companies have an incentive to reduce the costs of design in order to enhance their competitiveness and profits. These observations serve to emphasise the point made by (Hobday et al. 2000) that distinctions between mass-produced products and CoPS should not be overstated. Another way of saying this is that the production systems for these two types of artefacts are likely to co-evolve through processes of convergence and cross-fertilisation. A key feature of this co-evolution lies in how the process of system integration is managed.

It is in these processes of co-evolution and cross-fertilisation related to system integration that an examination of ‘standards’ is particularly useful. The integration of control systems into machinery is as old as the industrial revolution, involving

examples such as the use of governors to control the power output of the steam engine. In the language of electronic systems, the steam engine governor is integrated with the steam engine through an inter-operable interface, the governor controlling the steam engine, while the output of the steam engine determines the operation of the governor. The nature of the linkage between the two sub-systems in this case is mechanical. A key feature of the development of the electronics industry is the analysis of such mechanical interfaces, their 'decoupling' through the introduction of electronic rather than mechanical, hydraulic, or electro-mechanical linkages. As the introduction of electricity allowed the substantial re-design of factories by allowing electrical motors to substitute for power shafts from a central power drive (DuBoff 1979, Devine 1982, David 1991), the 'decoupling' of mechanical control linkages permits their replacement by digital control pathways using electronics. When considering these elements of technological history, a fundamental point about system integration emerges. System integration possibilities are inter-dependent, they 'co-evolve' with the means for de-coupling linkages that previously were necessary for system integration.

Some of the concepts and terminology employed to describe compatibility 'integration' drawn from electronics and telecommunication technology are illustrative of these processes of co-evolution and cross-fertilisation. In electrical and electronic systems, technical compatibility standards provide a means for creating 'inter-connectable' or 'inter-operable systems.' Two systems are inter-connectable when the outputs of one can be utilised as the input of the other. A simple technical compatibility standard is needed for the design of a voltage converter that transforms alternating to direct current and reduces the voltage to an appropriate value. Such converters are 'connectable' to a wide variety of electrical appliances that require a DC power source.ⁱ Systems are inter-operable when they mutually control each other's operations. For example, a personal computer modem controls and is controlled by the personal computer to which it is attached, the same modem is capable of controlling the modem on the other end of the telephone connection. In both cases, the aim is to synchronise the transmission and receipt of data between devices that are capable of operating at different rates and that must 'adapt' to line conditions and other factors affecting the attainable rate of data transfer.ⁱⁱ

Technical compatibility standards, inter-connection, and inter-operability are the building blocks of electronic systems, one of the types of systems that will be examined in this chapter. The means devised for the design of mass produced electronic products suggests more widespread opportunities for the use of compatibility standards in design processes and is linked to the emergence of the idea of ‘modularity.’ The discussion is organised around three themes: co-ordination, negotiation, and memory, each of which constitutes a chapter section. The final section of the chapter recapitulates the highlights of the chapter and suggests a focus for further research.

2 Co-ordination

A major source of the economic value of technical compatibility standards is that they enlarge the market for the supply of compatible components or sub-systems, enabling competition and price reduction. However, two other elements of compatibility standards are even more relevant for the production of CoPS.ⁱⁱⁱ The first is the role of these standards in providing a transitory ‘freeze’ in the progress of engineering designs and in supporting re-direction or re-deployment of design resources to other activities. The second element of compatibility standards to be considered is their support of functional specialisation within sub-systems of larger systems. The process of standards setting usually does not determine how larger systems are to be designed, but it does limit the range of technical decisions that must be made. Both of these elements serve useful purposes in achieving the inter-organisational co-ordination necessary for creating CoPS by creating a ‘fixed point’ around which co-ordination can occur.

