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# Articulation and codification of collective know-how in the steel industry: evidence from blast furnace control in France

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**Abstract**

In this article, we use the implementation of an expert system to improve blast furnace control in the French steel industry to illustrate the problem of knowledge articulation/codification. Blast furnace related knowledge still largely takes the form of empirical know-how in general and expert know-how tied to specific individuals in particular. Therefore, the articulation/codification of knowledge in this field is a difficult task requiring the identification and selection of 'best practices' for the purpose of codification. This process, in turn, affects daily routines and creates new forms of generic knowledge that make use of local knowledge. These new forms of generic information reinforce the tendency to appropriate private knowledge currently prevailing in Usinor, a large French steel company, and create new routes and new insights for R&D policy.


*Keywords:* Blast furnace; Articulation; Knowledge; Codification; Steel industry

> It's familiar enough that business firms and other organisations 'know-how to do things like computers to fly us from one continent to another. On second thoughts what does this mean? Is there not a sense in which only a human mind can possess knowledge? If so, can this proposition somehow be squared with the idea that organisations know-how to do things? And if organisational knowledge is a real phenomenon, what are the principles that govern how it is acquired, maintained, extended and sometimes lost?
>
> (Dosi et al., 2000, p. 1)

## 1. Introduction

Much attention has recently been paid to the articulation and codification of knowledge (Cohendet and Steinmuller, 2000; Cowan and Foray, 1997; Cowan et al., 2000), on the grounds that "the increase in the stock of useful knowledge and the extension of its application are the essence of modern economic growth" (Kuznets, 1966). The debate, which has been very heated, is open to a variety of interpretations as indeed are its implications (see Knudsen, 2000; Nightingale, 2001; Johnson et al., 2002). Instead of reviewing the entire debate, we will attempt to illustrate the degree and ways in which it applies to the French steel industry. We believe that sectoral differences are an important part of the story and can help explain the degree of and potential for transformation of different kinds of

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knowledge, be they scientific or empirical (Rosenberg, 1982; Pavitt, 1984; Balconi, 1993, 1999; Divry and Lazaric, 1998; Saviotti, 1998).

In the steel industry, the main challenge lies in de-contextualising the local knowledge anchored in experts often belonging to different 'communities of practice'. They therefore tend to use localised jargons and vary widely in the way they carry out their tasks and interpret technical phenomena. In order to shed some more light on these issues we will focus on the different stages of knowledge articulation and codification and integrate organisational dynamics and social links as driving forces in the process. The reason for this is that the cognitive and political dynamics are interlinked and the nature of their co-evolution can be crucial to the evolution of knowledge itself (Coombs and Hull, 1998; Simon, 1999; Cohendet and Llerena, 2001; Dosi et al., 2001). Articulation and codification transform the way in which communities habitually represent knowledge and share it between their members at different levels: new knowledge representations come into play at both the individual and the collective level, while new objectives concerning knowledge accumulation and knowledge preservation enter the organisational level.

In this article, we first try to show the ways in which the articulation and codification of knowledge undermine traditional daily routines related to the handling of blast furnaces. We emphasise the fact that the knowledge associated with the workings of the blast furnace is mainly empirical and difficult to master in its entirety. We also briefly review the basic concepts of routine, knowledge articulation and codification in order to clarify them.

Secondly, we discuss the difficulties encountered in the creation general knowledge in Usinor and the Système d'Aide à la Conduite des Hauts fourneaux En Marche (SACHEM) project, which saw the introduction of an important programme of knowledge articulation and codification over a number of stages.

Thirdly, we analyse the impact of this process, placing particular emphasis on the organisational and cognitive effects of generic knowledge implementation. The crucial role played by human skills and tacit knowledge in this new system, both in its present form and during the process that led to it, become apparent in this section, as does the system's ability to generate new beliefs and R&D routes for the company.

Finally, we conclude by reviewing the sectoral dynamics our case study highlights and the organisational and social forces involved in knowledge articulation and codification.

## 2. Articulation and codification of empirical know-how in the steel industry: implication and difficulties

We begin by discussing why blast furnace related knowledge is still largely empirical in its form, thereby increasing both the difficulties associated with its generalisation and the degree of uncertainty in process control. Any attempt to disentangle this knowledge from individual and collective practices by articulating parts of them disturbs daily routines. Articulation paves the way for codification and can only be achieved by making the relevant practices explicit within different "communities of practice". We will examine these issues at both the empirical and the analytical levels and then attempt to devise a theoretical framework with which to explain such changes.

