Codification of technological knowledge, firm boundaries, and “cognitive” barriers to entry

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CONTENTS

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1. The theoretical framework and the main notions introduced

1.1. Introduction

Since the Eighties, a number of authors have analysed the transition of firms to a post-Fordist organisation paradigm. Attention has been concentrated on the paradigmatic case of the reorganisation of the assembly chain in the car industry (assembling being a particularly complex and crucial step in this sector), according to the Japanese "new production concepts" (Abegglen and Stalk 1985, Aoki 1988, Best 1990 among many others) and new ways of using and motivating labour and of coordinating the flow of resources.

The importance of this debate on the new principles and on the application of lean production cannot be disputed. However I think that, partly as a consequence of focusing the attention on the assembly line, other fundamental changes which have been taking place during the last twenty years in the manufacturing sector have been neglected by the economic literature. In truth, the assembly line has been relatively little affected by the changes that have transformed the role of man in most processing phases due to the diffusion of computer-based technologies. But this is not a good reason to ignore the emergence of the new paradigm which is redefining skills in manufacturing, considering also that (i) in many sectors assembling is a relatively trivial task compared to processing in terms of knowledge and innovation content (e.g. semiconductors); (ii) the proportion of value added in manufacturing attributable to assembly operations is limited, since most of it is realized in processing activities (iii) even assembling will be increasingly reorganized according to the principles applied in processing stages.

The objectives of this research have been the following.

First, to shed light on the role men perform in a manufacturing system reshaped by the pervasive process of codification of technological knowledge enabled by the availability at low cost of electronic automation technologies and measurement instruments. Traditionally men in the shop-floor used to play two very clearly distinguished roles, which had however a fundamental feature in common. Unskilled workers were engaged in simple repetitive manual tasks, whereas skilled workers had to use their sensory organs and their brain to judge the moment when and the way how some operations had to be conducted, but in both cases they acted as if they were (more or less intelligent) machines or parts of machines, in the sense that they participated in the physical manipulation of some material or some object neither designed nor conceived by themselves[1].

This is in sharp contrast to the main role men have acquired as a result of computer-based automation: that of monitoring and controlling the action of intelligent machines fully freed from human "tools". Men in controlling automated equipment act mainly as problem solvers and must possess a (limited) discretionary power.

A pioneering contribution in the direction I am following has been offered by the Italian sociologist Butera (1987, 1997), who more than a decade ago explored the changes that were transforming the basis of vocational skills ("*professionalità*") of employees in the manufacturing industry. The new basis is founded, according to Butera (p.16, 1987), on "supervisory control and innovation tasks, more than processing ones". As he asserts, since an emerging paradigm is not immediately diffused at all levels and everywhere, one may still find very different work situations in the same sector or even in various areas of the same firm where 'automated "almost-chemical" process operators' and traditional workers may coexist (but the proportion of the different species has changed dramatically in the last decade). Conversely, both new automated processes (such as FMS in machining metal parts, continuous casting in the steel sector, dry hoods in the semiconductor industry) and traditional processes transformed by the massive insertion of computer-based automation make the work conducted in extremely different sectors quite similar.

The role of controllers is not completely repetitive over time and always new problems appear to be handled, since the technologies controlled and the products supplied are subject to change, more or less rapidly according to the technological dynamism of the various sectors[2]. Indeed, an increasing proportion of employees in the manufacturing sector is dedicated to the more sophisticated problem solving tasks of designing new artefacts, planning their manufacturing cycle and bringing them to the market.

The crucial importance of problem solving points to the fact that codification of technological knowledge does not imply that human tacit competences - meaning knowledges and abilities that are inherently embodied in individuals - have disappeared or lost their prominence. In order to make this point clear, I discuss the concept of tacit competences and attempt to identify the limits to codifiability. The examination of the incentives to codification will allow us to explain why small firms may still be highly dependent on uncodified know-how.

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[1] Only in craft production were both conception and execution performed by the same person, the craft-worker.

[2] According to Koike (1994, p.42) "Even in the most repetitive mass-production workshops, changes in production and unforeseen problems of minor scale frequently occur, and actions to deal with them are repeatedly called for to maintain the steady flow of production". The ability to deal skilfully with these problems and changes, namely to execute "unusual operations" is considered an "intellectual skill" that crucially contributes to the efficiency of Japanese industry. He also observes that "computerization and automation have made it possible to transfer usual operations to machines, but not unusual operations…. Thus, with advances in computerization intellectual skills will grow in importance." (1995, p.74)

Secondly, I aim to examine the economic consequences of the above briefly outlined changes. In particular I shall discuss the following issues: a) the emergence of a new source of increasing returns; b) the impact of codification of knowledge and automation on cognitive barriers to entry into various sectors. For a firm the possession of process know-how is a prerequisite to entry into an industry, in addition to knowledge regarding the product sold and its market. The question thus emerges of whether codification of know-how previously embodied in people and its transfer into software has made entry easier in those sectors (or segments of sectors) which are characterised also by low cognitive barriers regarding the product, due to an increased role played by the equipment and automation suppliers as supporters of new entrants; (c) firm boundaries. The issue concerns the link between the process of codification of know-how, automation and acceleration of the pace of technological innovation on the one hand and the increasing vertical disintegration which has been pursued by firms in the last decades on the other. Two different mechanisms may be at work, either of a Smithian or of a Coasian nature. According to the first, the argument runs this way. To automate, codify and invest in the new complex technologies the suppliers of components need to develop a specific competence and to incur heavy fixed costs. This job is better performed by specialists focused on a precise mission, than by vertically integrated firms that therefore prefer to buy than to make their components. A crucial connection is thus identified between the evolution of knowledge bases and technologies and the dynamics of internal versus external competences, which over time reshapes the social division of labour. In contrast, according to the second mechanism, the emphasis is moved to the effects of codification on transaction costs. Since they are lowered, this may explain increased externalisation. But can a decrease of transaction difficulties attract the attention of decision-makers so strongly as to elicit such a strategic move as reshaping the boundaries of the firm? I suspect it doesn't and that the Smithian story is a more robust candidate for explaining vertical disintegration.

To conduct this investigation, information has been collected through direct unstructured interviews at a number of firms operating in various sectors: in particular the steel *filière* (steel producers and their equipment suppliers), the semiconductor industry, a segment of the chemical industry (rubber production) and the mechanical sector, distinguishing between mass production and flexible specialisation, have been surveyed. The choice of firms was random, based on their willingness to cooperate. In various cases we - Stefania Borghini and Giorgio Greco participated in the research - made repeated interviews with many people of the same firms, spending many hours in discussion with them. A very prompt understanding of our points was found.

Unluckily it was impossible to find any reliable quantitative data to support our findings. Only some scanty figures could be collected at some firms, usually not comparable. Also, we cannot claim to have collected exhaustive qualitative evidence. However I think that the picture drawn is very significant in illustrating some general trends that have affected the whole manufacturing industry. The similarity of the changes found across sectors is striking.

Finally, the witnesses collected are precious, since many of the people who know the past (before change took place) and could compare it with the present will retire in a few years.

In this section I shall discuss the main notions and analytical foundations underpinning the hypothesis that our research will attempt to validate. Then I shall present the various cases investigated, namely the steel (section 2), semiconductor (section 3), chemical (section 4) and mechanical industries (section 5). The general conclusions emerging will be expounded in section 6.

1.2. Codified technological knowledge and dynamic tacit competences: the role of men in computer-based manufacturing

During the last twenty years the new electronic and computer-based automation technologies and a number of process innovations, themselves dependent on electronic control and sophisticated instruments of measure, have caused a radical change of the role of workers in manufacturing activity in most industrial sectors. A general obsolescence has taken place of: a) craftsmen, namely those skilled workers that were real "pieces" of the production process, since they conducted operations based on an uncodified knowledge content that required the deployment of the tacit knowledge they possessed. In general, either their tacit knowledge has been codified and the execution of their activity assigned to a machine/instrument, or a technological innovation has changed the production process and made their specific knowledge obsolete. This process is still taking place, and some functions/jobs based on tacit production competence are still existing, but the trend leading to their progressive elimination is very clear; b) a large part of unskilled workers, performing repetitive tasks, which do not require any application of knowledge and have been automated. The operations that have remained mostly manually performed are those of loading, moving, unloading.

Currently operators mainly perform the task of *monitoring and controlling automated processes*, as supervisory controllers of computer-managed machines that execute the process. They must promptly face the anomalies that hinder the correct functioning of machines and quickly intervene when the information shown on computer displays reveal that some problem is altering the smooth application of procedures. In general, the reasons underlying deviations from prescribed operation procedures may be numerous, the more this is so the higher the number of variables that come into play in relation to the complexity of the process. The task of interpreting available information in order to keep variances under control may not be trivial at all, and the intervention required calls for the exertion of discretionary power and judgement. The seriousness of the anomaly must be evaluated by the operator in order to decide whether the case is one that requires him to request the help of a specialist or whether their problem solving capability may suffice[3].

Moreover, line operators usually bear the responsibility of preventive maintenance (a practice which is spreading) and sometimes of ordinary maintenance as well. Specialists are assigned the most sophisticated maintenance operations. Depending on sectors, ordinary maintenance[4] may be either entrusted to internal services or externalised to specialised independent firms.

It appears that firms belonging to very capital intensive sectors, that produce products whose quality is strictly dependent on the ability to employ complex and highly specific equipment correctly and to accumulate proprietary know-how learned through its use, tend to rely on internal personnel for maintenance (considering this competence strategic), whereas in sectors where more widely adopted machines (such as machine tools or looms) are used, whose functioning is well understood, firms tend to outsource it. Examples of the first type are steel and semiconductor producers, of the second one firms in the machinery industry and in the textile *filière*.

However, the most sophisticated and specialised maintenance operations are almost always contracted to plant suppliers, or at least conducted under their supervision, in all sectors.

On the whole, the adoption of innovative computer-based technologies and the immission of automation into traditional ones had the effect of generally increasing capital intensity, reducing the workforce employed and considerably improving productivity and the quality of products. However, some "manufacturing areas" have remained very little affected by these changes, since a considerable part of the activity is still manual. Among these areas are some phases of various *filière* - such as the assembling phase in most sectors or the phase of sewing garment in the textile *filière* - and some craft-based industry segments, such as luxury shoes.

It is worth noting that the assembly phase is still generally conducted manually, except for some specific applications in sectors characterised by large batch production, or for operations that require extreme precision or the manipulation of noxious substances, even in

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3 It is worth quoting Butera's description of the role of supervisory controllers (1987, p.103): "The tasks of process supervisory controllers are of various kinds: monitoring, controlling the variables affecting plants, products, processes and/or flows, making instantaneous or historical comparisons. They consist of a reading and interpretation of signs (on/off information), signals (which require the urgent activation of a specific procedure), symbols (information requiring the knowledge of the context to which they refer, in order to be interpreted). Supervisory control tasks do not entail any physical intervention in the primary process: their object is information supplied by computers that display disturbances, variances or values of parameters that highlight the need for regulations of the system, such as setting-up the plant, transmitting information, regulating the value of parameters, totally or partially interrupting the production process for emergency, sometimes manually operating the plant or manually regulating driving gears."

4 Note that since plants are increasingly designed as sets of decomposable subsets a large part of maintenance is done simply by substituting subsets.

industries that in the processing phases employ very sophisticated and automated technologies. In fact human flexibility (comprising intellectual as well as bodily abilities) in most assembling operations still has a competitive edge over computer-based automation. If one visits a modern plant in the car industry, such as the most modern one of Fiat Auto in Melfi (Southern Italy), one sees under the same roof rather different worlds (or industrial ages) coexisting: the world of (the few) supervisory controllers, sitting in front of computer displays in the stamping, welding and painting departments, where automated machines process the metal, and the more traditional world (even if reshaped following Japanese concepts) of many manual operators assembling cars by hands.

The change illustrated above involved a radical process of obsolescence of tacit knowledge embodied in those operators upon whom in the past production processes depended. Current supervisory controllers must have a higher level of formal education than old craftsmen, in order to interact with computers. However, their competence (in performing an activity that involves problem solving) is also based on experience and on insight; it is enhanced by process innovation, whereas the craftsman's knowledge was made obsolete, since craftsmen were themselves “pieces” of given technological processes. Moreover, controllers' knowledge is more general and can be easily redeployed across various sectors, whereas that of the craftsmen was extremely sector specific, or even specific to a particular step of a given process.

In the new setting the activity of creating new operating practices has become increasingly important, in order to fully exploit the potentialities of the new complex pieces of equipment to produce a wide range of products (making them more specific to the various uses) and to obtain high levels of quality. This activity is not the task of controllers, but of technical personnel assisting production. The result of it is proprietary knowledge in the form of specific codified know-how expressible in software. Thus learning by using has become the planned activity of technical personnel dedicated to it, and it is one and the same with learning by doing. The traditional concept of learning by doing is meaningless in the new setting, since manual dexterity has no role where production is realised by machines (see the semiconductor case).

An examination of the changes that have affected the role and the type of human capital in manufacturing firms cannot overlook the importance of the acceleration of technical progress. Firms increasingly compete in most sectors on the basis of the ability to pre-empt the market (Dosi 1984), or at least to penetrate into a particular market niche, supplying new products. Consequently, researchers and technical experts are required to conduct research, development and design activities, thereby contributing to build those proprietary knowledge assets which are a fundamental source of the competitive advantage of firms.

The point to stress here is that the product of this searching activity is codified knowledge (know-how and know-what), whereas the process of problem solving and searching is partly based upon tacit euristic, embodied in individuals (Balconi 1998). Thus, it is no longer the content of knowledge underlying technical change which is tacit (as many authors erroneously claim), but instead it is the ability of firms to create new knowledge, to develop new artefacts, which is embodied in individual people and routines. Creating new knowledge depends on acts of insight (envisaging new connections between variables and, sometimes, the general laws underlying them) which are inherently embodied in individuals, whereas the knowledge created is explicit [5].

This contrasts with the previous situation, where the production process relied on the work of craftsmen and technological knowledge did not exist in the form of a structured set of information and rules, but was embodied in the craftsmen themselves.

The tacit competence of problem solvers, complementary to the explicit knowledge mastered by them and acquired through a formal school education, is a “dynamic capability”, instrumental to carrying out the tasks of firms of continuously producing new products and of learning incessantly.

1.3. A taxonomy of tacit skills relevant in manufacturing activities

I have already drawn a distinction between the tacit knowledge of craftsmen and that of modern problem solvers[6] (supervisory controllers, technical personnel, researchers, managers). A full taxonomy of human skills[7] relevant in manufacturing activity is presented below.

A) *Tacit skills relying on the perceptions of sensorial organs or manual ability.* They are created through experience only, are learned by flanking an expert and do not require any formal education. One can identify the following types:

1) Capability of evaluation of physical phenomena based on sensorial perceptions (through visual, auditory, tactile organs).

2) Manual dexterity: it may involve various degrees of difficulty, from trivial abilities to perform elementary and repetitive actions, to refined ones that need high levels of attention and precision and require an innate endowment in addition to experience.

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[5] On this point I find Arrow (1996, p.650) very confusing, since he identifies the capability to create new knowledge (new software, in his example) with *information*. “Tacit information”, in my view, is a misleading oxymoron.

[6] D.Leonard and S.Sensiper noted that “the most common application of tacit knowledge is to problem solving” (1998, p.114)

[7] Polany (1958, p.49) characterises skills as involving “the observance of a set of rules which are not known as such by the person following them”.

These two categories of tacit skills have become obsolete in many manufacturing processes since the introduction and diffusion of low cost instruments of measure and computer-based automation.

B) *Tacit euristic or interpretative skills.* They presuppose a basis of formal education and develop through experience. One can distinguish:

1) Capability of evaluating codified information, recognising underlying drifts from weak signals, drawing not easily predictable consequences from known data and establishing unexpected correlations among variables.

2) Ability to solve problems or to work out improvements to known solutions. These skills are required, for instance, in cases of machine breakdowns or to increase yields.

3) Capability to draw interpretations of a semantic nature (such as interpreting the evolution of consumer tastes).

4) Creative intellectual capabilities of a scientific or stylistic nature. They are strictly dependent on innate endowments, besides requiring a formal education.

The first three categories draw upon the way the human brain functions, on the basis of *pattern matching* (M.L. Ginsberg, 1998)[8]. Man has a clear advantage over computers in those situations that need to be addressed through a method of pattern matching instead of computing, like in the activity of creating novelties and controlling production processes whose smooth performance depends on the imperfectly known interplay of many variables and circumstances. Consequently, even in automated manufacturing activities human capabilities maintain a central role, not limited to the stages of making research and designing new products.

C) *Mixed skills of A and B types*

1) Creative manual and intellectual abilities of an artistic or handicraft sort. They require, more than the preceding ones, innate endowments.

2) Manual and intellectual abilities drawing upon vocational education and experience (craftsmen in the machinery industry, maintenance operators).

With regard to the difference between skills A and B, one may distinguish *tacitness in a strong sense*, which implies the absence of codified knowledge, from *tacitness complementary to a codified knowledge base*.

On the whole tacit competences are "reduced", compared to when men were "pieces of machines" embodying the tacit knowledge of production processes; they are different, since they are mostly complementary to a codified content (Cowan and Foray, 1997); however, they remain crucial. In fact the performance and survival of firms depends on their (tacit) ability to solve problems, to control, to understand and to improve processes, to find new

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[8] Simon (1981, p.106) had already asserted that the reason why experts on a given subject can solve a problem more readily than novices is that the experts have in mind a pattern born of experience, which they can overlay on a particular problem and use to quickly detect a solution. "The expert recognises not only the situation in which he finds himself, but also what action might be appropriate for dealing with it".

technical solutions and to design new products, to integrate various "bodies of understanding" and to build relations with clients and interpret market trends.