Compatibility standards define a standard for the interface between components and sub-systems. Assuming for the purposes of this section that these standards are ‘set’ by the system integrator (further discussion of the negotiation of such standards is the subject of Section 3), they serve as a means for defining what is delivered in terms of functionality and performance from a component or a sub-system to other parts of the system. It is useful to consider two extreme possibilities with regard to this interface between the system as a whole and its constituent components and sub-systems.

At one extreme is the possibility that the interface completely defines the range of effects that the sub-system may have on the larger system in which it is embedded. In this case, the engineering design of the component or sub-system does not have larger systemic effects. In other words, one may design the system as a whole without taking into account anything but the definition of the interfaces. This possibility gives rise to the idea of ‘modular’ systems (Robertson and Langlois 1992; Baldwin and Clark 1997).

At the other extreme is the possibility that, regardless of the definition of the interface, the system cannot be designed without taking the design characteristics and performance of the components and sub-systems into account. In this case, the design of components and sub-systems plays a major role in the integrated design of the system. When integrated design is required, design processes are likely to be more interactive and require, at a minimum, more extensive consultation processes and, more likely, require the construction of prototypes in order to trace overall system functionality and performance.

In practice, actual CoPS projects involve a complex mixture between interfaces that can be taken as a sufficient definition of the component or sub-system’s contribution to the entire system and interfaces that are ‘incomplete’ in defining or characterising the overall performance of the system. In the latter case, the definition of a technical compatibility interface is only a starting point for the design of the entire system. It is also not straightforward to assume that the entire system’s performance will be predictable even if designer’s act as if the interface is all that matters.

A common cause for this ‘mixture’ is that the range of possible effects that the sub-system may have on the system as a whole are not completely captured in the definition of the interface and, as a result, efforts to operate in the first situation (where standards are taken as complete) turn out to be involve operation in the second, i.e. where the interface is incomplete. In these circumstances, the role of technical compatibility standards is to provide a starting point for the iterative and interactive processes of integrating the entire system.

Because such standards ‘freeze’ technological capabilities by defining the contributions of the component or sub-system, they provide a first recourse in working through the system integration problem. They establish priority for the question, is the interface functioning as specified? If it is, then the issue becomes whether the definition of the interface is incomplete for the integration of the system as a whole, i.e. whether, inadvertently, there are features of the interface that are propagating effects in the system, or whether it is the interaction between supposedly well-defined interfaces that create effects making it necessary to re-define the compatibility standard of the interface. How these issues are resolved between system integrator and components suppliers is a key issue for the technical management of such projects.

A complementary way to conceptualise co-ordination issues is to begin with the overall architecture of the system and to take the view that its decomposition into subsystems and components is a design choice. In examining decomposition, one may begin with the simple observation that large systems such as CoPS involve interfaces between many different components and sub-systems. The interface or joining ‘places’ in the system are determined by the system’s design, which in turn is constrained by the technology employed. Some technologies inherently involve ‘tight coupling’ in which a component or sub-system strongly influences the performance of other components and sub-systems (e.g. internal combustion engines), other technologies support ‘loosely coupled’ systems (e.g. telecommunication networks), and still other technologies support ‘de-coupled’ systems (e.g. traditional batch manufacturing processes).

It is an interesting historical question with regard to any particular technology to ask how the tightness of component and sub-system coupling was initially specified and how it evolves over time. For many older mechanical technologies tight coupling between components and sub-systems was initially necessary because of the way that control systems operated. For example, the historic multi-stroke engine involved a mechanical coupling between the introduction of fuel, ignition (in petrol systems typically through mechanical rotation of electrical contacts), and exhaust. More recent designs involve separating the control system from mechanical coupling, in effect ‘loosening’ the connection within the system - a process that requires a different set of

capabilities in interface and system design than the older system.^{iv} Arguably an increasing array of designs involves the separation of control from other parts of the system and the creation of specific control interfaces. The demands that this separation of control places on other components and sub-systems depend upon the specific features of the system. It is possible that either looser or tighter coupling, or even decoupling, will result from the separation of control.