### 2.1. Empirical know-how and the blast furnace

The blast furnace is used for smelting and is capable of producing different grades of steel. The procedure involves coke, charred coal, various types of ore, hot air and gas being introduced into the furnace and then smelted. Dross is produced through a process of "decarburisation" and "dephosphorisation". Since the resulting smelted scraps vary, the melted metal must be analysed immediately in order to determine which gases should be added to it and at what temperatures.[1] Many of the thermal, chemical and mechanical phenomena taking place in this kind of large reactors are far from being well understood (Rosenberg, 1982).

The conversion process carried out by blast furnaces is continuous and takes up to 8 h from the introduction of the ores to the smelting stage. Any interruption is extremely costly and thus prohibited unless an emergency occurs. However, a blast furnace tends to work more or less as planned. Regular control is very

[1] A "speedy guidance" produces a molten metal that is "too hot" (i.e. including too much silicon), whereas a "slow guidance" can produce a "cold" molten metal (with insufficient silicon and too much sulphur), which is unusable.

important for both the smelting quality and the working life of the blast furnace, which, on average, is 15 years. If the flow of ores is not regular, it can provoke an above average erosion of the furnace's internal brickwork and tank. It can also cause deficient casting due to an iron notch. A number of problems can arise during this process, the most notorious occurring when ores do not tap properly and flow on one side of the tank. This happens when ores are insufficiently fluid and therefore create a kind of dome preventing gases from moving up the furnace's throat. The ductility of the metal, which is affected by this problem, is a very important quality of the final product and depends on the ability to carry out timely additions of oxygen and other gases. If intervention is limited in any way, ores and smelt scraps can suddenly sink back and cause a number of other problems, including obstructing the tuyeres and triggering explosions or gas emissions. Two things must be checked continuously to ensure the smooth operation of a blast furnace:

1. the quality of the smelting scraps and their proper repartition inside the throat;
2. the temperature inside the tank.

Team operators responsible for the continuous control of the blast furnace must be able to solve problems and make quick decisions. However, this ability depends not only on the integration of many pieces of articulated knowledge but also on the operators' understanding of what makes a 'good process' and what must be done to improve control.[2] One way of achieving the latter is to reduce the uncertainties associated with the process. To put it another way, in order to gain a better understanding of what happens inside a blast furnace, the firm must open the "black box" and try to analyse the causal links between the various parameters coming into play in different contexts and situations.

Although some mathematical models describing the physical–chemical reactions that take place inside the blast furnace have been produced, a formal model of the entire set of relevant chemical and physical reactions has yet to be devised. The scope of existing models is severely limited by the fact that most of the reactions cannot be observed. To summarise briefly, we can say that the blast furnace is a very complex structure that relies on empirical know-how and still represents a 'black box', in that very few physical or mathematical models have been developed to describe what happens inside it (Rosenberg, 1982; Steiler and Schneider, 1994). This lack of understanding enhances the importance of human judgement, tacit knowledge and labour skills, a fact that is widely recognised in the literature:

> One might naively regard a blast furnace as a deterministic chemical system, but in fact, its behaviour is stochastic. Many aspects of a furnace, its interior lines, the placement of tuyeres, the quality of raw materials, the degree of scaffolding, etc -exert an elusive but consequential effect on fuel consumption. Consequently, if one builds a taller blast furnace it is not immediately obvious whether its coke rate indicates the systematic effect of increasing height or is distorted by unusual random circumstances
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> (Allen, 1983, p. 12)

The blast furnace problem has attracted the attention of many scholars and practitioners who over the years have attempted to understand the processes associated with its operation and the resulting accumulation of knowledge. Bertin et al. (1996) studied the blast furnace process following the Great Depression and, among other things, highlighted the variation they encountered in the quality of labour input due to the critical role of experienced specialists, the difficulty of job sharing and a number of potential inefficiencies. The diversity they came across is a reflection of the variety of processes and reactions that take place inside each blast furnace. A recent examination of Brazilian blast furnaces (Unimas and CSN plants) has brought to light both the heterogeneity of existing practices and the efforts made to increase knowledge sharing and codification (Figueiredo, 2002). Different practices can lead to clearly visible changes in productivity, especially when the innovative capability of firms affects the final output (quality of steel, silicon content, coke rate level, energy consumption, etc.). Nev-

[2] Blast furnaces are extremely expensive: building one costs around €300 million and repair costs can reach €150 million. The casting process alone accounts for 56% of Usinor's average steel making costs. This is one of the reasons why improvements in casting and blast furnace guidance are crucial.