1.4. Limits, costs and advantages of codification

The content of know-how and know-what, as asserted above, is generally codifiable, thus transferable in the form of information. However, many pieces of knowledge, which are in principle codifiable, are not codified as long as the technical instruments required (for example, to measure peculiar physical phenomena) are not fully developed or codification is not profitable. Given the rapid pace of technical progress of electronic devices and instruments of measure, the reach of codification and automation expands over time quite rapidly.

A reason underlying a high cost of codification is that it may imply an explosion of information, when a synthetic insight has to be analytically decomposed into many threads. In general, which are the advantages and costs of codification in the production activity? Which are the forces that hinder it? Without addressing these questions in depth, I suggest some considerations.

Firstly, codification implies the burden of a fixed cost. Paraphrasing Arrow (1996, p.648), it may be said that an item of information needed for production is codified once and for all. Since the same cost of codification is born regardless of the scale of production, there is *an extreme form of increasing returns* in codifying and the profitability of codification is positively related to the intensity of use of the codified information (thus to the level of output realised through the application of codified procedures). Consequently, small firms might find codification unprofitable and prefer to rely on the tacit knowledge of their employees. On the other hand, once a firm has codified its know-how, it owns a resource which can be reused at no cost. This may be an inducement to grow, triggering a mechanism *à* la Penrose. Thus a multi-plant firm has a competitive advantage in comparison with a mono-plant one, which did not exist when know-how was incorporated in the head of master craftsmen. Then not only did a firm willing to increase its output by investing in a new plant have to face a proportional increase of its variable costs - the cost of hiring craftsmen -; it also might incur the risk of being hindered by a scarcity of the required human resource.

Secondly, since at least part of the technological knowledge to be codified is product specific, the cost of codification increases in relation to the level of product differentiation. Hence firms specialised in customised products will rely less on codified procedures and specifications than firms producing standardised goods.

Thirdly, the cost of codification increases with the number of variables that influence the performance of a process. For example, if the raw material processed is a natural one whose composition is not homogeneous, the required adaptation of process parameters usually tends to rely on human tacit knowledge and to remain uncodified, since it would be too costly and time-consuming to codify and automate an extremely large number of unrecurring possibilities.

Finally, technologies differ as to the level of standardisation and maturity. Mature technologies embody the result of past learning and do not in general present problems whose solutions require human problem solving activity. Their know-how tends to be fully codified and supplied by plant makers to plant users. In contrast, innovative technologies involve the necessity to improve them. Hence even though their knowledge content is fully codified (e.g. semiconductors), human tacit capabilities are needed to improve it. Only in this sense can it be said (as Leonard Barton, 1995, does) that new technologies are less codified than mature ones. In fact, if the production process is fully automated, the content of what is learned is straightforwardly codified in order to be used in production. Again, whereas know-how is codified, it is the act of improving it which inherently relies on tacit competences. Expert systems may help but as problem solvers humans have a clear competitive edge.

1.5. Role of plant suppliers and knowledge barriers to entry

In order to enter a market, a firm needs a minimum basic competence; then, after entry has occurred, the challenge it must meet over time consists of developing the distinctive capabilities required to build a competitive advantage. As Teece and Pisano (1994) among others argue, the very essence of capabilities/competences is that they cannot readily be imitated or assembled through markets.

Consequently, in addition to specialised equipment and traded know-how, a potential entrant into an industry needs (a minimum amount of) those crucial human skills that can be shaped into firm competences through coordination and integration[9]. These human skills requirements are a necessary, enabling condition to entry, though not a sufficient one, since other types of barrier may come into the reckoning (scale economies, distribution channels, reputation, trademarks and advertising etc.).

Since the complexity of coordination and integration is related to the number of individuals bearing crucial skills who must be coordinated, in order to assess the height of what I call "cognitive barriers to entry" in various sectors or industry segments, it is sufficient to consider the human competence requirements of firms characterising the sector. Thus I suggest a "knowledge-based" concept of minimum efficient size: the minimum number of individuals incorporating crucial knowledge (human capital threshold, HCT). I

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[9] "While knowledge assets are grounded in the *experience and expertise of individuals*, firms provide the physical, social, and resource allocation *structure* so that knowledge can be shaped into competences." (Teece 1998, p.62).

consider crucial those tacit skills experientially built needed by firms to successfully carry out the activities which are strategic in a given sector[10].

Crucial knowledge regards both products and process. Clearly, the increasingly rapid pace of innovation must have made knowledge entry barriers higher in the sectors where product innovation is the prime condition for survival. In fact the importance of the internal network of teams of problem solvers and novelty creators must has grown, and this makes entry more difficult.

What we want to find out is whether codification of knowledge and automation have had an impact in the opposite direction upon knowledge barriers related to production process. I hypothesise that this may have occurred only if i) process innovation is not strictly connected to product changes and ii) the reduction of costs is the main driver of innovation. These conditions characterise traditional sectors, or sections of them, where even style innovation does not play a particularly meaningful role.

To understand the mechanisms I envisage to be at work, the different role of equipment suppliers across sectors must be examined. This role, already discussed at length in the literature[11], merits further attention on the basis of (i) the consideration of the link existing between process and product innovation. (ii) a clear distinction between process innovation embodied in capital goods and disembodied.

In sophisticated sectors process innovation is strictly related to and driven by product innovation. Firms, in order to make new products, need to use new processes. Plant makers have the specialised plant engineering knowledge that plant users do not have, but the users are those who know the techno-functional features of the products to be realised and thus help define the functional characteristics of new plants. Thus users must cooperate with specialised plant makers to make them provide the new generations of machines which are required; moreover if the various plants employed to carry out the successive production steps are provided by different specialised plant providers, users must also master the know-how regarding the integration of the plants and the lay-out. Finally, while the basic procedures for the use of plants are provided by plant makers, their improvement relies on the experience of the users. Process and product knowledge can only partly be disentangled, and disembodied technical progress is important. For all these reasons the role of plant makers is limited. They are not in the condition to offer autonomously to a potential entrant in the users' industry the process knowledge they need.

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10 "Tacit knowledge is a tremendous resource for all activities - especially for innovation. The tacit dimensions of *individual* knowledge are not publicly available except as embodied in people to be hired, and the tacit dimensions of collective knowledge are woven into the very fabric of an organisation and are not easily imitated. Therefore tacit knowledge is a source of competitive advantage. The creativity necessary for innovation derives not only from obvious and visible expertise, but from invisible reservoirs of experience." D.Leonard, S.Sensiper, 1998, p.112.

11 In particular by Pavitt (1984) in his famous contribution on sectoral patterns of technical change.

The sectors where the above conditions hold, such as semiconductor or automotive, may be then considered “dominated by plant users”. With reference to Pavitt's well-known taxonomy, they correspond to the “production intensive” class, including both scale intensive and science based sectors. In passing it is worth noting that in the time elapsed since the publication of Pavitt contribution, plant provision, which was then (beginning of the 1980s) still realised partly internally, has been generally outsourced by firms operating in these sectors. Thus even in the latter the role of plant providers has grown, but it has remained very strictly dependent on the cooperation of the users.

In these sectors codification of technological knowledge did not impact upon knowledge entry barriers related to process know-how and on the whole knowledge barriers to entry are increasingly important.

In contrast, in more traditional sectors (“supplier dominated”) process innovation is mainly the task solely of plant suppliers. Users may innovate with regard to products, but new products may be realised with existing plants. Conversely, new plants are mainly aimed at cutting production costs and at the most may involve quality improvements or marginal product innovations. Cooperation with the users is naturally meaningful also in these sectors, but plant providers are able to introduce autonomously new types of plants. Since in these sectors plant suppliers may become the holders of the codified process know-how that in the past was embodied in the skills of the craftsmen (employed by the users), I suggest that they are now in the position to enable new entries in the user sector.

In conclusion, I hypothesise a polarisation among sectors. On the one hand in the traditional sectors (or in the segments of them where even style innovation is not a crucial competitive variable) entry should have become easier than in the past due to the disappearance of master craftsmen, parallel to the process of codification of knowledge and automation, and to the role acquired by plant makers as providers both of equipment and of know-how. On the other hand, the acceleration and increasing importance of product innovation, in addition to the cumulative deepening of the knowledge base, should have meant an increase of the HCT and corresponding knowledge barriers in other more complex sectors, where the role of plant suppliers is also more limited, since plant users substantially contribute to define process know-how.

1.6. Codification, computer-based technologies and outsourcing

Codification of technological knowledge affects transaction costs in various ways. Firstly, the habit of codifying helps customers to define more precisely their requirements. It may even occur that they provide to suppliers, in addition to the detailed specifications of the demanded products, also the codified procedures to be used in their production process. Secondly, numerically controlled equipment allow producers of components to obtain products with tolerances within microns, thus practically perfect for most applications, with no requirement of particularly expert and able craftsmen. Whereas in the past the expert worker using traditional machine tools could with great expertise be precise the hundredth of a millimetre, currently levels of precision which were reserved to particular products (such as mechanical watches) have become current. Thus codification of know-how and the use of computer-based technologies have notably lowered transaction costs due to the disputes for lack of conformity of the supplied products to customer's prescriptions. Thirdly, in sectors such as the mechanics industry, a new conception of components as autonomous products, not specific to a particular use, and the availability of flexible computer-based technologies, suited to supply a whole family of similar components, have contributed to reduce the specificity of resources, thereby decreasing transaction costs.

The question then arises whether the decrease of transaction costs brought about by codification of technological knowledge and computer-based automation might have been the driver of the process of externalisation of the supply of components and services which has been occurring over the last years, especially in the sectors of mechanical engineering, vehicles and other assembled goods. This empirical issue raises a more general problem, namely whether any relaxation of transaction concerns might constitute an inducement to action (as the cost minimisation imperative would dictate) in the same way as their intensification. If, as I suspect, transaction/coordination concerns urge firms to act only when they are perceived by decision-makers as a problem[12], externalisation could be induced by internal coordination difficulties, but not by a perceived release of the costs of using the price system[13]. According to this argument, the decrease of transaction costs having taken place could thus represent only an enabling condition for pursuing a strategy driven by other forces.

The alternative explanation stresses the importance of production costs and the advantages of the social division of labour to carry out increasingly complex activities. As argued by Teece (1998, p.76), the boundaries of the firm may be explained “not only with reference to transactions cost considerations, but also with reference to technological and knowledge concerns.” Moreover, decisions regarding vertical integration involve “questions of what assets *to build* inside the firm versus accessing externally”.

I thus suggest a story quite different from the transaction cost one, a story of *coevolution of knowledge bases, technologies, cost structures and social division of labour*[14].

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12 On the importance of managerial perceptions on transaction costs see Buckley and Chapman (1997).

13 This obviously means that firms are not transaction costs minimisers.

14 A pioneering contribution in this direction was offered by Rullani, 1992, where he asserts (p.181) that “a transformation has taken place that tends to face the problem of the excess of complexity and the excess of cost/risk of knowledge… by the extension and intensification of the division of cognitive labour”. A further elaboration of this idea is found in Arora, Gambardella and Rullani, 1997, and Gambardella and Rullani, 1999, where the advantages of the division of cognitive labour, which derive from the decomposition of knowledge in general and local knowledge, are discussed.

The idea is that a growing complexity and codification of knowledge bases and technologies, an ever increasing proportion of fixed costs with respect to variable ones (determining an increasing return bias) drive toward the conception of each stage of the *filière* as a business on its own and the emergence of specialists, who can concentrate on the mission of developing a specific competence and of investing in the required complex and costly specific technologies. As Pavitt puts it (1998, p.444), firms "try to compensate for greater technological complexity by greater focus".

The competitive advantage of specialists compared to integrated firms comprising many stages of their *filière* is perceived both by the existing integrated firms and by would-be specialists. A deverticalisation move by an integrated producer amounts to a specialization move (a reduction in "vertical diversification") in the selected area where resources will be concentrated in order to build a solid competitive advantage and sustain horizontal expansion. The advantages resulting from the purchase of components by specialists compared to their internal manufacturing are lower costs (due to their higher specific competence and the opportunity they have to capture increasing returns by aggregating the orders of many clients) and higher flexibility. Thus integrated firms may become the active supporters of spin-offs and start-ups of specialised suppliers.

Thus the hypothesis guiding this research is that the crucial factor affecting firm boundaries is the dynamics of internal versus external competences related to the evolution of technologies and knowledge bases. The imperative of economising on transaction costs, while unable to account for the evolution of the vertical organization of industries over time, is rather a condition enabling the unfolding of that dynamics.

2. The evolution of steel makers and steel plant suppliers and their contribution to the sectoral knowledge base

In the last thirty years innovative technologies, new methods of managing the production cycle and the automation of every process step have brought about great progress in the production of liquid steel and of hot and cold rolled steel products in terms of productivity, quality and product variety. The new means and methods of production vary in complexity and degree of standardization according to products. The simplest products, such as rebars, are produced in a fully standardized way, following established routines and call for a simple specialized knowledge. By contrast, the production of high grade special steels, or that of sheets used for car bodies is considerably more complex and demands a rather sophisticated proprietary know-how, since the variables interacting in determining performance outcomes are very numerous. Even though currently all technologies and procedures are developed on the basis of the modelling of the physical transformation taking place and thus rely upon a codified knowledge base, the scientific explanations and the understanding of the modelled phenomena are still very often lacking (see Balconi, 1998). However, the codification of technological knowledge represents a radical change with respect to the not very distant past.

In this section we aim to highlight this change and its implications in terms of (i) human competences required both by steel firms and by steel plant makers and (ii) "cognitive" barriers to entry into the steel sector.

2.1. The changes of skill requirements in the production of steel

In order to illustrate the changes which have taken place during the last thirty years in the steel sector due to the progressive codification of technological knowledge formerly embodied in skilled workers, we have focused our attention on an industry segment - the production of special steel from scraps by electric furnace - especially characterised by low volumes, high product variety and a rapid development in the last decade as a consequence of new entries. Since in this industry segment the economies of scale characterizing the integrated *filière* (whereby steel is made by oxygen converters which refine the liquid iron produced by blast furnaces, starting from iron ore and coke) are absent, the effects of a lowering of knowledge entry barriers are more discernible.

With the electric furnace steel is made by smelting scraps and then refining the liquid metal, by decarburising and dephosphorising it and carrying out the other modifications of its chemical content necessary to obtain the various steel grades. Since the chemical content of scrap is not known and is variable, it is not possible to standardize the refining stage; hence the molten metal must be analysed in real time and its content adjusted by adding various elements (oxygen, deslagging agents and ferro-alloys) at the proper temperature in an iterative process that ends when the desired composition of steel is obtained.

As until the end of the 1960s the instruments to measure the temperature of liquid steel (detectors) and to make rapid chemical analysis (electronic spectrometers) were not diffused, measurements were carried out by empirical methods based upon the association between some physical characteristic observable by sight and the value of the variables to be measured. Thus in order to know the temperature of liquid steel, a sample was taken out of the furnace, poured upon an iron plate and the temperature was deduced by observing the forming of the spot, its shape and the way it solidified and attached itself to the plate. The ability to recognize the temperature by sight was clearly tacit and acquired through a long practical experience. Moreover, in order "to analyse" the chemical content, a liquid steel sample was solidified in a mould and than extracted and beaten by a mall upon a V-shaped anvil. Depending on the carbon content, steel either broke or bent. When it broke, the shape of the fractures and of the grains revealed to the eyes of the expert the content of other elements, the ductility and other features of the metal, depending on which it could be decided what (and how much of) elements had to be added in the furnace. It is estimated that 5 years of experience or more were necessary to acquire the indispensable skills, while no formal school education was called for.

Since the 1970s the content of liquid steel has been analysed by electronic spectrometers, much more rapidly (in 3 or 4 minutes versus about 15) and precisely, and the temperature by detectors set inside the furnace. However up to the mid 1980s, when full automation began to be accomplished, the process of production remained largely dependent on the operative knowledge of the "master of the furnace", the figure who had to make decisions on the timing of the various operations, on the way to avoid breaking the electrodes and so on. Know-how was still embodied in this expert, even though some aspects were already partly codified and routinised. For example, the modifications of the chemical content of molten metal were largely based on codified instructions derived from accumulated experience, but personal sensitiveness and judgement still underpinned the furnace master's ability to introduce those minor adaptations which were fundamental in determining the quality of the final result.

Under the direction of the master of the furnace a few operatives worked assigned to the various areas, such as the craneman, the caster, the worker assisting at the refining and so on, while the head of the shift (usually a former master of the furnace) was responsible for the full coordination of the shift. He possessed all the knowledges relative to the realization of the various steel grades, the methods of casting it, the functioning of the plants and the management of the personnel.

Since the end of the 1980s machines - the so-called smelting terminals - have become available that automatize the whole processing cycle. These terminals are managed by a software which requires the user to set up the value of process parameters. In the choice of parameter values the accumulated knowledge of firms is called for. In the firm we visited, specialized in the production of special steels, the parameters had been fixed by observing the work methods of individual operators and drawing a weighted average of the values they set so as to give more weight to the methods employed by the most expert and able ones.

The automation of the production cycle relying upon the translation into software of the best practices of knowledgeable workers had the effect of levelling out performance outcomes (in terms of both quality, productivity and energy consumption), by removing the ability of the various operators from the range of the variables affecting it.