This trend towards separation of control systems is particularly apparent in some large technical systems such as telecommunication networks. After the early history of human-switched telecommunication connections, the innovation of mechanical telecommunication switches involved tight coupling between the originating terminal equipment (e.g. the telephone of the calling party) and the switch that set up the path to the receiving terminal equipment (e.g. the telephone of the receiving party). Because of the tight coupling inherent in the design of the system, telecommunication users were dependent upon a particular set of components operating according to design. A call that reached a defective part of the switching network died and had to be re-initiated. Modern electronic switches have the capacity to monitor the switching process and employ error recovery if some part of the network is not operating. The result is a much higher level of reliability and, because the control system is electronic rather than electro-mechanical, the performance of the system is also much higher.

More generally, loose coupling usually involves some degree of penalty in terms of 'performance' although it is important to distinguish between engineering and economic performance. A tightly coupled telecommunication system such as an undersea cable control system is able to achieve high 'performance' in terms of bandwidth utilisation at the cost of denying service when more signals arrive than can be accommodated.^v Thus, high throughput performance may come at the expense of reduction in connection reliability.

The advent of 'packet' transmission has further loosened the tightness of coupling at higher levels of the telecommunication system, making it possible to 'route around damage,' a defining characteristic of the Internet and the more general use of Internet protocol methods in telecommunication of both voice and data signals. In this case, the 'looseness' of the coupling involves both technical and economic advantages

which is one of the reasons that telecommunication companies are either adopting, or actively considering the adoption of, voice over packet networks. The growth of the Internet has dramatically *de-coupled* a variety of communication processes. For example, while the transmission and receipt of e-mail involves loosely coupled exchange of information, most users prefer to remain ‘de-coupled’ from the receipt of e-mail messages, using the mail server as a de-coupled ‘store’ of messages in their system of communication. In a similar fashion peer to peer exchange of information, audio and video messaging, and other ‘background’ processes often involve the de-coupling of at least one of the communication parties from the need to be connected, i.e. coupled into the communication system.

More generally, the case of ‘de-coupled’ systems involves operations in which the connection between parts of the system is only indirectly linked. Traditional methods of manufacture, involving the accumulation of ‘work in process’ that is entered into an inventory for future assembly, is one example of a ‘de-coupled’ system. Such ‘de-coupled’ systems may generate their own design issues (e.g. how to govern the logistical problems of planning and storing outputs), but it is stretching the idea of ‘system integration’ to encompass these possibilities. Instead, it is more useful to analyse ‘de-coupled’ systems as involving a product platform incorporating a number of distinct systems. For example, in the design of an aircraft, the in-flight entertainment system is ‘de-coupled’ from the integrated systems controlling the flight. It would be disconcerting, to say the least, if such systems were made interoperable and the regulations concerning in-flight use of wireless electronic devices is an example of an attempt to maintain the integrity of wireless systems within the aircraft from possible interference with other wireless interfaces (such as those used by mobile phones).

This section has considered the system design problem largely within the framework of a ‘master designer,’ a situation in which the system integrator not only plans for the implementation of the entire system but also understands the source of all potential problems and their possible resolution. This is a highly idealised model of the actual design of CoPS. Nonetheless, it is a useful starting point as it indicates the processes of system integration and decomposition as design decisions and highlights the significance of the growing use of electronic control systems to ‘loosen’ the coupling

between components and sub-systems. Looser coupling heightens the importance of interface design and implementation and the role of standards, formed either at the level of the industry or locally. In practice uncertainties about the source of ‘bugs’ or bottlenecks in the overall system present major technical management problems since in a multi-organisational context knowledge is distributed between different organisations. The distribution of knowledge also makes it unrealistic for the system integrator to dictate the interfaces between system components and sub-systems, at least in an autarkic manner. This is the starting point for the discussion of ‘negotiation,’ the subject of the next section.