ertheless, the successful change of a particular work trajectory, which is invariably historically grounded, depends on the willingness to improve routines in operation and performance radically enough to allow progress beyond the trial-and-error stage. Building capabilities have to be based on dedicated investments (tools, computers, simulations, etc.) aimed at improving local knowledge and at creating abstract knowledge by testing the robustness of empirical beliefs (Arora and Gambardella, 1994). Consequently, existing knowledge of the workings of the blast furnace may be difficult to generalise because such knowledge invariably relates to a number of different technological artefacts. In the circumstances, any attempt at a generalisation is confronted with the problem of learning from partial experience involving great uncertainty—a considerable difficulty in knowledge comparisons.

### *2.2. Routinisation, knowledge articulation and codification: a theoretical framework for understanding the blast furnace*

The starting point of our attempt to come to grips with the operation of a blast furnace is provided by the concept of routine. In defining this notion, Nelson and Winter (1982) emphasise that a "routinised" organisation can be understood by reference to specific competencies. These encompass and embody different types of know-how, knowledge and part of the social context in which they are embedded. Different forms of know-how are memorised using a variety of mechanisms (different kinds of equipment, tools, procedures, data, human know-how, etc.). In order to illustrate the interplay between various forms of know-how, we use the notion of "repertoire": just as a more or less talented acting troupe interprets different plays in its repertoire more or less successfully, teams in the steel industry avail of and can mobilise different kinds of know-how. These can remain inactive or, when eventually activated, produce pig and cast iron.

An activated routine is an expression of the repertoire and can be judged on the basis of technical indicators such as casting delivery, steel quality, raw material and energy input and process fluidity. Collective activity involves procedures and rules and uses artefacts and know-how as well as skills. The collective ability to solve problems and co-ordinate different incidents is highly dependent on the existing repertoire. The co-ordination of different routines is sometimes compared to a "circuit" that must work "smoothly" (Lazaric and Mangolte, 1999; Lazaric, 2000). This means that some degree of cognitive coherence between different kinds of repertoires is necessary before they can operate successfully. Effective co-ordination also depends on the relevant "motivational/relational context" (Winter, in Cohen et al., 1996), which includes the "good will" of individuals, the prevailing interests and latent conflicts and the discretionary aspect of behaviour within organisations (Dosi et al., 2001).

Overall performance in the casting process is highly dependent upon:

(a) the state of cognitive repertoires, i.e. the accumulated stock of knowledge, and
(b) the social and relational context in which the repertoires are activated.

Most firms in this sector have looked into technical solutions, such as the implementation of expert systems, in an attempt to improve blast furnace regularity. An expert system, however, involves the transformation of all the knowledge stored in a particular firm, including its previous repertoires, and therefore affects both organisational memory and routine activation. This raises a number of questions as to where this knowledge is stored, who its carriers are, how it can be extracted, etc. As has been recently pointed out by a number of authors, this problem is far from trivial.

Indeed, the preservation of collective knowledge through the articulation and memorisation of best practice has a number of effects. It can generate specific assets for a firm by rendering the product of human experience more "manageable" and by contributing to the selection of routines and practices located within the organisational memory (Winter, 1987). Let us examine this point further: we argue that knowledge is "articulable" (and eventually "articulated") when the knowledge of a person or an organisation can be made explicit by means of language. In the same vein, "articulated knowledge" is knowledge that has been rendered explicit through language. Language, in this context, refers to a system of signs and conventions that allow the reproduction and storage of knowledge in such a way that it can then be communicated and transferred between individuals.[3]

The process of articulation involves the extraction of knowledge from the person holding it and the transformation of personal knowledge into a generic form (Winter, 1987; Mangolte, 1997). Although some forms of knowledge can benefit from it, parts of tacit knowledge may defy articulation and be poorly reproduced and communicated.[4] In other words, only a small fraction of articulable knowledge can in fact be articulated. Moreover, the degree to which articulation will actually be taken up as an option may differ radically between firms, depending on the associated costs and benefits accruing to a particular firm, its strategic vision and the importance it places on the building of capabilities (Teece, 1998; Zollo and Winter, 2002). Articulation, however, is distinct from codification (Zollo and Winter, 2002). Following Zollo and Winter (2002), we will take 'reutilisation', articulation and codification to be three interlinked stages. The three forms can exist and evolve together. So, codification, while not excluding 'reutilisation' and the presence of tacit knowledge, may well produce new useful insights and therefore enrich old repertoires or create new ones. However, as we shall see in the case of Usinor, this co-evolution is far from perfect because encoding has to face the problem of practice selection in the presence of different technological visions. Moreover, relational and social aspects are fundamental to the preservation of consensus between the different "communities of practice" co-existing in a company. Such communities play an active role by helping determine both the validity and the content of the relevant knowledge and by contributing to or questioning the articulation process. Let us discuss this point in the context of the SACHEM project.