Currently the results of the analysis of steel are transmitted by the computer to the operator standing at the pulpit, together with a proposal of the chemical correction to be carried out (for example, "add so much oxygen" or "the metal can be cast since it is already within the admitted tolerances"). The operator's task consists of judging, drawing upon his knowledge, whether the proposed interventions are really necessary and correct (for example, they may be not, because an input inserted into the computer was wrong, as an instrument had gone out of calibration) and to control that the interventions have produced the expected results (e.g. they may have not, since plants have not functioned properly). Thus automation permits great precision and speed, but in the iterative process leading to the production of the planned steel grade, ratifications and controls from operators mastering the needed metallurgical knowledge are called for repeatedly.

In all, operators, besides being able to interact with computers, must understand the consequences of the deviations from parameters signalled by computers and be ready to carry out the necessary rectifications very quickly (in seconds or fractions of a second). The approach of the operators is different from the past, since it is based on a structured knowledge and on the ability to systematise experiences on the ground of an abstract model of the functioning of the process. Clearly this presupposes a certain level of formal education (involving 5 years at a technical high school), besides basic computer literacy.

However, the required skill does not simply arise from codified knowledge but from experience as well. The new operator requires a specific training on the job, by flanking an expert for a period of time (on average a few months) which varies according to the personal capabilities and to the complexity of the job, in terms of the number and variety of situations that may occur. Overall it is estimated that in one year of practice (but more in the most sophisticated plants) operators are able to acquire the necessary capability to react to unexpected situations.

Regarding the search after adjusting process parameter values over time - with the aim of continuously increasing productivity, lowering energy consumption, obtaining stable performances, improving the quality of steel and widening the range of products supplied to meet user needs - this is no longer an activity based on simple trial and error, but on the study of data and on modelling. Depending on firms and especially on the industry segment shop-floor workers may play a role in working out improvements, together with shift-heads and technicians. In particular, in firms specialized in producing short batches of unstandardized products, they have some discretion in changing parameter values (and hence they may contribute to improving them) with respect to the pre-established ones. The more the automation of production guarantees stable performances, the more the attention of firms is strategically focused on optimizing and improving, in all industry segments where opportunities for improvements are perceived as significant.

The technical experts specifically attending to continuous optimization are increasingly university graduates, with the habit of studying and approaching problems in general terms; they are used to reading specialized technical journals so as to keep themselves informed and to preparing reports to senior managers and they are able to train younger employees. Small firms, lacking the necessary resources to conduct a proper research activity, when have to meet problems they are unable to solve, contract out researches to specialized research companies (such as CSM in Europe) or to universities.

As for maintenance, the culture and practice of preventive maintenance, usually assigned to line operators, have diffused widely. In order to carry out a planned maintenance, all the data regarding the type, the frequency and the seriousness of breakdowns and the ways to face them are collected in databases. To carry out maintenance various specialists are necessary, with competences in electronics, mechanics, electricity, software, while the head of the service must be able to integrate the various approaches.

The degree of externalization of ordinary maintenance services does not simply depend on the availability of external specialized firms on the spot, since some are keener to keep this function internal than others. It appears that the more determined ones are those which perceive the competence of maintenance specialists as strategic, since they do not rely simply on standardized plants and know-how and want to keep secret their proprietary operating methods and the special features of their equipment.

2.2. Competences, drivers and scope of innovation in the steel sector

Among steel producers there is usually considerable diversity in terms of technological competence and efforts made to develop new know-how. The large integrated producers who are specialized in flat products undertake research and create new products mainly to satisfy the needs of the most sophisticated clients (above all the car industry). They thus conduct metallurgical research and carry out disembodied process innovation, since the creation of new products or the improvement in the quality of existing ones does not usually require the use of new plants (but rather some adaptations which may be made with the help of the plant supplier), the use of special operation methods and procedures. This goes with the attempts to lower the costs of production, which is necessary for the survival of all steel producers, included those that manufacture standard products.

Actually lowering costs has been the main goal of technological innovation in this sector and plant innovation carried out by plant suppliers has played a crucial role. For the latter, the collaboration with the more advanced and innovative steel producers has been very important, also as a source of new ideas[15].

Steel companies making standard products do not need to invest in research and development, since they are able to keep up to date their process technology by simply acquiring new machines and adopting the new operation methods transferred by plant suppliers.

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[15] Such cooperation may take many forms. For example, clients allow plant suppliers tied by a long run relation of trust to install new pieces of equipment at their plants, in order to test it and get their consultancy. Conversely, plant suppliers are ready to assist promptly their preferential clients in any case they need (for example, a rapid adaptation of a plant might be required, if the market demands a different product).

Some steel producers are thus supplier dominated, while others are not, or are so to a lesser degree. The supplier dominated producers specializing in low value-added segments, using standardized know-how and technology, require only workers to guide the automated process (capable of dealing with anomalies and variability) and some technicians specialized in maintenance, in addition to a few administrative, purchasing and sales staff. The producers of more sophisticated and innovative products instead need technical personnel able to improve processes and to modify the existing plants, as well as personnel involved in research (in the laboratories and at pilot plants).

For this segment of the industry technological knowledge is not mainly incorporated in the equipment and in the standardized procedures, but is also embodied in the technicians who manage and direct a production flow whose composition changes over time. This implies that knowledge barriers are still meaning full, in spite of the elimination of artisan knowledge in the shop-floors.

What we want to address now is the interaction between plant suppliers and users in the low value added segment, in order to discuss the issue of entry. However, before analyzing that interaction we focus the attention on the specific competences of plant suppliers and on how they in turn have been affected by computer-based technologies.

2.3. The changes of skill requirements of plant suppliers

The design phase

As to plant suppliers, the issue of the change of skills due to the codification of know-how is more complicated.

The core competence characterizing this sector consists of plant design capability, but in general the most qualified actors must be able to undertake research as well.

Designing has changed drastically with the introduction of CAD (computer aided design), which, with the elimination of ink designing and of the drafting device, has led to an extraordinary increase in productivity. Moreover, computer aided design has facilitated the growing standardization of components and machine parts, making it possible to produce data bases of pre-existing constructive solutions that are easy to access. A new way of working has arisen as a result of moving beyond the "handicraft" mentality, with its tendency to always look for personal solutions without considering solutions which have already been tried in the past. Today the usual practice is to search above all in the data bases for pre-existing solutions that apply to the situation in question; new solutions are sought only if absolutely necessary.

The standardization of components and the codification of their technical features by plant makers has influenced the relationship with suppliers of components not produced internally. The design of the machine is no longer constrained by the choice of supplier as in the past, when, according to who the supplier was, a company was forced to accept a different set of components that conditioned the design of the machine. The standardization of components thus makes it possible to avoid being dependent on one supplier, and at the same time widens the market for the suppliers, due to the reduction of switching costs born by clients.

These changes have greatly reduced design costs and allowed the designers to focus on tasks which are truly innovative and on the more sophisticated parts of the project.

Moreover, the last decade has seen the spread of CAE (computer aided engineering) for the structural analysis of objects (machine parts). In fact, the computers available for this are powerful enough to carry out the complex calculations necessary to understand in detail the structural features of an object, through the use of commercial software packages available on the market. This knowledge is necessary to respond to questions such as: "does the shape and the choice of materials enable a certain part to bear the mechanical and thermal stresses it will undergo during the life of the machine?", and thus to optimally choose the materials to use and the proper thickness and size for the design.

On the whole the various design phases can be outlined as follows.

The work starts with a pre-project that meets the functions that the machine must perform, given the needs of the client, the attempt being made to use as much as possible the existing ("the historical") knowledge and deciding where to innovate. A feasibility study is thus done to verify if the technology exists to support the idea. The insight and experience of the designers is crucial during this phase. The next step is an initial design that implies the definition of a shape and the choice of material. The CAD system produces a solid (three-dimensional) model of the object, divides it into several elementary units, imposes the constraints that connect it to the rest of the world and applies to each element the various stresses (force, temperature) the object will encounter and the constraint conditions. An equation is written for each element and the computer is used to solve the complex system of equations from which a field of the mechanical and thermal stresses of the object is obtained (CAE). At this point further analysis is done on the critical parts and the decision is made whether or not to increase the material in some points or diminish it in others. The designers then go back and modify the original project, once again checking the new object. This step is repeated a number of times, depending on the complexity of the object to be constructed. The process ends with the determination of the shape and the ideal material for the object. At this point the various components are put together and a study is made of both the conditions of interference regarding the objects in their various positions and the assembly problems. By means of the subsequent phases of the analysis a kind of virtual prototype of the object is created.

The engineer using CAE must understand how a component works and why it has a certain shape; he must know what the loads will be during the life of the machine, how the machine is secured to the foundations and in which points it is connected to other elements.

He must therefore build a model containing all the useful information, make the model "revolve", interpret its results and understand if more information is needed. The computer serves only to solve the complex system of equations that have been formulated. Of crucial importance here is the high level of tacit knowledge of the engineers, implying the ability to select, integrate, assess and interpret information.

The concept of structural analysis began in the aeronautics industry. Instead the producers of machines used to make an approximate calculation regarding certain critical points and made use of redundancies and oversizing. A much more sophisticated calculation is needed to optimize the model of the machine, reducing it to its lowest terms.

The solid model contains much information useful in the workshop, which can thus serve to guide the numerical control machines through a CAM (computer aided manufacturing) interface. The manufacturing process provides additional information that can lead to changes in the original design in order to obtain a simpler manufacturing process. Integration through a CAD-CAE-CAM (together called CIM, computer integrated manufacturing) iterative process thus serves at the same time to optimize the structure of the machine parts, the assembly conditions and the manufacturing cycle, while the result of the design activity includes both the design of the machines and the manufacturing plan for the machine tools. The number of iterations can be increased on the basis of an assessment of the trade-off between the cost of the design and the cost of production.

Research and development

Research makes use of both computer simulations and experiments on more or less simplified physical models, according to need. For example, the studies on the fluid dynamics of steel in the mould were undertaken by the Italian Danieli group on the basis of experiences with a water model, since water produces effects similar to that of liquid steel. The last phase in developing a new technology generally involves experimenting on pilot plants.

Also very important is the gathering of data on the functioning of existing plants. This is done systematically during the commissioning phase, and subsequently only on the basis of collaboration agreements between the supplier and the client. The automation system memorises the process data (also by means of the system's self-adaptation), and the supplier of the automation has free access to this data. This brings an advantage to plant makers who directly supply the automation systems.

The research results are patented, even if the patents are easily avoided through some minor modification. Technical information spreads very fast through congresses, journals and contacts among researchers. It is no coincidence that technologies which lead to similar results are in many cases realized by almost all plant makers (as in the case of thin slab casting technology), even though the first one to reach the market has a considerable advantage, above all for two reasons. First, they accumulate experience, and thus it is very likely that they will remain ahead of the others; secondly, reputation is extremely important in the equipment market and reputation is achieved by the practical demonstration that a machine works. The firm that has already won over a client is thus more likely to attract the next one, compared to those who have yet to sell a machine. In order to enter the market the followers thus must normally i) offer a machine at a lowered price, even free, in order to demonstrate its good functioning and thus overcome the barrier that derives from the lack of a reputation, or ii) if they are capable of doing so, offer a better model by exploiting the experience of the leader. Or do both things together.

2.4. Internal production and outsourcing by plant suppliers

Not all plant makers construct plants themselves, since some completely outsource both their production and assembly.

The biggest producers have their own workshops where they produce the main parts of the plant, since the components with the lowest value added or the more specialized parts (such as the hydraulic parts and the electronic controls) are purchased from outside. They also produce internally (or commission ad hoc) the specific calculation codes regarding the functioning of the machines, namely, the corporate know-how. Except for the most innovative machines, past codes are reused, which are incrementally improved through ordinary maintenance activity.

The tendency which has already taken hold in the largest firms is to use automatized numerical control machine tools interfaced with CAM. The typical tacit knowledge of the mechanics worker who had to fix the piece to manufacture to the machine, manoeuvre the machine, change the tools and measure the finished piece has thus been passed by for the most part. Today's operative must instead join his knowledge of the workings of the machine to his ability to interact with the computer, which is used to control the deviations regarding the production in progress. While before the know-how was contained in the head and the notebooks that the mechanics workers jealously guarded, jotting down notes not available to others, today it is codified and transferred to the software. This implies an increased sharing of the know-how within the firm, which can be exploited if supported by an adequate organizational structure. The other side of the coin is that, once systematized, know-how can also easily leak out and the problem arises of the maintenance of secrecy.

The reasons of outsourcing are:

1) To achieve a change of the cost structure, by transforming fixed costs into variable ones. This allows to reduce risks and to increase flexibility.

2) To reduce the cost of components compared to internal production. In fact suppliers, selling to a number of clients, find it more profitable to invest in the specific equipment

which allows to minimize production costs. By contrast, their internal realization by user firms would involve a high risk of a low rate of utilization.

3) To concentrate activity in the core business. Given the acceleration in the rate of innovation in all fields and the heightening of competition, it is necessary to choose a narrow field of activity in which to allocate the scarce resources, develop the distinctive competences and on which to rely to obtain the highest profitability. The principle of inter-firm specialization and division of labour is becoming ever more relevant. Accentuating this evolution is the fact that product innovation is increasingly more intense, even for individual components (which thus together determine the evolution of the products they make up), and this requires the development of specific skills.

The growing trend toward codification and the related standardisation of components contributes to reducing transaction costs, as well as the use by parts suppliers of numerical control machines. In fact the extremely low tolerance and perfect repetitiveness they guarantee make disputes regarding the product's non-conformity with the specifications very improbable. However, this reduction of transaction costs, even though clearly recognised, is not considered to be a driver of outsourcing.

2.5. Barriers to entry in the steel industry

Codification of technological knowledge has lowered knowledge barriers to entry into the steel industry. In fact, steel firms are less dependent on key operators with tacit competences developed over many years of work activity and tied to the use of specific technologies, who typically are not mobile or flexible, since they have a low level of formal education and are without a base of structured knowledge. Thus in the last decade a number of industrializing countries could enter the steel industry through the initiative not only of state-owned enterprises but also of private entrepreneurs with previous experience in different businesses.

This occurred because plant makers were able to supply not only the equipment but also the know-how to operate the plants and to organize on-site assistance by highly-skilled personnel. In fact in recent years a global market has developed for highly-skilled people having a base of formal knowledge and experience gained in Western firms. In many cases this involves managers who have retired or have been affected by the drastic reductions in personnel that occurred beginning in the 1980s and who then became consultants. These people are usually flexible and are able to understand the problems raised by the varied technologies, precisely because they possess a base of structured and general knowledge as well as experience. They are also willing to spend long periods abroad, drawn not only by enticing salaries but also the possibility to exploit their skills and to remain active in their field. The new companies in the market which are guided by these “mercenaries” thus have the time to develop the local personnel that will eventually replace them.

This tendency began in the *filière* of the steel production from scraps and in the field of the simplest iron and steel products (such as rebars and other long products) and of the most mature and standardized technologies. Since in these segments minimum efficient size is low, no barrier to entry due to scale economies could counterbalance the fall of knowledge barriers.

Recently the innovative technology of thin slab casting, drastically reducing minimun efficient size also in the field of flat products, removed barriers to entry in this segment as well. Consequently new entrants are emerging here too, relying upon the transfer of technologies and of know-how by plant suppliers (or from established steel producers) and on the assistance of “mercenaries” much further the commissioning phase, during which typically plant suppliers provide on site servicing. An emblematic case is that of the entry in the field of wide strips by the group Ezz Heavy Industry (EHI) of Egypt, to whom the Danieli group of Italy supplied a greenfield minimill plant with an innovative thin slab caster on a turnkey basis. The EHI group is owned by the entrepreneur Amed Ezz, who previously operated in the field of ceramic tiles and at the beginning of the nineties had started the production of steel rebars, with the support of Danieli as well and a few English consultants.

In order to impede that financial barriers could discourage new entries among the users, plant suppliers are widening the scope of their initiative, by promoting project financing plans, often supported by the state of the domestic country.

A problem for new entrants in industrialising countries may be the acquisition of the ability to learn enough and the absorption of the culture which underpins continuous performance improvements. However, they may survive since they enjoy the advantages of low cost inputs (labour, energy) and of a local protected market.

Instead in industrialised countries new entrants can more easily learn fast and develop quickly the required competence, even if they start with rather few expert people (usually technicians or managers coming from a competing firm). The case of the successful entry and competence development of US mini-mills is paradigmatic. The culture and the supply of an educated and skilled labour force in the country where firms are embedded is a fundamental externality upon which their prospective productivity and ability to interact with (capital) input suppliers depends.

Knowledge barriers to entry have remained in the segments where know-how internally developed is required in order to realize the sophisticated steel grades demanded by the market. This know-how is proprietary and untraded. In these cases the recourse to a certain number of “mercenaries” is not a sufficient condition for entry, since wide organizational competences based on complex managerial structures are needed, in addition to the capability to interact with sophisticated clients, to innovate and adapt to their unstandardized demands. A significant human capital threshold, among other barriers, hinders entry.

3. The semiconductors case

3.1. Searching for new devices

The main problem for semiconductor producers is coming up with new types of devices which are reliable and getting new products on the market in a short period of time.

In order to produce a new elementary device (which will be more miniaturised than those previously produced, or have a better performance) it is necessary to develop new processes, which involves innovating in both the individual steps in the productive process as well as the integration of the various steps. On the basis of the elementary devices made feasible, the design engineers are able to create new products, keeping in mind the useful functions the new products can offer to the market[16].