3 Negotiation

CoPS differ in the extent to which the system integrator is able to control the overall design and specification of components. The most conspicuous cases where the system integrator relies upon other companies are particularly important for the analysis of industrial structure. In these cases, there is often an early and thorough partition of sub-system producers such as the division of labour between aircraft engine and airframe producer (Prencipe and Paoli 1999) or between hardware and software producers (Steinmueller 1996). Such major structural fractures in the division of labour suggest that the benefits of vertical integration are overwhelmed by risks in integrated production and the advantages of competing suppliers.

Economists have argued that the division of labour is related to the size of the market since Adam Smith coined the phrase ‘the division of labour is limited by the extent of the market’ (Young 1928; Stigler 1951). Nonetheless, how a firm or an industry progresses from integrated production to inter-organisational division of labour has not been a central issue in economic analysis. This is largely because economists have encapsulated or ‘black boxed’ the issue as the outcome of the ‘make or buy’ decision. Integrated production occurs when the costs of internally co-ordinating production are lower than the costs of external co-ordination of production. The costs of inter-organisational division of labour are influenced by the potential for economies of scale and specialisation in external supply. Although this formulation ‘answers’ the question of what determines the division of labour, it fails to answer important

questions about the pre- and co-requisites to the emergence of an effective supplier industry. Where do such suppliers come from and how do they gain the competencies or knowledge necessary for making effective offers to incumbent integrated producers? More particularly, how might a company that wished to outsource production create the conditions for a supplier industry to emerge?

One possibility is to create technical compatibility standards. However, if system integrators define standards that are for their exclusive use, there will be a problem in recruiting suppliers whose market opportunities will be limited to the system integrator. Suppliers' economic prospects will be contingent upon their power to negotiate favourable deals with the system integrator. Moreover, arrangements of this type are not likely to lead to economies of scale or offer an 'upside' for the supplier, further increasing the costs of this arrangement and diminishing the pool of potential entrants. A solution is to make the technical compatibility generic or industry-wide, so that additional companies may become purchasers. Assuming that other companies do in fact become purchasers, an opportunity for further entry of suppliers is opened and a more complete market may develop. This alternative, however, raises problems for both the system integrators and suppliers. For suppliers, no company wants to be the producer of a commodity product in which it has no competitive advantage relative to other suppliers. In many cases, this issue can be resolved by learning or other dynamic economies of scale realised by the initial entrant and its immediate followers. For system integrators, the use of generic standards threatens to provide an advantage to rivals or new entrants. The component or sub-system to be standardised must not be the principal source of competitive advantage for the system integrator. This issue is often resolved by the complexity of the system integration and the existence of critical components that are either not outsourced or only outsourced to captive suppliers.

A second possibility is to define supply opportunities in terms of generic industry capacities. For example, the production of die cast metal or plastic parts of a certain order (increasing over time) of complexity at a modest level of specification tolerance is something that is within the competence of hundreds or thousands of suppliers. Components of this type are unlikely to require technical compatibility standards at all and likely to rely on the 'local' specification provided by the engineering drawing and tolerance specifications.

Between the possibilities of captive supply, industry-wide standards, and generic components or subsystems there are many possible arrangements. All of them involve negotiation between the system integrator and potential suppliers. These negotiations involve the creation of supplier capabilities that are specialised to the needs of the system integrator, but may also, to varying degrees provide the supplier with the capability of servicing other customers. These capabilities are what (Teece 1986) calls co-specialised assets.^{vi} Because of the specialisation of the supplier capabilities to the system integrator needs, the system integrator is likely to have to co-invest with the supplier. Although price is an essential part of these negotiations, it is likely that the engineer's idea of 'cost price' rather than the economists' idea of 'market price' will be the principle of negotiation. In situations where the supplier has market power due to unique technological knowledge or intellectual property, the system integrator's ability to pay may be a 'hidden principle' of the negotiation.^{vii} The result of such negotiations is a 'local technical compatibility standard,' which will meet the needs of the system integrator and may even be proprietary, but which will also allow the supplier to adapt or re-configure the design to meet the needs of other customers.^{viii}