In order to innovate at the level of the individual steps of the manufacturing cycle, new generation plants are needed, which are offered by the plant suppliers (who develop these new plants in conjunction with their users) with the basic know-how (use specifications) for their utilisation. Over time the user must improve these basic specifications, in order to increase the electrical yield, as well as develop and gradually adjust new specifications, in order to broaden the range of products. The learning curve for a product essentially refers to the improvement in the electrical yield.

Since new products are introduced at a rapid pace, problem-solving activity along the production line is not only continuous but also very intense. In those plants involved in more advanced production this is aided by the presence of researchers who specialize in various tasks and who interact among themselves, with the researchers in the labs, with the clients, and with the suppliers of equipment.

Even maintenance and the continuous control activities regarding the functioning of the plants are very intense, and are carried out by means of various types of test.

Over the last twenty years manufacturing activity has undergone some basic changes, which were necessary to permit an increasing level of miniaturization and precision. In short, while in the past the task of producing was entrusted to the hands, eyes and head of the workers, who undertook operations such as lining up the wafer to the mask, or recognising by sight when the etching phase was ended, today these activities are entirely automatized and the role of the workers has become that of controlling the functioning of the plants and

[16] Elementary devices (such as transistors) must be distinguished from the products which are sold, which can be defined as systems formed of various types of elementary devices. More precisely, sets of elementary devices constitute the base blocks; various base blocks constitute subsystems; and various subsystems give rise to new products.

the success of the various operative steps, as well as of dealing with general maintenance, along with their traditional task of moving pieces among the various plants. Their main responsibility has become that of interpreting the computer's messages (based on which microdecisions are made regarding whether or not production should continue or which corrective measures to take). In general, in order to interpret the data and graphs workers are needed with a formal education, in addition to being experienced, since they have to understand what the mechanisms are that lie behind the data. The high-school graduate manages these tasks more easily. Interpretive ability (for example, concerning an etching graph) is tacit (i.e. personal) but complementary to a codified knowledge basis and is not so widespread.

Overall a large quantity of human activities have been eliminated which, in order to be undertaken, needed a purely tacit knowledge and ability. Nevertheless, the human role remains very important in interpreting data, understanding unrecurring problems, building hypothesis, correlating variables in fuzzy contexts, rapidly judging how to act and taking effective decisions in incompletely structured settings. All these capabilities are personal (embodied in people), draw upon experience and are complementary to a highly codified knowledge context.

3.2. The evolution of the role of workers over the last thirty years

Three decades ago, in the 1970s, silicon wafers were two inches in diameter size, six or seven maskings were done and production of semiconductors was almost entirely manual. The few machines available were operated by workers seated in front of a microscope.

The personnel, who in general were highly involved in an intense job that required great care, were aided by the so called in-line technician, who undertook particular operations. He dealt with the important set-ups of the equipment, its cleaning, preventive maintenance and coming up with solutions (adding the missing elements). For each shift there was someone who performed these tasks.

In those departments where the physical effort was greater there were only men. On the other hand, women were predominant in those departments, such as photolithography and diffusion, requiring much manual precision (consider, for example, the manual positioning of the masks).

Control was achieved by workers at microscopes; as a result these workers had to have a high level of concentration in order to recognize defects, making use of their mental data bases ammassed through experience ("recognition know-how"). Today such control activities are carried out through automation due to the increased complexity from the reduction in the geometric size and the greater number of maskings. Women also possessed the "know-how of care and assessment by sight" during the process. Consider the example of doping. In the tube of the oven chamber smoke rings are formed from the gas, and from the distance between these rings they could determine if the temperature was correct and if there was a uniformity of doping for all the slices. Or they had the ability to understand when it was the right moment to put the wafers in the oven and how long they were to remain there. They also had to recognize by sight the moment of the etching "end-point" with great precision, since taking out the wafers from the solution too early would lead to residues, while taking them out too late would produce corrosion. With the introduction of measuring instruments and new production technologies all these skills have become obsolete.

Quality control (QC) was undertaken by workers who specialized in this activity. After the manufacturing stage there was a QC woman in-line who checked the work done by the workers.

This job has not existed for ten years now, and each worker has become responsible for the quality of his or her own work. This has meant training and giving responsibility to workers in a way that differs from the past.

The head of the shift is a figure of particular interest for the period in question. He had white-collar qualifications and usually had a technical education. He represented a point of reference for the team and managed, gave orders to and trained the personnel. In a rotating fashion he subjected the personnel to a continuous training, explaining what a transistor consisted of, what an electron was, or why a certain operation was undertaken (for example, why a certain type of dopant was added). Even bringing the specifications up-to-date (which was not, however, very frequent, since the technology was still rather static) was the task of the shift-head.

In the three and four-inch phases there was a semi-automatic structure, and the division remained between the tasks of the technicians and those of the workers. Even today there are still people specialized in the carrying out of particular operations which are rarely undertaken (and thus that could be forgotten and undertaken with low efficiency); but there is no longer the clear-cut division between workers and technicians.

We must nevertheless point out that the division of labour in the semiconductor field has never been as marked as in other sectors of production. For example, the female workers have always rotated among different stations, so that in case someone is absent the others (male or female) would be able to do the former's tasks. Moreover the operations have always had a limited amount of fragmentation and required some mental effort [17].

An important change began during the five-inch period (1985), with the disappearance of in-line technicians and the introduction of the protechs (production technicians). Then consideration was given to introducing college graduates in in-line positions.

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[17] The subdivision among the various areas limited the possibility of rotation. For example, the worker could not move from the exposition area, since in that phase it was necessary to optimize his time in order not to decrease productivity; this, however, did not occur in the other stations.

The protechs are trained workers, usually with high-school diplomas and clerical qualifications who, in addition to undertaking part of the tasks which the in-line technicians did in the past, also have the responsibility of managing the equipment and processes. They must therefore possess both the ability to interpret data as well as manual skills. At the same time the addition of solutions, as well as the cleaning of the equipment and some small maintenance tasks began to be entrusted to in-line workers.

Note that in the past women and in-line technicians had a low educational level, limited to elementary and junior high school, while beginning in the five-inch period those hired were at least high-school graduates.

In addition there began to be a preference for male workers, in relation to the appearance of new responsibilities and the changes in the equipment, which had become increasingly complex and automated. At the same time the information system also changed, keeping pace with new technological developments.

Within each department a unit specialized in training was formed which plans, together with the area head, the operations each worker must perform and provides them with the specific training needed to make them self-sufficient. The custom whereby the older workers helped to train the younger ones has moreover been formalized, and those who undertake this are known as tutors. The shift-head has instead become specialized in managing the personnel and responsible for production results.

Beginning with the introduction of the six-inch wafer changes have been more marked and rapid. In the 1990s the equipment needing manual operation has gradually been eliminated: for example, the wet benches for etching the oxide have gradually been replaced by dry hoods (which permits a repetition of the process which is 100 times superior), washers have taken the place of chemical bathes etc.

Another interesting aspect concerns maintenance, which requires a much greater effort that in the past. For example, while the manual wet benches required a small amount of maintenance, the dry hoods, which are much more complex, require more careful maintenance: they must be opened, cleaned regularly and frequently checked, since their mechanical parts wear out easily.

3.3. Present-day tasks of the workers

In short, let us examine the actual tasks carried out by the workers.

First af all, they have become both equipment and process controllers. In fact, an important part of the work consists in doing tests on the equipment in order to verify that the machines are able to work with the required amount of precision. For example, if the refractive index must have a certain value based on the specifications, the worker must measure the refraction index.

The computer indicates which tests are necessary before the machine is used[18]. In particular, the workers must analyse the control chart and, if this indicates a problem, a check-list appears on the computer that tells the worker to undertake an entire series of checks and interventions, at the end of which help must be called if the problem is not solved. A certain amount of experience is needed to be able to handle all the information supplied by the machines. All the machines have a self-diagnostic service, and thus continually send warning rather than error messages. It is not easy to interpret the diagnostic signals, on which depends the decision whether or not to proceed or interrupt production. For example, before filling the oven, if the control chart shows a bad functioning (values outside the guideline parameters) the workers must decide if the difference is significant and whether or not they should seek the help of a technician and use another oven, or if the values are within the limits of normal variability.

The problem is that if the workers stopped the machines each time the computer gave a warning signal, the number of stoppages would often be excessive, and this would lead to a uselessly low productivity level. Thus of great importance is the ability of the workers to interpret the information and judge its significance, in addition to their experimental abilities in a broad sense. To a large extent this ability is based on experience.

The worker has discretion in determining the significance of the deviations. We must point out that the most modern measuring machines are for the most part interfaced with the software and thus require less judgement ability, as they themselves decide on the basis of codified rules. Nevertheless rigidity still represents the greatest limit to automated controls. Only the human mind (for now) has the capacity to understand when the results of an apparently correct analysis are not reliable, and to suspect the existence of measuring errors, which may be due to various reasons, such as the malfunctioning of the measuring instrument itself or the carrying out of an incorrect operation, such as using a dirty wafer or introducing erroneous data into the computer (if the machine is not interfaced with the CAM system).

The workers must move the baskets filled with wafers to the machines, insert the code (the “name”) of the batch being produced so that the machine, interfaced with the CAM, can choose the recipe to use, begin the operation, and thus undertake that part of the process the workers are responsible for. They must also carry out simple cleaning and preventive maintenance tasks, as we have mentioned above; that is, the tasks called for by the operational certification. The work is repetitive and there is recourse to a manual.

Increasingly the tendency is for the worker to solve the simplest technical problems. The most expert workers (with higher qualifications) carry out more complicated operations:

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[18] Some tests can be carried out while the machine is in operation, while more critical ones cannot, and their execution is time consuming (various tests can even last a week). In order to do a test, a virgin wafer is first inserted and worked in the machine to be tested and than it is placed in the measuring instrument.

particular cleanings and maintenance interventions on equipment which requires a certain specialized knowledge. The protechs, in particular, make an initial diagnosis of the breakdowns and an initial repair of the machines (thus they have a “diagnostic know-how”).

The training of the protechs lasts two years. Through the courses the production technician becomes aware of his work: he understands what he does and why he does it, what the consequence is of undertaking one action as opposed to another, how to interpret graphs and data in general concerning the production process. By contrast the simple worker does not understand the reasons why he operates in a certain way.

The workers mentioned above represent the “direct personnel”; that is, they are directly involved in the production activity of the various departments. There is then the so-called “indirect personnel”, which includes the supervising personnel (the area head, the shift-head, the person in charge of production or the factory), the maintenance workers, the engineers, and the personnel involved in general services (such as facilities monitoring etc.).

With the acceleration in recent years in the pace of the introduction of new products the group of engineers have acquired increasing importance; these engineers are for the most part technicians with degrees in physics. This group has the task of introducing new products and processes and is responsible for in-line technological support, especially regarding the improvement of the electrical yield, productivity, production cycle times, the efficiency of the facilities and the utilized resources; it also deals with the improvement in quality, determining the most suitable controls, on both the machines and the wafers, in order to recognize and prevent any deviation in the pre-established standards, as well as the improvement in the economic indicators (for example, the cost and revenue per wafer), optimizing the use of both the equipment and the silicon, and, finally, environmental problems.

The following table shows the distribution of the workforce in two modern semiconductor factories. The second one is specialized in producing new products and has the role, to a certain extent, of pilot plant. One sees that the activity of problem solving carried out by engineers involves 23% of the total workforce, whereas in the first one, whose mission is mass production and high productivity, the share is “only” of 13%. In both plants maintenance specialists amount to about 10% of the total number of employees.

Tab.1 - Distribution of the workforce by functions (1999)

	Indirect personnel	Direct personnel	Total	
Factory specialization: Flash and epron memories, chips.		Number of workers		%
Quantity processed: 5.500 slices/week				
General services*	25	15	40	7%
Engineers'assistance	70	9	79	13%
Manufacturing	18	400	418	70%
Maintenance	51	5	56	9%
Total	164	429	593	100%
Indirect and direct personnel (%)	28%	72%	100%	
Factory specialization: Flash memories.				
Quantity processed: 2.700 slices/week		Number of workers		
General services*	31	8	39	11%
Engineers' assistance	75	5	80	23%
Manufacturing	35	159	194	56%
Maintenance	32	2	34	10%
Total	173	174	347	100%
Indirect and direct personnel (%)	50%	50%	100%	

*General management, training and quality, production planning and control, information technology.

Source: company data.

In particular, together with the suppliers of the machines the process engineers (i.e. the engineers connected to the process who deal with the individual technological areas in the factory, such as the masking and exposition areas) must determine the type of preventive maintenance to undertake, the daily and weekly tests of the machines in order to keep the process under control and to avoid deviations from the targets (in terms of both electrical yield as well as mechanical performance), and reduce the workers' margin of discretion.

The process engineers also control the process and correct errors. Through the statistical control of the process they read trend data. If the analysis of the data indicates a problem involving a machine, the machine is stopped and particular tests are carried out. Moreover, they critically analyse the old products in order to understand where the problems arise from and define and implement actions to eliminate these, coming up with procedures for small corrections in the various processes. Finally, the process engineer is responsible for the transfer of technology from one plant to another and for the preparation of complete documents concerning the technologies employed.

There is also the "support personnel", among whom is the equipment engineer, who oversees the equipment in terms of its installation and purchase, deals with the development of new projects and relations with plant suppliers, the maintenance contracts with outside companies, the upgrading of the hardware and software and coordinating activities with the general services. He keeps the assets inventory, the final data for past down-time, and determines which pieces can be recovered and re-utilised for the maintenance of the other machines. The obsolete machine becomes in fact a sort of warehouse of replacement parts.

3.4. The learning curve

The learning curve in the field of semiconductors is connected to the electrical yield[19].

Given the importance of a rapid time to market - since reaching the market soon leads to a big advantage in terms of price and market share - the production of a new device is started as soon as an acceptable yield is obtained, with the aim of improving it over time. Thus while production takes place the task is carried out of increasing the electrical yield and solving the various problems entailed by a new product whose production process has not yet been tested. The production line is thus a laboratory where many researchers work alongside of the true production personnel and the new devices represent the experimental field.

The process engineers assigned to the new machines, together with the device engineers (DE, the technicians whose task is to follow the functioning of the various devices, such as the BCD1, BCD2 ones, etc.) are the main actors underpinning the learning curve. Their particular task is to carry out the fine tuning of the process by modifying the specifications[20] of the new machines, along with that of proposing improvements in the design of the device so as to obtain a greater electrical yield.

The plant suppliers offer a product, the plant, along with know-how that is perfectible. In fact, the equipment that is sold is a new product for which feedback from its use does not yet exist, especially regarding the electrical yield of the output[21]. The problem is that these improvements require time for various reasons. Above all the cycle time is usually long, from one month to more than two months, according to the semiconductor factories (named fabs). The more highly developed and complex are the products, the longer the cycle time is.

[19] We must remember that during the production process there is also a loss of mechanical output, that is, a loss of wafers due to operational errors. The mechanical output (wafer fab yield, WFY) is the yield calculated by counting the wafers; that is, the ratio between the number of wafers that enter the production cycle and the number that exit from it. In fact, since the workers handle the baskets containing the wafers, individual wafers may be broken. In other cases a worker might make a mistake in setting the recipe (for example, instead of setting recipe n. 1 he sets recipe n. 10, because he is confused). Or the breaking of the wafer can depend on a machine that is not working well or is not well adjusted. Errors of this kind can always occur and do not depend on the accumulated volume of production.

[20] The process specifications include codified work instructions (that is, a software protocol that orders the machine to undertake certain operations), a description of the process, a description of the equipment, and a description of the physical parameters of the product (for example, all the characteristics the machine produces by making a film and what the machine guarantees in the way of performance of a certain layer). The product specifications for the client are something else: basically they describe the functionality of the product.

[21] The feedback from the machines in use is at the basis of various improvements. Sometimes these changes are passed on to the client who already has the machine, since this is specified in the contract; in other cases the improvements must be paid for.

Moreover, determining which step has caused the low yield requires time[22]. At first it is not at all clear which is the critical step. Then a suspicion arises; in a particular batch a certain number of wafers are separated out from a certain step in order to check if there is a difference in yield from introducing some change; finally, an evaluation can be made when the cycle time has ended.

The plant maker's code of ethics prescribes that he not pass on information obtained by collaborating with a certain user to the competitors of the latter. The plant maker also has confidential information on the products and processes that the user will patent. It must be noted that in general new chips are designed before an adequate supply of machinery allows them to be actually produced.

Another aspect to consider is that the plant supplier sells the machine, whose performance he guarantees, together with the recipe for producing a limited number of things. But over its lifetime the machine must carry out many more functions. To do all these other things the recipes are produced by the user by means of a variation (estimated at around 10%) in the procedural indications supplied by the plant maker. These changes are also the responsibility of the process engineer and represent part of the learning process.

It should be remembered that the laboratories where the final controls on the individual devices are carried out (with the T84 and EWS - Electrical Wafer Sort - tests) interact with the production departments. In fact, with the T 84 the DE checks how the wafers have been constructed. Here there is already a feedback to the process engineers, in order to guarantee that the devices conform to the production specifications given by the designer.

The EWS serves to check how the devices function and those devices that do not function properly are "inked" and eliminated. In the case of a low electrical yield (thus when many devices are eliminated) the DE must understand what the causes are, together with the product engineer (whose job it is to follow the product from its design to its sale to the customer, with whom they interact) and the design engineer (who designs the product).

We can say that the main work instruments of the DE are both the EWS laboratory and the production line, where they have tests done on batches of the product with regard to critical steps, instituting changes in the product and process specifications; and if the changes work they propose them to the design engineers (the device designers) and the process engineers. For example, if the functioning of the chip is not good due to a technical problem

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[22] For example in a fab of ST Microelectoronics the production process lasts around 65 days. The wafers go through some 200 steps, which are subdivided into micro-operations called tasks. The technological step can be defined as a certain physical result, to which corresponds a certain recipe; that is, a software protocol that commands the machine to undertake certain operations. In general at least two machines are needed for each step; that is, there are at least 500 machines. Note that two different products can be differentiated with respect to each other in only 15 out of 200 steps. In Fab 3, where less innovative production takes place, 200 different types of wafers are produced in a day, with an overall production of 25,000 wafers. Each day 75,000 operations (steps) are carried out on average, and on average three steps a day are applied to each slice. Each device requires 100 operations, which are thus carried out in about 33 days. The first oxidation lasts 12 hours, but other operations are shorter, lasting a few seconds.

involving the resistivity of the layers, since subsequent analyses show that perhaps too little oxygen has been introduced, they propose how much of this element should be added.

In conclusion, there has been a complete integration between learning - understood as problem solving linked to continuous innovation - and production, which has heightened the role of the human presence in the production process, even though the latter is fully automated. The man-embodied (personal, tacit) competences relying upon experience and a codified knowledge base have won the day, while purely tacit knowledge has become marginal, even if it has not been totally eliminated.

For example, there is still the visual final control of the slices (and this has become more complicated), and the understanding of the process level which has caused a scratch is still based on a tacit understanding in a strong sense. In fact, the assistance of the machines is limited to signalling a defect[23] with reference to a geometry without defects. The experience of the worker thus comes into play in the identification of the type of defect, and not the formal preparation: in fact for this task the older workers are consulted, whose mental data base of circuitry images is larger, as educational levels are not important. At present the attempt is being made to even make the recognition of defects less subjective, by creating a data base of photographs to refer to, by means of a system of data collection in real time from the microscope used in the manufacturing process[24] . Nevertheless the ability to determine the source of the defects owing to errors will continue to fall to people, even if they are assisted in this: a tacit ability based purely on experience, since the amount of the variables in play is so high that it appears to exclude the possibility (and the economic advantage) of a complete codification.

3.5. Complexity and barriers to entry

The conclusion emerging from the picture of the changes which have transformed semiconductor manufacturing is that knowledge barriers to entry are currently probably higher than they were in the past. Problem solving has in fact become much more intense, almost frantic, due to the increased complexity of the manufactured devices and the more rapid pace of innovation. Technological knowledge has been completely codified, but its dynamism involves the need of continuous learning and improving. Thus people embodied

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[23] Defectiveness has fallen thanks to automation, and thus the importance of the ability to understand defects has fallen from the quantitative point of view, while it has risen from the qualitative one. If certain levels of defectiveness were accepted twenty years ago, today the customers are much more demanding. A scratch or a dirt mark on a device has much more of an effect today, since the geometry has shifted from 30-40 microns to 1.2 microns (the 0.35 micron level is being approached). The clothing of the workers has been regulated in a very strict way precisely to avoid the possibility of dirtying the environment.

[24] As soon as someone spots a defect he can send the information to a central system that stores it, reprocesses the data, and sends the information to the workers in case of need.

capabilities are of the utmost importance, while old tacit knowledges are almost totally obsolete, as well as the technologies complementary to them.

If in addition one considered the true research activity undertaken in the labs, this conclusion would be even reinforced.

4. The chemical sector: the case of rubber*

4. 1. The production of rubber materials

A distinctive feature of production processes in the chemical sector is that they are essentially *continuous flow* processes, with operative phases and sequences closely interconnected and automated. Moreover, since both production cycles and quality standards are highly defined and codified, the chemical sector appears representative of the pattern of technological change that is spreading in many other sectors. Indeed computer-based automation makes it possible to converge towards a model of almost unmanned factories with few operators as controllers of continuous processes[25].

In this section the attention will be focused on the production of synthetic rubber materials, the range and number of uses of which extend to tires of all kinds, footwear, tubes, packaging, technological and sporting articles. Also, the growing competitiveness of the markets and sophistication in customer needs have driven the continuous search for new formulations and innovative, environment-friendly grades. Since the production cycle is similar for all the synthetic elastomers, contrary to what occurs with other chemical or petrochemical products, it is possible to produce with the same plant a wide range of products, that derive from different formulation of the same material, and to realise economies of scope. Different quantities and qualities of rubber are then produced adapting the continuous production flow to a batch logic.

In particular, we shall consider the production process of a synthetic rubber known as SBR (Styrene-Butadiene Rubber)[26]. This is realized by the polymerization of the two

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25 Other typical features of most basic chemical production processes are i) large production volumes of a low number of standardized product types (typical of commodities aimed at mass markets or subject to many applications, such as intermediate products); ii) highly specialized equipment (high capital intensity and high fixed costs); iii) long and detailed plant lay-outs. In such a production context, staff activities (scheduling, capacity planning, quality control, security etc.) play a particularly important role and indirect workers are a higher proportion of the total workforce than in most other industries.

26 Synthetic rubbers are named according to international convention, and differ mainly in their organoleptic features. These names basically refer to the raw material used to produce them. Regarding SBR we can distinguish between E-SBR (Emulsion Polymerized Styrene-Butadiene Rubber) and S-SBR (Solution Polymerized Styrene-Butadiene Rubber), on the basis of the polymerization process by which they are obtained.

principal monomers, butadiene, which derives from a particular process of distillation and grinding of petroleum, and styrene, which is obtained from benzene, a by-product of coal.

The bales of rubber the client will use in the manufacturing process must satisfy specific qualitative standards, which are becoming increasingly stricter. In addition to the ability to widen the product range, in part through research and development, and to realise low production costs, firm competitiveness is thus based on the quality standards obtained. The search for higher levels of productive efficiency and quality improvements have led, in the 1970s and beyond, to large investments in the automation of the production process.

4.2. Automation and evolution of the role of the operative personnel

The traditional skills predating the introduction of computer-based technology

To understand the impact of automation on the role and competencies of plant operators, it is useful to briefly examine the evolution in the production process for rubber.

At the end of the 1950s, when in Europe the first rubber producing plants were established, the operations to start up and control the running of the plants were undertaken mostly manually, by unskilled operators specialized in individual tasks and activities.

An analysis of the organization chart and of job descriptions of a large European producer for this period clearly shows a rather limited automation level, given the large number of operations still done manually, and an organizational structure characterised by many tiers, with a high division of work and specialization of functions. In fact, there was a clear separation between manual activities and control activities, and in both cases responsibilities were subdivided according to each individual operation.

As the organisation chart in fig. 1 (at the end of this section) shows, in the lowest hierarchical levels in the elastomer producing departments there were various employees carrying out a strictly manual activity, such as, among others, the preparation of the ingredients, the actions necessary to initiate, control, regulate and interrupt the reactions produced in the plant, the preparation of the mixtures, the taking of samples for analysis. These activities were carried out based on directives from the operatives' superiors and according to the indications and information supplied by the operators in the control room.

Control room operators in turn were responsible for controlling the various phases of the production process through the use of instrumentation; for this they followed the conditions of particular parameters provided on special panels in the control room, such as the temperature and pressure of the copolymerization, the calibration of the ingredients, the functioning of the reactors, the level of latex in the various tanks, and so on. By appropriately regulating remote-control devices in this room they could, as much as possible, maintain the pre-established operating conditions of the plant and provide the outside personnel with the indications they needed to carry out possible manual maneuvers. In order to deal with anomalies, they were very often forced to personally intervene on the equipment by carrying out the necessary measures to maintain the process under control (see below).

The upper levels in the hierarchy were filled by the team leader, the shift head, the department head, and the plant head. For example, the team leader was responsible for coordinating and controlling the production activities of the manual workers; he was responsible to the shift head for the operations carried out in the plant to assure the rubber produced met the specifications. The shift leader was the person in charge of the production activities during the shift: he had to see that the established production programs were met and ensure the proper security measures were taken, and for this he answered to the division head.

The higher up you went in the hierarchy there was an increase in the tasks and responsibilities of a managerial, as opposed to an operational, nature. The department head had production planning and control functions and supervised the production processes and the work of the department employees, while the plant head, in his role as supervisor, had the function of ensuring the production programs were carried out and overseeing the functioning of the machinery and its maintenance and preservation according to the budgets of the production department. Together with this function was that of ensuring the adoption of the necessary security measures for the personnel and the machinery, which was fundamental to the management of any chemical plant.

The main feature of this production context was the strict guidelines according to which each activity had to be carried out, and thus the possibility to establish - and formalize in special operations manuals - rules, norms and procedures for every operation. In this situation each worker knew, or could know, the activity he had to carry out in every possible situation. This was particularly true for managing situations involving the normal running of the machinery or routine interventions.

Formalized procedures for carrying out the operations and a clear division of responsibilities did not, however, guarantee the complete control of the plant in all circumstances. Whenever the control panels showed a divergence of the parameters from the desired values, corrective measures were necessary. As already mentioned, it was not always possible to operate effectively by means of remote-control devices, and often it was not even easy to identify the real causes of the problems. In this case, the workers acted directly through trial and error interventions aimed at identifying the most suitable corrective measures to definitively remove the causes of the problems. To achieve this result it was not enough to make use of the explicit knowledge of the procedures in the operations manuals; the variables that could have led to the problem were so numerous that unknown situations could occur whose codification would cost more than the benefits it would bring.

Thus in these cases it was much more useful to rely on the experience of people, their familiarity with production, and their ability to quickly recognize the different types of problems in order to identify and immediately remove the causes. Thus the accumulated knowledge regarding the functioning of the production process was incorporated in expert personnel, whose role was crucial. Over time, in fact, the workers were able to assimilate information and knowledge about the nature of the process, to memorize the placement of the plant's various component parts, to recognize the correspondence between these and the signals on the control panels, and so on. For the firm this experience accumulated over time was necessary to guarantee the efficient carrying out of the production processes and an optimal management of the plant.

Skills in the context of automatized production

Computer-based automation entered into the production of SBR rubber between the end of the 1970s and the beginning of the 1980s. This was of crucial importance, since it led to a considerable reduction in manual operations and an improvement in the effectiveness of the command and control activities of production plants.[27]

This automation system, which is part of DCS technology (distributed control system), is based on control units within a communications network that directly manage the process. Connected to operating-stations, these units allow the operators to govern the process, guiding it through the use of keyboard commands and keeping it under control by observing the parameters on the terminal videos.

Following the introduction of this new system there was no longer the need to undertake manual interventions to prepare the ingredients, start the reaction, open or close the valves, measure the temperature and pressure of the reactions, and so on. Each time a parameter moved away from the established values the operators could undertake corrective actions, by pushing the start command for the sequence of operations the terminal itself had to undertake. In this case the operator is able to verify in real time the effectiveness of his intervention and, subsequently, to monitor its effects on the process. It is rarely necessary to directly intervene manually on the machine or to take time to search by trial and error for the solution to the problem, as was the case in the past. Basically the operator's role is to control an automatized process.

An analysis of the job description and organization chart in the 1990s for the same SBR plant described above clearly show this transition (see fig. 2 below). Many of the figures in the old organizational structure have disappeared, since their functions have been automatized and the operators have become polyvalent. This together with the higher educational levels today have moreover permitted a reduction in the number of hierarchical levels. In particular there is no longer the figure of the team leader.

It is important to note that even in the new context the tacit knowledge from experience

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[27] In this case electronic automation took place in a production context that by nature was already automatized, where by "automation" we mean any substitution process, by means of the automatism, of human intervention with regard to the service, command and control of a machine or process. Thus what occurred is the movement from the use of inferior automatisms (mechanic or pneumatic) to that of superior automatisms (based in fact on electronics).

and the ability to correlate variables and solve problems are still indispensable for guaranteeing the efficient working of the production cycle. In his role of supervisor the operator has not lost but increased the use of his intelligence and ability to synthesize. These capabilities are indispensable for solving problems and managing troubles by quickly determining the cause and taking the appropriate actions. Indeed it is still not convenient today to completely codify all the possible and non-recurring cases of anomalies.

We must note in this regard that in the production of SBR rubber many variables influence the production process. Rubber is a product defined as "*variable*", since its specifications cannot always be precisely established. By nature the raw materials used, which are derived from refining processes, are not always available with the same properties and characteristics. Each time they thus require various treatments and interventions in order to obtain the desired conversion percentage of the monomers.

What is more, if it has been possible to successfully codify knowledge regarding the way to carry out the production process, this has not been the case for knowledge concerning the plant and, in particular, the location of its component parts.

An example here is emblematic: the applied software for the control of the productive system makes available a stylized video model of the plant based on the use of specific symbols which, no matter how detailed, cannot reproduce the physical arrangement of its component parts. When there are malfunctions and anomalies and there is a need to manually operate the machine, it is fundamental that the operator knows the exact placement of the plant part to be checked; the same can also be indispensable when there are replacements or maintenance to be made on the equipment. The physical distancing of the machine caused by the new control system, in which the operator spends most of his time in front of terminals in the operating station, causes problems in such emergency cases.

It is nevertheless important to point out that recourse to the knowledge incorporated in the operators can be partially reduced as more new-generation technologies appear that are able to guarantee greater stability and reliability. For example, in the production of other types of rubber such as polybutadiene CIS, a more complete codification of knowledge and level of automation have considerably reduced the need for emergency interventions by the operators. Nevertheless, the experts maintain that the abilities of careful operators, with proven experience and the ability to suggest solutions and advice for the better use of the existing machinery, will always be a resource of the highest value to the firm, since the anomalies and non-recurring problems will never be totally eliminated.

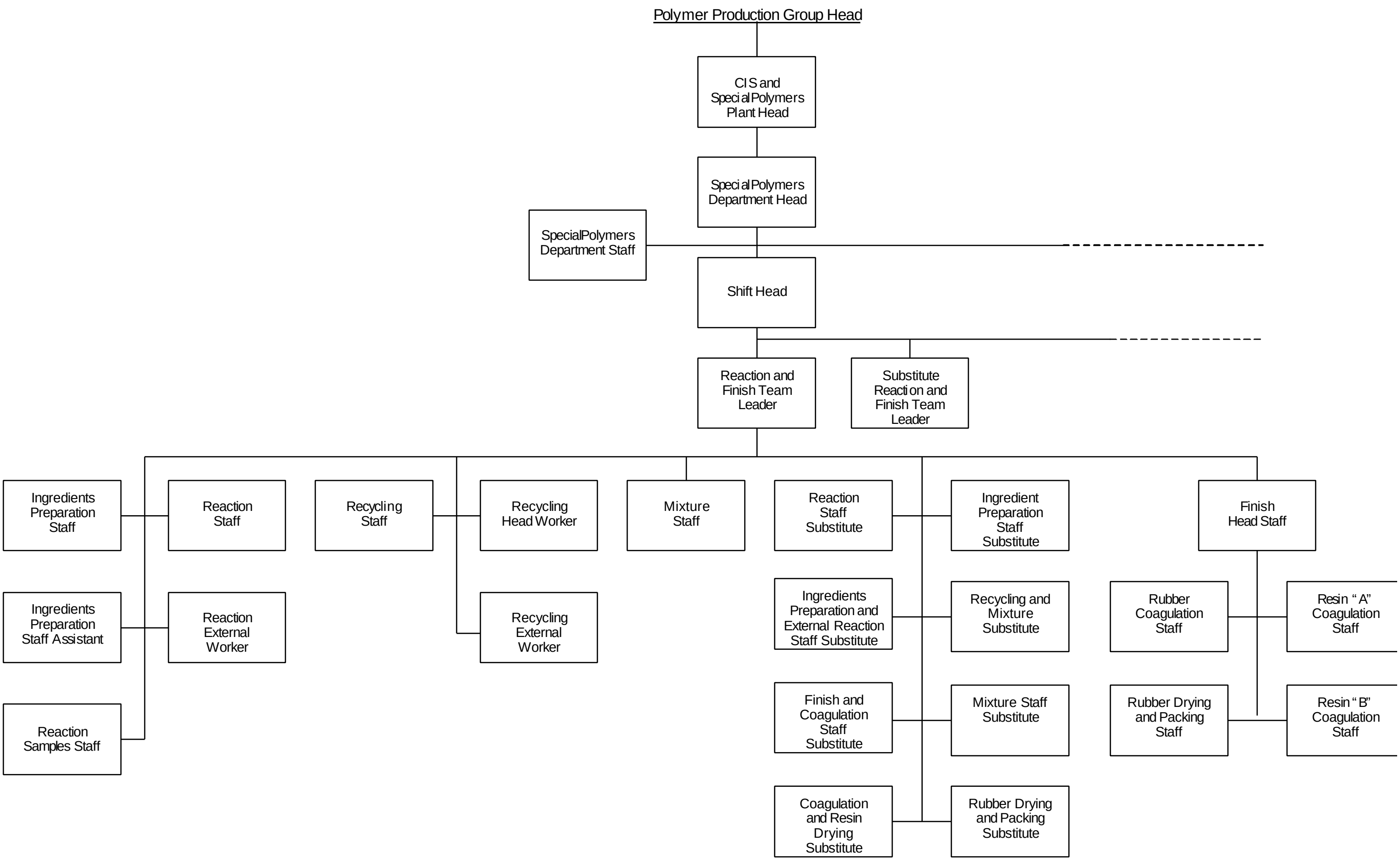

Figure 1 - Part of an organizational chart of a production plant for rubber in the 1960s

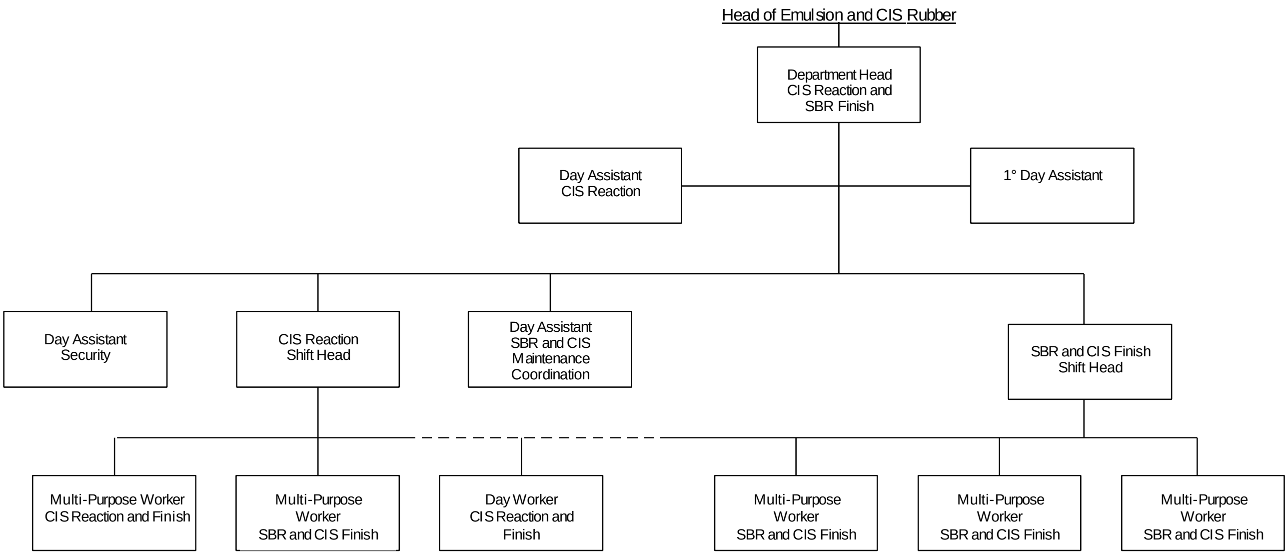

Figure 2 - Part of an organizational chart of a rubber production plant in the 1990s

4.3. The role of plant suppliers and cognitive barriers to entry in the sector

In the case of rubber production, as in general in the chemical industry, the users do not appear to have a subordinate role with respect to the equipment suppliers.