The principal contributions of local technical compatibility standards to the negotiation in these intermediate cases are to reduce the extent of specialisation involved in the co-specialisation process, thereby creating a more incentive compatible basis for supply. For example, by limiting the product specification to the interface standard, the system integrator's purchaser need not become involved with how suppliers meet the requirements of the standard. The system integrator is thus less able to displace the supplier and the supplier is able to maintain knowledge about the 'inner workings' of its component or sub-system as proprietary. This provides a clear incentive for the supplier to agree to a standardisation process. The incentive for the system integrator to utilise technical compatibility standards is that they, in principle, open the market to alternative suppliers who can employ a somewhat different design of the 'inner workings' or the interface to satisfy the needs of other customers. The local technical compatibility standard has some potential to reduce the market power of the supplier in the short run and more potential in the medium term because they are vulnerable to other suppliers devising better ways of meeting this standard. On the other hand, the supplier is able to employ the development resources

provided by the system integrator as a 'subsidy' for their entry into other markets, an advantage that the suppliers' rivals may not have.

If technical compatibility standards are an incentive compatible means of reducing the extent of co-specialised asset negotiation processes, why are they not used more frequently, i.e. why are they not a central principle in the operation of CoPS industries? There are at least three reasons.

First, the nature of the technologies employed to make components and sub-systems may not offer a realistic possibility for alternative supply. Without an incentive for the system integrator, there is no basis for engaging in the costs of standards making and captive supply (either internal or through exclusive arrangement) will be the prevailing arrangement.

Second, even if standards could, in principle, enable competitive supply, they may be too transitory to serve this purpose. Standards making itself takes time^{ix} and thus a technical compatibility standard has to be relevant for long enough to enable competitive supply. Rapid technological change, especially in high performance 'state of the art' systems will reduce the relevance of technical compatibility standards for the system integrator.

Third, the system integrator may wish to maintain proprietary control over the component or sub-system. A standard not only opens the possibility for alternative suppliers, it also creates the possibility for alternative system integrators or an externality that can be employed by rivals. Thus, as noted earlier, the system integrator's competitive advantage must lie outside of the component or sub-system. If it does not, standards are irrelevant and the sole question is whether a supplier is willing to make the buy option in the make or buy decision viable for the system integrator.

In summary, technical compatibility standards have a role in mitigating the negotiation problems that arise when co-specialised assets are created in the division of labour between complex product system integrators and component and sub-system suppliers. This role is shaped by several technological and economic influences. A

first influence is the consequence of technological opportunities available for producing a particular CoPS. Abundant technological opportunities support rapid technological progress and make standards ephemeral; they also support the creation of alternative suppliers and, possibly, alternative system integrators. A second influence is whether the component or sub-system is a source of competitive advantage for the system integrator. When it is, standards are unlikely to be employed because of the risks of creating advantages for rival or new entrant system integrators. A third influence is whether there are likely to be multiple potential purchasers for the component or sub-system. When there are not, standards are likely to be irrelevant. Fourth, and finally, the technology in question has to be one in which technical compatibility standards are relevant, i.e. they can be implemented. Electronic technologies are particularly noteworthy sources of standardisation opportunities, subject to the constraints suggested by the other influences. Further assessing this potential in relation to engineering design issues is the subject of the next two sections, the first on the role of compatibility standards in stabilising design processes and the second on the growing opportunities to employ simulation techniques in the design process.