In this sector the equipment, mainly made up of vessels, reactors, connecting pipes, and valves to control the flow of the product from one stage to another, have a long utilization cycle and function even for decades if partial replacements are made. In any case, they are supplied to meet the specifications of the user. In fact, the function of a chemical plant is to permit the large-scale production of a certain material, allowing reactions to take place according to specific parameters (pressure, temperature, conversion percentage, etc.). The process know-how usually belongs to the chemical firm and is protected by specific patents. The supplier's role is thus to design specific machines (in terms of the length and thickness of the tubes, etc.) and a lay-out that permits this process to be carried out.

Moreover, in the particular case of rubber production it is the users themselves who adapt the equipment to produce the various formulations of the material by using internal technical competencies.

A particular class of suppliers involves automation processes and system software programmers. Here too, however, the user plays a fundamental role. He collaborates with the supplier's project team to design a system that meets all the desired performance and operating specifications. In fact, of fundamental importance in the design of adequate control systems are: i) an in-depth knowledge of the process; ii) the in-depth knowledge of the plant; iii) a clear definition of the results desired through automation. These are competencies and information that only the user, working with the engineering firms, can possess.

These considerations and the crucial importance of product know-how (mostly protected through patents) explain why the cognitive barriers in the chemical sector play a central role in influencing competitive dynamics. In the past the leading rubber producing firms, and more generally the chemical firms, maintained their leadership positions largely on the basis of highly integrated structures that offered a considerable competitive advantage, such as the provision of feedstock.[28] At present, on the other hand, competition seems to depend more on other aspects, above all the amount of investment to favour the generation and spread of knowledge within the producing firms.

The present case clearly shows how the internal generation of knowledge, through both experience and research and development, represents one of the start-up factors which is most difficult to imitate; it thus represents not only an obstacle to the entry of new firms and a competitive advantage, but also a conspicuous part of the firm's value.

The firms in the chemical sector, traditionally protected by capital-intensity, count

[28] This is especially true for oil companies that, by directly producing monomers (such as butadiene), have been able to integrate themselves downstream.

heavily today on the cognitive barriers represented by the possession of patents and the knowledge incorporated in people. In the synthetic rubber industry the potential new-comers can only succeed with the help of existing firms who are willing to transfer knowledge by selling patents and licenses, or by entering into joint-ventures and alliances.[29] Also, plant makers and engineering firms cannot transfer know-how independently due to secrecy agreements with established rubber producers.

In conclusion, the continuous innovations in the search for new materials, the ability to respond to the rapid evolution in the demands of users, and the need to make the most efficient use of the machinery by gradually reducing costs, have led to a higher value being placed on the human resources within the firm, and this tendency will continue into the future. Clearly the most important group in the latter regard are those in charge of research and development, and together with these the production workers who daily gather useful knowledge for the continuous improvement necessary to preserve a competitive advantage.

5. The mechanics industry: the impact of computer-based technology upon flexibly specialised firms and mass producers

So far our investigation of the process of knowledge codification and of the impact of computer-based automation has been restricted to activities taking place inside rather big or medium-sized firms in sectors where Taylorist organisation principles, even if applied, never predominated and skilled workers continued to play a notable role in manufacturing. In this section the discussion of the mechanics industry, which includes a large variety of firms in terms of organisation forms and size, will offer the opportunity to widen the scope of our inquiry in three directions. Firstly, we can take into account small firms, which have usually remained immune to Taylorism, or, more generally, the category of flexibly specialised firms, characterised by the reliance on skilled workers, high organisational flexibility and product variety. Secondly, we have the possibility to consider the evolution of typical mass producers fully applying Taylorist organisation methods, characterised by standardised production, a high subdivision of labour and a large population of unskilled workers. Finally, we shall also shed light on the emergence of hybrid forms, which substantiate the deepening of the social division of labour and competences which has been taking place.

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[29] Joint ventures and alliances are essentially pursued by established firms in order to obtain the guarantee by the new-comers of a supply of feedstock at low cost (as is the case with the Middle Eastern firms that supply oil), or to gain new markets, otherwise unexplored, for products which in the West are already mature (as occurs with firms in developing countries in the Far East that can count on the support of a local government interested in national economic development).

5.1. Flexible specialization and hybrid forms in the mechanical sector

Firms of any size may be included within the category of flexible specialisation, even though the most typical examples are small craft producers. According to Zeitlin (1998, p.1) flexible specialization is a model of productive efficiency "based on the manufacture of a wide and changing array of customized products using flexible, general-purpose machinery and skilled adaptable workers". Were also flexibly specialized firms affected by the emergent paradigm of computer-based automation, incorporating codified know-how and leading operators to perform the role of controllers, it would follow that flexible specialization should be transformed into a model of production activity whereby *a wide and changing array of customized products are supplied using flexible, general-purpose computer-automated machinery attended to by process controllers,* by firms on the shop floor of which "skilled adaptable workers" (of the craft type) are no longer required and the definition of the production cycle is shifted in the production engineering department.

The aim of this section is precisely to find out whether this type of flexibly specialized *and* computer-based (instead of craft-based) firms has actually emerged.

In order to do this I decided to interview a few randomly chosen firms and not to stop to collect interviewees and to visit factories until two constraints were met: firstly, that all the types of flexible general-purpose technologies currently available (namely CNC machine tools, work centres and FMS) were represented. Secondly, that both small and medium-sized firms as well as both district embedded and independent firms were included. I concentrated my attention especially on the Cusio-Valsesia district, specialised in the production of valves and water taps and recently in rapid growth. Moreover, since the main manufacturing stages, whatever product is delivered, are the machining of metal parts (such as bars and cast or stamped pieces) and the assembling of the finished product, other phases being more product specific, such as particular surface treatments and others, I mainly focused on these two production stages.

When I started my visits, I was soon confronted with an unexpected finding, namely the widespread adoption of special-purpose machinery, such as CNC transfers with rotating table, even by very small district embedded firms, which had specialised in machining large batches of a very restricted array of products by aggregating the orders of a number of clients. Clearly, if *the use of general-purpose machinery* (attended by skilled workers) is a defining character of flexible-specialisation, I had run into a hybrid form, the existence of which could have been explained on the basis of the process of deverticalization, which has been taking place in the last decades. In fact, the reliance of firms selling final products on suppliers of components and on performers of particular manufacturing phases able to develop specific competences and to invest in the most modern specific technologies, since by aggregating orders they are in the condition to fully employ them, implies the existence of small supplier firms delivering a restricted range of products produced in large batches.

Indeed, the *post-Fordist regime of variety plus vertical disintegration* implies the emergence of a network of hyper-specialised "small mass producers", serving the needs of many clients committed to deliver product variety to the final market. But the ability to deliver variety is not only a property of single firms, since variety at a wider scale is obtained at the level of a whole networked production system, in which a vast number of hyper-specialised (in terms both of production phase and of specific product) suppliers play an important role.

Moreover, even flexibly specialized suppliers delivering a wide array of final products to their customers often obtain differentiation at the assembling stage, whereas at the machining level they may manufacture larger batches. Thus, if the production of medium/large batches is important even in the regime of variety plus vertical disintegration, and if the batch length is a crucial variable in determining both the choice of technology and the benefits of codification, to assess the impact of computer-based technology upon "the world of flexible specialization", it is correct to collect a sample of firms including those producing not only short batches or single products, but also medium/large batches, in spite of being small sized and non-Fordist.

We cannot ignore the hybrids. The penetration of computer-based technology and its consequences in terms of skills and tasks must be assessed with reference to all the most important firm typologies.

5.2. The firms analyzed (flexibly specialized and hybrids)

Our investigation was conducted through in-depth interviews and visits of the plants of 13 firms, 9 of which undertaking both machining and assembling, one only a machining phase and one only design and assembling, one brass foundry and one specialized in polishing semifinished metal parts. Since the last two do not conduct typical mechanical activities, we shall not consider them in this paper. With one exception, all firms interviewed design their products in-house, currently by means of CAD. Since we have already discussed the importance of CAD in design activity, we shall not deal with the issue in this section, even though all the firms investigated emphasised it.

Some of the firms are of considerable size (relative to the sector average or to firms belonging to the same district) with a position of international leadership in their branch of activity, whereas others are small size district firms (i.e. embedded in a dense network of relationships with other firms acting in the same area and in the same sector). The sample includes three segments of the mechanical sector: machinery (the biggest European loom supplier, a leading supplier of special machinery for making rubber etc., one leader of the packaging machinery for the food industry, one small supplier of shoe machinery and one, small as well, of machinery for mixing cereals etc.), valves and water taps. All firms interviewed making valves and water taps, except one, belong to the north-Italian Cusio-

Valsesia district, whereas some of the machinery suppliers considered belong to other districts. In the following table we list the firms interviewed, subdividing them according to sector, size, length of batches and to whether they are district members or not.

Table 5.1. – List of flexibly specialised and hybrid firms interviewed

Sectors	Machinery	Valves	Water taps
List	Ali, Cav, Mat, Pom, Rad	Bran, Gro, Vr	Ass, Mach, Om
Size (N. employees)			
< 15	Ali		Ass, Mach
15-99	Mat	Bran	
99-200	Cav	Vr	Om
> 200	Pom, Rad	Gro	
Length of batches			
Single piece	Mat, Ali, Pom	Gro	
Short, medium batches	Rad, Cav	Bran, Ass	
Large batches		Vr	Mach, Om
Within a district	Ali, Mat, Rad	Bran, Vr	Ass, Mach, Om
Outside a district	Cav, Pom	Gro	

It is important to note that the ranking according to size is not correlated to the one according to batch length.

5.3. The traditional tasks carried out by the mechanical operator

All types of numerically controlled machines involve some fundamental differences with respect to the traditional manual machine tools, namely that i) they are no longer manually guided by the operator and ii) the electronic control not only permits a high precision level but also to perfectly reproduce a given shape in any number of pieces[30]. There is thus no longer need of manual dexterity and specific knowledge based on experience, on how to obtain the required technological performance, since the quality of the product is

[30] Note also that numerical control as such only regulates the synchronised movement of the axis of the machine in order to make the tool realise the trajectories necessary to create the desired shape. This simplifies work, but all other parameters (the speed of advancing of the axes, the speed of the rotation of the tool, etc.) must be established first and then translated into software. Moreover, if a machine tool is integrated with CAD/CAM, the geometrical parameters are set automatically.

guaranteed by the electronic control. However, the extent of automation and its impact on the knowledge requirements and role of the operators depend on the type of equipment used.

The following list enumerates the typical tasks of a mechanical operator using a simple CNC machine tool in an artisanal workshop. All these tasks may be automated, depending on the extent of automation chosen, except *the conception of what needs to be done in order to obtain a certain result*, namely task 2 in the list, which is inherently a human problem solving activity, involving tacit knowledge, in addition to a technical education.

The tasks are: 1) reading the drawing of the piece to be machined (obviously, understanding of technical drawing is required); 2) establishing the operating parameters of the machines and the tools they need and programming the machine[31]; 3) setting the piece in the machine (this may be an easy and repetitive task if the product is simple, but a difficult task involving judgement and manual ability if different and complex pieces are machined); 4) setting the tools (the difficulty depends on the complexity of the machine used); 5) setting the parameters of work; 6) taking measures and/or visually inspecting the piece machined, in order to control it (it may involve carrying out a codified simple procedure, that however entails some knowledge and understanding, or it may consist of a visual inspection based on tacit knowledge); 7) unloading the worked pieces.

With the exception of small artisanal firms, mechanical workshops usually comprise a number of machines, in order to perform more than one operation (micro-phases in the machining cycle). Thus the definition of the cycle involves the planning of the various operations required to realize the product, in addition to establishing how to use a single machine. The higher production variety and the more rapid the pace of introduction of new products are, the more important is the role of tacit conceptual competences, that tend to be located in the production engineering department, in addition to the design department.

Finally it must be observed that the typical craft worker was able to carry out the maintenance operations required to keep his machines functioning. The disappearance of craft mechanical workers from the line of production implies that firms currently need specialised maintenance workers, namely expert problem solvers that take care of all the equipment installed, as happens in the other sectors already analysed. Moreover, since modern equipment like robots, work centres and others are increasingly complex and incorporate many electronic devices, the assistance of plant suppliers is becoming more and more important, especially for small firms. Specialized maintenance may also be completely externalized.

[31] Software programs have become very simple, and therefore the knowledge required to make them is no more a significant factor. In fact standard software development programs are currently available (such as Visual basic and other languages) which are easy to implement, whereas in the past each type of machine had a proprietary software which required a specialised knowledge.

5.4. The modern technological landscape and the roles of the operators

In the following pages I shall attempt to highlight the extent to which all the tasks listed above, except task 2, are eliminated through automation, with the disappearance of the traditional skilled mechanical worker and his substitution by automated machines and human controllers. This is possible since the knowledge required to perform the above tasks is inherently codifiable (and largely codified), even if the traditional mechanical worker based his know-how principally on experience.

The evolution of the role played by the operators will be related to the type of equipment they use, since the degree of automation is the key determinant of the tasks men must carry out. In the following table the various types of equipment currently available to carry out machining operations are listed: the choice of firms among the various typologies of equipment is based mainly on the batch length they have to realize and on the number of operations they must perform.

Table 5.2 – The equipment available to carry out machining operations

Length of batches/degree of variety	*Type of equipment*		
	Single machining operation	*A few machining operations*	*Many machining operations*
Single pieces/ very high variety	CNC machine tool	Various CNC machine tools	Various CNC machine tools
Short-medium batches/ high-medium variety	Partly automated CNC machine tool	Work centre (stand- alone)	FMS
Long batches/ low variety	Fully automated CNC machine tool	CNC transfer (with rotating table)	CNC transfer (line system)

While the types of equipment listed in the first two rows in the table above are general-purpose and very flexible production means, that fit the definition of flexible specialisation, those listed in the last row are special-purpose and highly productive ones. The latter are typically adopted both by hybrids, such as small mass producers, and by full-fledged traditional mass producers.

5.5. General-purpose technologies and skills

As synthesised in the table above, various types of general-purpose technologies are suited to produce short batches (see Warnecke and Steinhilper, 1987), ranging from single products to few dozens.

Normal CNC machine tools involving no automation are still used by the typical artisan firms described by the literature, where the workers plan the cycle and program the machines on their own, to realise single products or very short batches (examples in our group of firms are Ali and Mat). They are also used in the tool-workshops of firms of any size, by craft workers who perform both conception and execution tasks. On the whole it takes years to become an expert craft worker and the complete mechanical expertise (comprising all the tasks in the list and even the design of the product) is becoming rare in the labour market. These craft workers are problem solvers able to carry out most maintenance operations themselves.

Even medium-size or big structured firms (such as Pom and Gro), where the planning of the work cycle is established in the production engineering department, use normal CNC machine tools to manufacture complex pieces different from one another. The machinist, in spite of using a machine already programmed, still has to perform engaging tasks which entail discretionary choices and tacit knowledge. In fact, he has to correct the program, based on his experience; to find the way to set the piece from analysing the drawing; to decide when substituting worn tools, in addition to positioning the tool in the initial point, inserting the work parameters and taking measures.

Those illustrated above are the cases which require a higher level of tacit knowledge and experience. The opposite extreme is that of fully automated machine tools (but they are used only to machine large batches), which may function unattended, being automatically loaded and unloaded. Most cases stand in between, as the one of Brand illustrated below shows.

Work centres are general-purpose machines which can carry out manifold machining operations (such as milling, drilling, threading and others) by means of a wide array of tools which are automatically picked up from an incorporated tools store. When product variety is limited, it may be profitable to interface them with robots that set the workpieces and unload them. Programming of work centres is more complex than in the case of more traditional machine tools (especially if they are interfaced with robots) and tends to be performed by technicians in the production engineering department (usually with the assistance of the equipment supplier if robots are adopted).

At Brand (a firm producing valves with 40 employees, using 2 CNC lathes and two work centres), a mechanical engineer in the production engineering department establishes the cycle required to realize every new product, which is usually produced in batches of about 500 exemplars. He studies the data, decides the sequence of the operations, the various corrections of tools and inserts, the cutting data (such as speeds, advancements, removals of metal etc.), the kind of tools to use, the systems to set the workpieces and the scheduling of the various batches. The trajectories followed by the tools of the lathes are instead set automatically by CAM. The engineer's knowledge was acquired at university: it concerns how to make and read drawings, structural calculus, the assessment of forces, the functioning of the different typologies of equipment. Practical experience was however required, which was attained by flanking an expert employee.

The data are then transmitted to the machine tools programmer, a person who also bears the function of setting-up the tools (task 4) and works partly in the office and partly in the workshop. He defines the program of the machine tool on the basis of the data received, but he still needs to complete the instructions concerning the specific machine data (movements of the ribbon etc). His competence on the mechanics of the machine and on the specific manufacturing process derives from work experience (in the past he was a lathe operator), while in order to learn the programming language of CNC he had attended a course.

Problems are met and improvements are realized based on decisions taken together by the tooler-programmer, the head of the workshop, the employee responsible for quality and the planning engineer, who make up a team of problem solvers.

The lathe operators are left with the tasks of setting the pieces (which is easy and repetitive) and unloading the machine, carrying out the required measures for the dimensional statistical control and giving their "ok" if the needed tolerances are attained, making visual control of quality, interacting with computer to collect production data and executing ordinary maintenance. The computer calculates the wear of tools and establishes the required corrections and the frequency of tool changes. Information is mostly codified, with the exception of visual control. On the whole the operators must be able to read the drawings, need some manual ability to use the instruments of measure and must understand the meaning of the measures taken. They still have a very limited discretion (they can stop production if they judge it to be necessary because of quality problems) and must exert some easy judgement, but in case of problems they must call for help. They are technical schools graduates and in a few months of flanking learn the necessary specific know-how. They may be considered semiskilled workers, no longer traditional mechanics and not yet controllers since they still have to conduct a few physical interventions.

What is interesting to note is that in the second shift the allocation of tasks is different, since the tooler-programmer is absent. The operators of this shift have then to absorb some of the responsibilities and problem solving activities of the latter, like setting-up the tools, taking some decisions about small interventions on the machines and corrections of software. A higher level of autonomy is thus conceded to the workers, who have to increase their skill level in order to do without assistance.

As to workcentres, one of the two is charged by robots and the other, which serves for shorter batches, manually. The robotized line operates 24 hours per day. During two shifts it is attended by an operator, whereas in the third it works *completely unattended*. The workpieces are loaded by the operator on a load drawer and set on the machine by the robot. Another robots unloads the worked pieces and sets them on pallets. The high precision of the machines means that measures need not be taken frequently. The operator also sets the tools (a purely executive task) and governs rather complex equipment, which he must know in order to operate correctly and to be able to control emergencies. The diagnosis of drawbacks appears in the computer display and the machinist must verify if the various contingencies correspond to what is suggested and calls for the help of the head of the workshop if something exceeding his responsibilities takes place. This function, as well as his cooperation with the tooler-programmer aimed at carrying out software adjustments, entails some discretion. Clearly, a technical school graduate is needed to perform this function of skilled tooler-controller.

In all, considering all the cases examined, we found out that the allocation of tasks (tooling, controlling the machine, loading, controlling the pieces) and the division of labour largely depend on firm size and on the need to fully employ the existing human resources, but they are also based on the particular firm culture.

Flexible manufacturing systems (FMS) are the most complex kind of general-purpose technologies, and are adopted only by rather big firms, since they are very costly. They consists of a number of flexible cells and final test devices linked by an automated materials transfer system, all under the control of a central computer. In turn a flexible cell consists of a work centre or a CNC machine tool connected to a tools store, some robots which handle the pieces and change the tools, as well as automatic control and supervision systems. Since pieces following different routes may be machined simultaneously and the various cells may work either in sequence or in parallel, a multi-product and multi-phases manufacturing process may be carried out.

A system of this kind of the latest generation has been just introduced by the loom maker named Rad, belonging to the biggest European group producing looms, to produce the most complex loom parts in short batches of about 15 pieces. These parts, which make up the mechanical core of the looms, require an absolute level of precision, and this system is able to provide it. The macro-programming of the whole cycle is assigned to a specialized programmer (who works in the production engineering department) and memorized in the system, whereas the geometrical details are self-programmed by means of a self-learning system, based upon an electronic sounder that collects the data to implement by scanning a prototype of the workpiece.

This type of equipment, completely automated, leads to the clear emergence also in the mechanics industry of the role of controller of the system (the "system supervisor", as put by B.Jones and P.Scott, 1987) and to the disappearance of the traditional craft worker in the shop-floor, since all his tasks (except programming the cycle) have been assumed by automated machinery. The computer display indicates the emergence of drawbacks, such as a drift, and the task of the controller, who is a skilled worker with a broad knowledge of the system, is to understand the reason for it, or, if the problem is too complicated and requires sophisticated intervention, to call specialist problem solvers for help.

At this level of automation the machining cycle has become fully continuous and the role of people is practically the same as in the steel or chemical industry (or in the semiconductor one, even if at a lower level of complexity).

5.6. The hybrids in a networked environment: the emergence of small mass producers

The highest productivity levels are realised when production is organised in large batches and carried out by dedicated machinery. Electronic control has improved the trade-off between productivity and flexibility, by increasing the flexibility of dedicated equipment.

In the economic literature the use of dedicated machinery is considered a reserve of large mass producers, seeking low costs as a main goal. As already mentioned, an intriguing element is that in the context of a networked environment small specialised suppliers of components aggregating the orders of various clients may be adopters of dedicated machinery as well. In particular, modern CNC transfers with rotating table (whereby the workpieces are set on a rotating circular stand) are a compact equipment suited to be used also by small firms[32].

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[32] At modern CNC flexible transfers the position, speed and advancing of tools is regulated by computer. All pieces rigidly follow the same route and are machined simultaneously by a number of machining stations, each one performing a particular operation or test, interconnected by a system of moving the workpieces from one station to the next. Typically mass

The equipment suppliers thus cooperate with small firms in order to provide the specific dedicated equipment they need, together with the basic software, leaving to the user the task of adapting the program to the specific products realized. Thus small firms are able both to supply a family of products slightly differentiated with very high productivity levels, and to respond quickly to the clients' needs in terms of rapid delivery and adaptability to their peculiar requests. To satisfy user needs they may make in-house in the tool-workshop the specific tools required to obtain a particular result, or may order such tools from artisanal firms, belonging to the local network.

A typical small mass producer is Mach, *a firm where only* 6 *people work (a young entrepreneur, a secretary, and 4 blue collars),* specialised in threading parts of water taps by a transfer machine and in making small parts by a CNC machine tool. Mach aggregates the orders of a few clients and works batches in the range between 500 and 30.000 pieces, making yearly sales of 5 million Euros. The transfer machine is considered very flexible and was especially studied with the supplier, who also cooperates in its programming. Details and corrections are instead programmed in-house by a very skilled mechanical worker (head of the workshop). He also makes tools, using traditional machine tools, and shares with his assistant the responsibility of setting-up and problem solving. Two semiskilled workers are controllers and loaders while the entrepreneur interacts with the clients and suppliers.

On the whole the tasks associated to the use of transfers are: planning the cycle and programming, simple loading and unloading, controlling the machine, problem solving, setting-up. Moreover, if handling operations are also automated by means of robots, no manual activity remains to be conducted during the production process, and workers are left with the task of controlling and setting-up.

5.7. Assembling and other phases

Dealing with flexibly specialised producers, we find that the phase of assembling varies greatly in complexity across products, from simple manual operations to quite complex problem solving activities. In general, it has, so far, scarcely been automated, since the cost of automation outweighs the expected benefits. Moreover, the simple operations automated often still rely on traditional mechanic devices, even though the situation may rapidly evolve.

In the case of complex unique products (such as machinery or special valves) the tacit skill of the expert operator is of the utmost importance: he must be able to assemble pieces never seen before, to detect design flaws which cause defects in the final product (as in the case of too much friction between various components), to understand by intuition whether the product will work properly and to suggest modifications to the designer (as in the case of Gro or Cav). Clearly, only through a long lasting flanking of an expert assembler can such a demanding skill be acquired.

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producers employ linear transfers, that usually include a higher number of machining operations than transfers with rotating table.

Note also that part of the assembling may be made in-house and partly at the user site, where the assemblers are part of the team attending to the start-up of a new plant.

To conclude, it is worth recalling that another operation which is often performed manually by expert workers is the welding of pieces that require special attention (as at Gro or Ali). For example, a large part of the workforce employed in the glass framing industry consists of manual welders. A contrary example is that of metal cutting, since to conduct this activity laser metal cutting machines connected to a CAD/CAM system are increasingly adopted even by very small firms, substituting for many manual operations and calling for employees with a technical education (as again at Ali).

5.8. Fordist mass production: the coevolution of technologies, skills and firm boundaries*

In addition to the firms listed in the table 5.1., we have also examined a traditional Fordist mass producer. The case is that of a leading European producer of compressors for refrigeration and industrial sewing machines. Indicators of the high scale intensity of the production process are the total number of employees in the main plant (still >1.000, but it was > 5.000 in the 1970s), the length of batches produced (hundreds of thousands of pieces) and the total production volume (> 1 million pieces per year).

Both compressors and sewing machines have a significant technological content and their mass production is organized on the basis of a high degree of structuring and codification of knowledge, as regards both product and process. In fact, starting with the design, the succeeding phase in the development of the production process leads to the definition, for each component, group, subgroup, or product, of a manufacturing or assembling routing where, for each individual operation, the following are specified: the method by which the operation must be performed, the machinery or the tooling that must be used, the tools to be applied, the controls to undertake during or at the end of the operation, the time allowed for carrying it out. The production is carried out in accordance with the strict observance of the specifications prescribed by the manufacturing and assembling cycles.

In the 1950s and in the 1960s the typical manufacturing line for the production of large batches consisted of a series of traditional dedicated machines. Those specialised in successive operations were placed in sequence and made up a dedicated flow line. On the other hand, the departments where small and medium batches were realised were specialised according to the type of manufacturing they did (functional lay-out). Each of them had

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flexible machinery technologically homogeneous and suitable for carrying out a single type of manufacturing, such as pressing, turning, milling, grinding, boring, heat treatment, and so on. Whereas in the latter departments there were workers, such as turners or milling-machine operators, who were highly specialised and brought to the production process largely tacit knowledge (manual ability and understanding of technical drawing), in the former ones the skills of the operators varied according to the type of machine used and a higher proportion of unskilled workers engaged in moving and loading pieces was employed. To operate drilling machines or presses, for example, a much lower skill level was required than in the case of lathes. On the whole, the characterisation of mass production in terms "dedicated machined plus unskilled labour" seems an oversimplification.

In general, the tasks of the operators were separated by those of the set-up specialist, who had to prepare the machine with the required tools and implements, and of the quality inspector, who had to check, during or at the end of the manufacturing stage, the conformity of the resulting quality.

The set-up specialist had to be able to understand very well both the problems regarding the operation of the machine as well as the technology itself. Usually the tool setter reached his position after a more or less lengthy experience as an operator, and even if he combined his knowledge with training courses, it was mainly through direct experience on the job that he fully acquired his skill. The task of the quality inspector was instead based on codified knowledge, since he operated by rigidly following the procedures in the quality manual.

As far as the assembly line is concerned, for the assembly of products built of many components the operations assigned to each worker lasted few minutes, while for products composed of few components and with high volumes of production the length of each phase fell to tens of seconds. In the latter case unskilled workers, trained in a very short time, were employed.

There was also a maintenance department equipped with special machines with an extremely high operational precision. The workers of this department provided maintenance for all the machines in the firm (rapidly intervening in cases of breakdowns) as well as constructing, when necessary, machine spare parts not available in the warehouse. It was also possible to construct specific implements and at times even complete machines not available on the market for special manufacturing needs. Moreover, in this department the prototypes of new products were created almost in their entirety, based only on the drawings from the design activities, as the technical staff was able to define on their own a manufacturing and assembling cycle that responded to the functional/technical needs of the project.

Clearly the personnel of the maintenance department needed a strong technical preparation; but at the same time, having to carry out work that required knowledge that was largely tacit (insight, ability to solve problems, manual dexterity), their professional advancement derived above all from the experience acquired.

Starting in the 1970s the increasingly severe international competition forced our firm to redesign its production system and organization. In particular, since production plans had become subject to frequent variations in terms of levels and mix among the various models of the same product, the traditional assembly line started to appear inefficient, due to its rigidity and high setting-up times. It became also clear that the strict division of labour had a negative effect on quality, requiring final controls and interventions for the repair of defective pieces, and that a more responsible work could offer the possibility for timely and effective informational feedback. There was a growing awareness that a new flexible organisational model could enable a reduction in the costs of quality and be suited to meet variations by reducing lead times and work in process.

In a first phase, however, process innovations tended still to increase productivity, only partly and indirectly favouring the reorganisation which was needed.

The most important innovation for the production of large batches of high-precision mechanical components was the introduction of transfer machines, namely high-productivity machines capable of carrying out the entire manufacturing cycle, attended by a single operator, substituting for a series of stand alone dedicated machines each attended by its operator. They arose from the cooperation between the plant supplier and the process analysts of user firms, since they are special machines that require a specific design for each application. Their limit was a low flexibility, since interventions on the hardware were necessary to move from one component to another or even to change the dimensions of the same type of component.

The operator attending a transfer machine began assuming the task of carrying out himself the statistical control of the pieces. He also started the machine, loaded and unloaded, made part of the set-up, which was complex but resorted to only to make minimal changes. This enlargements of tasks was favoured by the diminution of manual operations resulting from automation.

Another very important aspect is that the technological evolution under way profoundly affected the conception of traditionally mechanical products, that evolved toward a combination of mechanics and electronics. In general, mechanical devices for regulation and control purposes were replaced with a reduced number of electronic ones. Sewing machines are a clear example of this change which led to a remarkable simplification of their design.

Moreover, the design of new products moved toward a modular-type concept on the basis of which the product was structured into divisible groups, whose assembly and test started to be carried out separately from the final assembly line. This trend developed together with the effort to identify similar components and to form families of pieces with similar design and manufacturing features (such as shafts, connecting rods, pistons), which could attain the general characteristic of being autonomous products instead of being *firm-specific*. The attempt was also made to change the lay-out in order to obtain new flow lines, by placing the machines needed to realise a certain family of components in a sequence.

The following phase (beginning at end of the 1980s) is characterised by the connection between the automation of information systems and that of the production process. The design activity is transformed by the introduction of CAD and the computer becomes the ideal means also for defining the manufacturing cycle and gives rise to a manufacturing process based on CAD/CAM integration.

In the production departments CNC flexible transfers are introduced for the manufacture of a family of different pieces. This system of production, which is composed of a group of numerical control machines and of equipment for moving the pieces which are entirely managed by process computers, is capable of carrying out in a continuous fashion the whole manufacturing cycle for an entire family of different pieces.

This gives rise to the possibility of changing the lay-out of the factory into a set of flexibly automated flow lines. However, the general transformation of production departments according to the logic of large-batch production, albeit without any of the constraints set by inflexibility, leads to an increase of sunk costs and augments the risks of an insufficient utilisation of dedicated resources. Moreover, a specific competence needs to be developed in various directions.

In this context externalization of the provision of components (transformed into firm unspecific products) appears increasingly beneficial, since it permits to turn fixed costs into variable ones, to distribute the risk of investing specific resources to various actors in the supply chain, and to concentrate activity in the core business. Specialised suppliers thus multiply (they may be, as in the case examined, spin-offs encouraged by the externalising firms themselves), who are able to supply high-quality products at reduced costs, by employing highly productive plants and benefiting from economies of scale, since they sell to many clients.

As far as the tasks of the operator of a CNC flexible linear transfer are concerned, they consist of: i) starting the machine by setting the data and if necessary changing the tools, according to what is prescribed by the manufacturing cycle; ii) loading the pieces on the automatic feeder; iii) controlling the machine by intervening in a timely fashion to eliminate any cause of stoppage or improper functioning; iii) carrying out quality controls on samples of the pieces, to check that the machine continues to operate within the tolerance limits; iv) replacing instruments that wear out before they cause production losses; v) making the established preventive maintenance operations[33]. Controlling the functioning of the system has thus become the most important task of the operator, who must both understand the general principles of its functioning and know its peculiar features from experience.

[33] As to maintenance, an evident trend is that of rapidly substituting broken down pieces and of repairing them only if it is profitable. Modern machines are built so as to make disassembly and substitution of the various parts easy. Owing to this reason, to the practice of preventive maintenance and to the high reliability of machinery, the use of increasingly sophisticated plants does not involve a proportional growth of maintenance expenses. Finally, maintenance services tend to be outsourced to specialised companies.