4 Memory

Further inquiry into the processes of division of labour in industries that produce large technical systems or complex products and systems entail examining how capabilities are constructed and retained over time. A useful focus for such examination is the issue of organisational memory, the retention and enhancement over time in the firm's capabilities for problem solving as well as the replication and enhancement of past performance.^x In some technological intensive industries, organisational memory is secondary to the ability to engage in rapid *ad hoc* problem solving and reconfiguration of inter-organisational arrangements, see Brown and Eisenhardt (1998) for examples. The role of technical compatibility standards in these industries is often to consolidate the ownership of a market by creating a coterie of complementary products and services, e.g. the efforts of Intel and Microsoft to stimulate the development of multimedia standards. In these cases, standards have more to do with enhancing the demand for technology 'platforms' in products that are highly modular than in complex integration processes such as those necessary to

construct a large building, the complex producer goods used to make integrated circuits, or produce a flight simulator. In these latter cases, it is often necessary to retain knowledge from one period to another. Moreover, it is common for such systems to be made on a one off basis, reconfigured with different or additional options to different customers, and upgraded incrementally with modest or no change to some of the components or sub-systems.

Under these conditions, it is important to have specific guidance about how changes can be introduced in components and sub-systems without the requirement of achieving in-depth knowledge of how these parts of the system work. Local technical compatibility standards generally and interface standards specifically provide this sort of guidance. These standards support the division of labour across time and between organisations by providing a memory of how the pieces of the system fit together. Creating standards is therefore an act of defining what is to be remembered about how the system is constructed. In addition, the collection of interface standards provides a guide to alternative ways that the system might be decomposed into different sub-systems, how, for example, a tightly coupled system might be re-designed to employ looser coupling by embedding the critical elements responsible for the tight coupling within a particular sub-system.

Organisational memory and the competences that are linked to it are particular to individual organisations. Divisions of labour that assign responsibility for sub-systems and components across organisational boundaries are divestitures of the organisational memory and competences necessary to make these components and sub-systems. This process is sometimes viewed with alarm and described as the ‘hollowing’ out of company competences. There is certainly the possibility that short term cost minimisation in the production of a single generation of products might lead a company to divest the sources of memory and competence necessary for creating the next generation of products. At the same time, however, by divesting itself of accumulated capabilities, a system integrator attains the freedom to rethink the complex products and systems that it makes. The pressures to respond to the problems and difficulties of external contractors is likely to be lower than the pressures that can be exerted by colleagues operating within the same organisation. Of course, it is quite possible that companies may over-estimate their own understanding of the products

that they produce and inadvertently sever an arterial source of knowledge in the excision process represented by outsourcing. However, it is also possible that retaining particular competences may bias the design of the entire product to satisfy internal constituencies and lead to disadvantages with rivals, the incumbent or entrant, that take a fresher approach to design issues. In effect, outsourcing is a dialectical process in which the excision of capabilities creates a tension or ‘contradiction’ between what is internal and external that is resolved through a process of synthesis. In this case the synthesis involves developing memory and competence around the process of resolving these contradictions, i.e. in the problem-solving related to inter-organisational co-ordination rather than processes of design that are based upon internal competences.

What is being synthesised also enters into this process. Outsourcing also sets in motion an independent accumulation of memory and competence in the supplier firms. A key observation to how this process works was made in Rosenberg’s (1976) study of the machine tool industry. Rosenberg observed that the technical design of machine tools became more generic when they were produced by an independent sector. In effect, a technological trajectory involving the creation of ever more general-purpose devices replaced a pattern of product specialisation in which machine tools were designed around the specific needs of one class of user firms. The exploration of the potential for more generic products in which the supplier can retain competitive competence is the essence of this process. From the supplier’s perspective the ideal component or sub-system is one that can be customised to the needs of a variety of system integrators, affords supplier rivals very little ability for imitation, and is subject to decreasing costs of production.

Electronic components and sub-systems meet all of these criteria except for the difficulty to imitate. The capacity for imitation in electronic components and sub-systems creates strong incentives to continuously innovate in, or at least change, the design of the product. It may be responsible for the common observation in industry that modern producer goods are ‘over-specified’ in terms of the complexity of their control systems (mostly electronic) and thereby are more difficult to maintain and more difficult for human operators to learn to use. These problems can be seen as outcomes of the supplier incentives to set a moving target for rivals while

simultaneously creating products that appeal to broader markets (features useless and confusing to some are valuable to others).

Technical compatibility standards have an unexpected role in this context. While suppliers seek to bind their customers closer by better meeting many of their needs (albeit with more complex products that are not necessarily appreciated), system integrators can discipline this production of variety and the threat of being bound to proprietary standards of the supplier by specifying or agreeing to standards. In doing so, system integrators may benefit rivals, but failure to do so may incur higher costs in terms of the unwanted proliferation of variety. In this sense, standards serve as a means of simplifying the complexity of producer good systems and thereby limiting the divergence created by dispersing the memory and competence for component and sub-system production.

The purpose of this section has been to examine how technical compatibility standards influence the accumulation of organisational memory and competence as system integrators operate in an environment characterised by ever increasing division of labour and knowledge. Inter-organisational distribution of knowledge necessarily leads to distribution of memory and competence. It also creates a specific set of incentives for technological improvement and change. By way of example, it has been argued here that these incentives may produce ‘excess variety’ as suppliers attempt to increase the generic qualities of their products (to enlarge their market), to offer proprietary features (to increase their market power with respect to system integrators), and to make frequent improvements or changes in their products (to defeat the imitative efforts of rivals). Technical compatibility standards can be seen as a means for system integrators to govern these incentives and to ‘simplify’ what might otherwise, from the system integrator’s viewpoint, be seen as the production of excess variety.

5 Conclusion

It is now well recognised that technical compatibility standards play an important role in permitting the dis-integration of the development and production of components and sub-systems designed to be integrated into complex products and systems (as

defined in the Introduction, Section 1). Analyses of the processes by which these standards are set have focussed on the contrast between *de facto* (market led) and *de jure* (co-operative standard-setting by voluntary standards organisations) mechanisms. This dichotomy directs researcher attention to the standards-making process itself. This chapter returns to the more fundamental question of why companies have interests in forming technical compatibility standards including those that are ‘local’ within the networks of firms responsible for the production of complex products and systems.

The discussion in this chapter has emphasised the role of technical compatibility standards in supporting the division of labour by providing a means of defining the interfaces connecting the components and sub-systems of large technical systems or complex products and systems. The principal purpose of the section on co-ordination (Section 2) was to assess the constraints including the feasibility of inter-organisational division of labour. This investigation of feasibility highlighted the importance of tight and loose coupling in the design of systems and observed the growing use of electronic control systems as a means of creating more flexibility in system design.

While the initial assessment of co-ordination issues and the feasibility of division of labour were framed in terms of system integrator (or master designer) control, a deeper analysis involves considering the negotiation (Section 3) between system integrator and suppliers. The limiting cases of captive and generic suppliers were defined and this led to the definition of negotiation problems related to the co-specialisation of assets between system integrators and suppliers of components and sub-systems. It was argued that technical compatibility standards provide an incentive compatible means for solving this specific negotiation problem. The relatively modest use of public standards making processes in complex product and system industries stems from the continuing importance of captive supply, the transitory nature of some designs, and system integrator desires to maintain proprietary control of component and sub-system designs.

The section on memory (Section 4), examines the prospects for extending the use of technical compatibility standards in supporting solutions to inter-organisational co-

ordination problems when knowledge is distributed between system integrators and component and sub-system suppliers. As this (and preceding sections) observe, the dis-integration process creates specialised competences with their own trajectories of change and improvement and thus an inter-organisational distribution of knowledge generating and production activities. The process of recalling this knowledge, memory, becomes a central issue in which standards can play a central role.

As Section 4 notes, recent history has demonstrated the facility with which design and production of electronic systems using standard defined interfaces can be distributed. This lesson has not been ignored by other industries and has been broadly applied to production in other industries including complex products and systems where reliance on electronic systems for control further supports this growth of inter-organisational division of labour.