The assembly area is where the changes in the skills of the operatives are less marked. The more simple and repetitive operations have been automatised and buffers created between one phase and another, thereby reducing the line's rigidity, but the replacement of a large part of manual work with flexible automated lines has been only partially accomplished. In fact the automation of some operations, even those which are not particularly complex if carried out manually, can present considerable technical difficulties, and thus be prevented by cost considerations. Where sections of automated assembly lines are installed the skills of the operatives are entirely similar to those of the operator of the automated machines for the manufacturing of components. We can thus conclude that, due to the spread of automation, the competencies of the personnel in the manufacturing and assembly departments are becoming increasingly more uniform.

We do not have the space here to account for the organizational changes realized *intra moenia* in this phase; suffice it to say that they were all directed to apply the principles of lean production.

5.9. Barriers to entry and the role of equipment suppliers in the mechanics industry

The increasing role of equipment suppliers (associated to knowledge codification and computer-based automation) in facilitating entries has been confirmed both by equipment suppliers and users.

Regarding entry into various plant users' industries, our hypothesis about the "barriers-lowering codification and automation effect" seems to hold even in industries where firms use many different pieces of equipment to carry out the sequence of operations making up the manufacturing process and no single plant supplier controls the whole cycle (as Danieli does in the steel sector). In fact in these cases plant makers may organise themselves in pools in order to be able to supply all the machines needed to build a whole factory. For instance, pools of plant suppliers have been active supporters of new entrants into the industries of packaged biscuits in Latin America or of valves in China.

As far as entry into the industry of equipment suppliers is concerned (or more precisely, into the many separated segments of specialised equipment suppliers) important cognitive barriers are constituted by the design and assembling capabilities, which are partly people embodied. The continuous product innovation also requires human capital in the form multidisciplinary design teams, specialized in mechanics, electronics, computers, and in the production processes of the user industries. Moreover reputation, which is considered the most important barrier to entry, cannot be built by firms lacking high level human resources in those fields. Thus knowledge entry barriers have remained high.

Nevertheless, for specific applications market niches may open up which are at the reach of new firms usually founded by former employees of established equipment producers. Because they possess the above-mentioned set of competencies, these people may be able to create new products that are able to solve particular manufacturing needs.

Another factor to consider is the importance of knowledge barriers concerning organisation know-how, which offers much more resistance to codification than technologies do.

For example in the refrigerator compressor industry, which produces a mature product, it is above all the crucial role of human competencies in the study and definition of the manufacturing cycles and in the organisation and management of the productive resources that makes it practically impossible to enter this sector on the basis of simple outside consulting, even if qualified. Even the transfer of know-how in the form of the supply of turn-key plants by the incumbents may not suffice (as was in the case of the transfer to the former Soviet Union and the Middle East at the beginning of the 1990s). The history of the sector shows that only joint ventures between the new entrant and the technology transferor that induce the latter to directly bring his organizational and managerial skills to the venture are a suitable arrangement for a would be entrant to overcome the "cognitive" entry barrier. Actually this governance mode, which involves a long lasting commitment by the transferor of know-how, can provide those tacit competencies that cannot be transferred through an arm's length contractual relation. Thus, a negotiated entry with an incumbent appears as the proper means to overcome organizational knowledge barriers.

In conclusion, the role of the incumbents in industrialised countries seems to be sustainable only where product knowledge is important, innovation is a continuous process (conditions which hold, for example, in weaving quality textiles, but not in spinning, since the output of this phase is more rough and uniform) and organisation forms not easy to transplant constitute a competitive advantage, such as localised dense networks of specialised producers (a condition which is more important, for instance, in the case of water taps than in the case of valves, since the formers, being made up of more numerous different pieces, derive a higher benefit by a networked supply chain of competent specialists).

5.10. On the variety of manufacturing patterns: craft *and* codified knowledge

What results from our inquiry is a hybrid manufacturing world, where flexibly specialized manufacturers of various kinds and sizes coexist. The “emerging paradigm” is really emerging, in some case as the distinguishing manufacturing pattern, while the “old craft paradigm” is still alive, in most firms within the border of the assembling hall or the prototyping and tools workshop and in some very small firms with a still predominant role[34].

[34] This is the case of firms Ali and Mat in our sample. However even these firms, organisationally very unstructured and flexible, where skilled craft workers are interchangeable in most positions, have started being affected by computer-based automation, both in the offices (where CAD is used) and in the workshop.

Whereas only most modern fully automated FMS or CNC transfers create a manufacturing setting wholly similar to that of a process industry, even the use of much less sophisticated equipment, such as more or less automated CNC machine tools, has strongly impacted upon the work pattern. In general, the bundle of tasks which make up the content of craft work has been divided, and single functions have been assigned to various operators, while others have been absorbed by automated equipment. Tasks tend to be more defined and their execution more predetermined by the production engineering department than they used to be, where the conception of "what needs to be done and how it must be done" has been mainly concentrated, shifted away from the workshop. Increasingly workers must perform the task (*alien to the nature of craft work*) of controlling what the equipment is automatically doing, which is more or less demanding in terms of knowledge and problem solving responsibilities, depending on the kind of equipment controlled and managerial choices. A basis of technical education is generally required, except for those workers that are still engaged in manual operations, such as easy assembling or loading and unloading. Typically, in the average factories of the mechanical engineering industry, which are not fully automated, unskilled workers move objects, machines transform them, skilled workers control both the machines (and/or set them up) and the product quality and specialised problem solvers intervene in case of need. A growing proportion of human work time is spent in introducing novelties, organising their introduction and optimising their process of production. The role of design activity (computer aided) has thus become strategic.

Among the hybrid forms we found the typology (totally unexplored by the literature) of "*small mass producers*" of a particular family of components that use special purpose equipment (such as CNC transfers), serving the needs of a few clients by aggregating their orders. The prime reason why they are post-Fordist is that their workforce is engaged in the post-Fordist task of controlling automated equipment and is not unskilled: the work that used to be parcelled has been taken over by the machines. They are "mass producers" in that they produce large batches of a restricted array of products, even though the volumes of the total output are not high. What is required is a volume of output that permits the full employment of a single piece of modern dedicated equipment. The form of division of labour which is still developing is the social division of labour among actors specialised in terms of specific competences.

This is connected to the reorganisation of industry which permits a high variety of products to be promptly delivered, without giving up high levels of productivity along most of the supply chain. In fact both firms making short batches of customised products (by means of general-purpose equipment) and modern lean mass producers, in order to gain in flexibility and to benefit by the low costs delivered by economies of scale, allot the task of realising a number of components or manufacturing phases to small hyper-specialised suppliers, who can attain high levels of productivity by using specialised equipment that can be fully and profitably employed only by making long production batches of similar products. However, even specialised equipment is to a certain extent flexible.

In the post-Fordist, increasingly vertically disintegrated and networked environment we thus find, with regard to families of similar components, the *re-emergence of the importance of economies of scale* (mostly in the form of economies of scope captured on a restricted array of similar products) *and their dissociation from firm size.* Increasing returns derive from the shift of costs from variable to fixed, connected to the use of increasingly complex equipment and to the codification of technological knowledge.

Brusco (see, for example, Brusco and Sabel, 1989) has already pointed to the fact that economies of scale are realised at the level of single machinery and thus are within the reach of small firms. However according to Brusco (1982) the fragmentation of demand since the middle of the 1960s was the driver of the fragmentation of supply among small firms: in fact the latter were particularly suited to realise small batches of differentiated components by means of flexible machinery, at a time when big firms employed a rigid technology such as fixed transfers to produce large batches of standardised products. This is still true (the flexibility of small producers), but the evidence I collected witnesses a further evolution, which is connected to the new types of equipment available in the 1990s, namely flexible transfers, at a cost affordable by small firms. This leads to the fact that small producers may be more efficient than bigger ones - *in turn driven by market forces to produce shorter batches of final products than in the past* – to produce families of similar components in large batches, since they aggregate various orders. In a certain sense, the respective roles of small *versus* big firms have become reversed.

In general, the distinction (*à* la Piore and Sabel) between mass production and flexible specialisation tends to be increasingly blurred by modern computer-based technologies and post-Fordist organisational models required to deliver product variety.

6. Conclusions

In approaching the issues of organisational changes and work patterns on the shop floor, the economic literature has always concentrated on the assembly line. The shift of focus carried out by this research from the assembly line to the processing stages has produced some interesting results.

First of all, light could be shed on the new paradigmatic role played by men in a manufacturing world reshaped by the widespread adoption of computer-based automation and by the related codification of technological knowledge. Put succinctly, in modern factories people no longer "do" things, but control that things are done correctly by automatic equipment. In controlling, they must exert some judgement and their ability in understanding and assessing anomalous situations is based both on some formal education (computer literacy included) and on the experience acquired on the job. In the terms proposed in this paper, their tacit knowledge is complementary to a codified knowledge base. Even though the role of controlling inherently calls for the intellectual capability of the controller, the discretion controllers enjoy is rather limited, since when some demanding problem solving activity is required the responsibility is usually shifted to problem solvers possessing knowledge of a higher level.

Another result worthy of our attention is that the flattening of the hierarchical ladder and the broadening of the tasks assigned to shop floor workers appear to be to a large extent a "natural" consequence of i) the elimination both of most manual repetitive tasks and of tacit-skills-requiring ones; ii) the increasing reliability of equipment; iii) the higher education levels of the workforce. Since Adam Smith's pins are currently made by an automated manufacturing line, one worker suffices to control the equipment and product quality (which is usually practically perfect), to make some preventive maintenance and set-up. Thus the division of labour amounts to a division of functions among workers with different levels of competence. On the one hand (above the controller in the knowledge ladder) the conception of products and of the manufacturing cycles are assigned to specialised white collars and demanding maintenance operations to highly skilled technicians. On the other hand (below the controller), unskilled labourers have to carry out ancillary services, such as moving objects and cleaning. This simplified framework roughly captures the essence of current organization in manufacturing. Moreover, whereas the tasks of employees situated at different layers in the knowledge ladder clearly differ in terms of responsibility and degree of discretion, on the whole decision making tends to be more widely distributed than in the past. The availability of information (when not purposely impeded) in real time in any department and in any computer terminal allowed by information systems contributed to this evolution[35].

However it must be remembered that, especially in assembling but in many others manufacturing phases in various sectors as well, traditional simple manual operations are still carried out. Obviously, codification of knowledge and automation are not yet profitable in every case, so that different work patterns are bound to coexist for a long time: the emerging paradigm needs time to spread. Where traditional manual work is still carried out the broadening of the tasks assigned to single workers appears to be more directly dictated by an organizational choice than to constitute a "natural" evolution largely determined by the new technological context.

On the whole, skills are less specific than they used to be, since they are grounded on a more general knowledge. This holds in terms both of sector and job specificity. For workers

[35] Note that both the deskilling and the reskilling notions (Braverman 1974, Kern and Schumann 1984) are unsuited to capture the sense of the changes which have been taking place, since they both refer to the craft paradigm (and myth), characterised by the union in the same person of the conception and execution of manufactured goods.

it may be easy to be multiskilled and for firms it may be profitable to rely on a multiskilled workforce. Inter-sector mobility of workers has become less demanding as well, in terms of the time and cost of acquiring new knowledges.

The situation changes at the high levels in the knowledge ladder. It takes time to become an expert problem solver or a new knowledge creator. And it is upon the sectors or segment of sectors where problem solvers and knowledge creators play an important role on which the European industry should base its future competitiveness and specialization.

A final aspect emerging from our survey is that even in Fordist contexts the tacit skills of workers have continued to play an indispensable role. A historical reappraisal of the extent to which the world of mass production (not only in Japan) was shaped by a context-bound economic rationale (the context including technological features and imperatives, the characteristics of the labour force etc.) and by the influence of local traditions, instead of being levelled by dominant organisational paradigms, seems called for, especially with respect to a European context divided for many decades into separated product and labour markets[36].

The process of automation and of codification of technological knowledge implies an increasing weight of fixed costs. Also, in a very uncertain environment, the rapid pace of innovation entails the need of investing resources to keep up with it, while the increasing complexity of knowledge bases demands highly specialized competences. From our investigation it clearly results that externalisation has been pursued by firms primarily in order to respond to these new challenges. In fact, since investments (in knowledge creation, capital equipment etc.) are increasingly demanding and available resources are limited, firms tend to be more selective than in the past and find it more profitable to sink their resources in particular areas then to spread them in many directions; moreover, they look for arrangements injecting flexibility into their cost structure. Outsourcing is thus increasingly preferred to internal production since it permits: i) to modify the cost structure, with the transformation of fixed costs into variable ones; ii) to lower the costs of components, since they can be produced on a larger scale, with best practice specialised equipment, by specialised firms committed to accumulating the required specific knowledge.

We found no evidence that the reduction of transaction costs *per se* was perceived by firms as an incentive to externalise. Rather it worked as an enabling condition for pursuing a strategy driven by the above mentioned motives. Lower transaction costs derive from the codification of manufacturing processes, the standardisation of components, the flexibility acquired by CNC dedicated equipment, the high product quality delivered by computer-based

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36 In addition to the literature on flexible specialization and districts, a very interesting reappraisal of the influence of "local economic and institutional circumstances" on the world of mass production in Europe has been recently undertaken by Zeitlin and Herrigel (2000) with other historians. See also Zeitlin (2000).

automation. In particular, whereas any new component used to be designed totally *ex novo* by each user and was specific to a particular application, computer-based design technologies contributed to reduce their specificity. In fact the rationalisation of the conception of components facilitated by computers leads to the creation of standard families of products *firm-unspecific*, hence producible at a large scale and saleable to many buyers. This rationalisation was accomplished by identifying the main common features characterising the standard design of a family of products, and then designing each different component of the family simply by adding variations to the standard[37].

As far as cognitive barriers to entry are concerned, our survey definitely shows a polarisation between sectors or segments of sectors.

On the one hand, in the sectors (or segment of sectors) where firms need to rapidly and continuously bring to the market new products to compete a substantial human capital endowment is required, in order to carry out a series of complex activities which are strictly connected and unavoidable, such as designing new products, creating new processes, learning by using new technologies, cooperating both with customers and with plant and component suppliers. Building the necessary endowment of problem solvers and new knowledge creators, establishing the structure and the organisational routines to make them effectively interact is difficult and takes time: hence cognitive barriers to entry are high.

On the other hand, in the sectors where innovation, being mainly driven by cost concerns, is embodied in plant and equipment, the release from the dependence on the tacit knowledge of skilled workers, enabled by the codification of know-how and its translation into software, has made human capital requirement very low and entry easy. Plant makers, automation suppliers and teams of consultants have acquired the capability to provide to new entrants the knowledge they need to start up production from scratch. On the whole, machines, codified know-how, the services of a team of maintenance specialists and of management consultants are tradable goods which can be bought by a would-be entrant. Thus low input costs and a local market (that offers a sheltered niche useful for taking time to learn) may induce outsiders to enter.

When process know-how was embedded in the master craftsmen's heads, and a novice needed to spend years flanking an expert to absorb it, entry into traditional sectors not characterised by intensity of unskilled labour was much more difficult. Craftsmen developed locally during many years of experience; they were a scarce and not mobile resource, not available in the market. In contrast, current process controllers with a basic general school

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37 On the effects of software and new computer-based design technologies on the conception of products see also Arora, Gambardella and Rullani, 1997. They emphasise the application of the principle of modularity, which permits technologies to be decomposed into elementary standardised modules which can be subsequently modified by their user. The similarity with the evolution I am examining consists of the separation of the general knowledge content (in our case, the general "shape" of a component) incorporated into an object from the specific adjustment determined by user needs.

education acquire the specific knowledge useful in their work activity through a period of field experience much shorter than was needed to form the old craftsmen. They constitute a much more readily available resource.

Thus the migration of manufacturing activity in the latter sectors from Europe into newly industrialising countries, where factor costs are lower, should develop in the coming years. Equipment suppliers, managerial consultants and technical experts from industrialised areas are fundamental players in this game, providing local firms in industrializing countries with their assistance to overcome the low knowledge barriers to entry. This trend has already affected areas of the steel sector (not including, among others, the segment providing steel to the automotive industry, where product innovation is important and proprietary process know-how as well), of the textile industry (excluding the highest quality segments, where style matters most), of the food industry and various segments of the mechanics industry, among others, which started to delocate out of Europe.

In this respect it must be observed that these sectors or segments are not characterised by a high intensity of unskilled labour (like the assembling of semiconductors, garments or shoes), but by a relative capital intensity and a low human capital threshold; therefore they do not correspond to the activities usually delocated by established firms in order to lower production costs (according to a product cycle pattern or whatever else). Indeed the delocation trend here discussed may develop counter to the interests of established producers and completely beyond their control. This contrasts also with what occurs in other more knowledge intensive sectors, where new entries depend on the cooperation of the incumbents as organisation or product knowledge providers. In these cases would-be entrants usually resort to joint ventures with the incumbents as entry-enabling arrangements.

Thus reduction of employment in Europe in the traditional standardised segments seems inevitable and this calls for increased efforts to develop those parts of the same sectors or of other sectors characterised by a higher content of innovation and problem solving activity conducted by a highly qualified personnel, which is the resource on which European countries should base their competitive strength. Usually these more dynamic sectors also require high level organizational capabilities, an intangible asset difficult to transfer and imitate. With regard to this we also noted that organisational settings involving a competitive edge, instead of resulting from firm capabilities, may be an emergent property of local production systems, the process of emergence being totally spontaneous and unplanned, practically impossible to imitate. Whether a disintegrated and networked organisation form is more effective than more traditional ones depends however on factors which are in general sector (or even product) specific.

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