The issues of memory cannot, however, be disentangled from struggles for control or the emergence of separate lines of initiative within the network of firms involved in knowledge accumulation. The inter-organisational division of labour ignites rather than extinguishing further struggles for control and technical compatibility standards can play an important regulatory role in this struggle for control.

A principal conclusion of this chapter is that technical compatibility standards are as relevant to complex product and system industries as they are to industries that employ mass production. This relevance does not mean, however, that technical compatibility standards are employed to create the same form of competitive selection process or advantages in the industries where complex and flexible system integration is a central feature as in those industries based on mass production of standardised products. Instead of a competitive process struggling for adoption of a dominant design, the competitive process in the system integration industries involves implementing design through the processes of co-ordination, negotiation, and memory. These processes have the capacity to determine competitive outcomes between firms and hence the 'competitiveness' of particular managerial approaches or practices, and merit continued and intensified examination.

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ⁱ A more complex example illustrating the problems of inter-connection is the case of alternating current voltage converters such as those used to transform European 220 volt power mains for the use of North American and Japanese 120 volt equipment. Such devices offer much more limited ‘compatibility’ due to the more complex characteristics of alternating current compared with direct current. For example, such converters do not typically shift the frequency of the alternating current, which in Europe is 50 hz whereas in the US it is 60 hz. This difference in frequency is enough to defeat inter-connection for some types of electrical products.

ⁱⁱ One might think that more complex devices would require more complex compatibility standards. This is not necessarily so, as it is possible to locate the functions of adaptation and interoperability within the device itself rather than within the interface or its implementation. Thus, a computer modem may be used to receive a video transmission without any of its specific features being devoted to the video information itself. This is possible because the data interpretation occurs within the personal computer while the modem is simply passing a bitstream between devices.

ⁱⁱⁱ It is important to note that CoPS may involve large numbers of standardised components. For example, civil engineering projects may involve the use of concrete and steel construction in which both technical compatibility and reference standards are ubiquitous.

^{iv} Early difficulties with the electronic control of fuel injection systems are a historical example of the difficulties in building these new capabilities.

^v While there is currently a surfeit of intercontinental telecommunication capacity, this was not always so.

^{vi} Co-specialisation involves the older economic issue of bilateral market power, the case where both supplier and purchaser have market power over each other, i.e. the purchaser has monopsonistic power because of the absence of alternative customers and the supplier has monopolistic power because of the absence of alternative suppliers. The textbook solution to this problem is vertical integration. However, this does not address the potential advantages arising from the vertical division of labour between supplier and purchaser.

^{vii} Quite naturally, it is not a very fruitful strategy to adopt ‘ability to pay’ as an explicit principle in a price negotiation. Instead, the negotiation proceeds from an alternative definition of ‘cost price’ in which a full cost rather than an incremental cost accounting principle is employed. Cost plus an allowed profit is a typical implementation of the full cost principle.

^{viii} In the case of proprietary compatibility standards, an accommodation must be made with the system integrator or the co-specialised asset must be incompletely specialised, i.e. it must be sufficiently adaptable that non-infringing products can be produced.

^{ix} The timeliness of standards-making is an important subject, see e.g. Weiss and Sirbu (1990). One source of ‘delays’ in public standards making is the need to take all stakeholders’ interests into account. Increasingly, a variety of standards are quasi-public goods (produced by a ‘club’ of interested parties). While the private approach may be more rapid, it also may erect barriers to entry by settling on standards that advantage a more limited number of suppliers, see David and Steinmueller (1996).

^x The latter capability is often considered in the evolutionary economics framework of ‘routines’ as defined by (Nelson and Winter (1982). In the case of complex products and systems considered in this chapter it is common for activities and procedures to be restructured or changed continuously. It is therefore more appropriate to focus on the replication and enhancement of performance (e.g. timely completion of projects within budget and meeting expectations) than routines (e.g. achieving the same outcome using the same activities and procedures).