## 3. The building of general and abstract knowledge: the SACHEM project

Before turning to the review of the SACHEM project's different stages, we shall briefly discuss the difficulties involved in the comparison of different and often contradictory beliefs based on long standing experiences of the same technical phenomena. We will see how Usinor's R&D centre (IRSID)[5] compares localised experience in order to manage variety and generate abstract knowledge. We will then discuss the different stages of the SACHEM project, which begins with knowledge articulation in order to gradually create the necessary conditions for the identification and selection of 'best practices' for blast furnace operation.

### *3.1. Local practices and heterogeneity of beliefs: the role played by IRSID towards the creation of general knowledge*

The project of articulation and codification in Usinor was implemented following the creation of an autonomous entity that helped combine the most important French steel producers.[6] Industrial concentra-

[3] Natural language has a more precise definition because its grammar produces a certain degree of consistency between the various signs. On this important debate, see Choamsky (1988), Piaget (1970) and Polanyi (1958). For a debate on codification, see Cowan and Foray (1997), Cowan et al. (2000) and Nightingale's (2001) reply. Nightingale argues that tacit and codified knowledge are not substitutes and presents some doubts on the way in which codification may precede articulation, most notably via a "codebook".

[4] Traditional know-how may be difficult to articulate as it is affected by the way in which its "master" transmits his know-how during training and apprenticeships and because of the presence of important tacit know-how. For example, Verry (1955) reviewed the sensorial know-how involved in the steel industry's casting process. Before 1914, rollers in the Ardennes region were directly involved in the temperature control of metal before it was put into the rolling mill. They directly observed the colour of the metal, which can take a variety of colours ranging from pale straw (225°) to brownish purple (260°), dark purple (280°) and sea green (350°). Six different shades of red were known. Rollers would strike a piece of dry wood on the hot metal and determine the metal's temperature by observing the reaction (slippery wood indicated 350°, smoking wood indicated 400° and a spark indicated 425°). Even though some of this know-how was written down and articulated in a book, it did not entirely capture the knowledge held by the rollers. The refined perception of colours remained unformulated and deeply tacit. Acquiring this skill required a long apprenticeship with a master.

[5] The acronym stands for "Institut de Recherché de la SIDérurgie Française" (the French steel industry research institute) whereas SACHEM's acronym stands for "Système d'Aide à la Conduite des Hauts fourneaux En Marche" (guidance and aid system for a working blast furnace).

[6] Consolidation in the steel industry continues to this date and recently saw the birth of Arcelor (November 2001). Usinor is Arcelor's main shareholder, while two other European industrial partners, Arbed (Luxembourg) and Aceralia (Spain), hold large stakes.

tion in the sector while creating the necessity also offered the opportunity to engage in this process because a shared level of knowledge had to be established in order to improve productivity and know-how within the separate but newly merged plants.

For example, in order to improve sinter, blast furnace operators must have a good understanding of the fluidisation process and of the trajectories followed by the material falling from the bell-less top chute. This knowledge is essential in order to optimise gas distribution and provide high quality sinter. High quality sinter is determined by its grain size distribution and strength and is characterised by high reducibility, high "porosity" and appropriate softening behaviour (in turn depending on a suitable chemical composition, FeO content and "basicity"). A uniform distribution of all additives contributes to the formation of a homogeneous raw sinter mix. High permeability allows the bed height to be increased, which in turn has beneficial effects on fuel consumption, sintering, the temperature of the sinter itself, its strength and reducibility. In brief, burden trajectories must be monitored regularly because they can change due to several burden-related effects (fluctuation of the burden's grain size distribution over time, grain size segregation occurring when the hopper feeding chute is charged and emptied, etc.).

Despite the fact that frequent measurements of the trajectories are required in order to accurately control the burden distribution, before the implementation of SACHEM they were only carried out occasionally during scheduled shutdowns. Moreover, units of measurement varied considerably between plants creating different and distinctive knowledge. In this context, beliefs about the process (fluidisation, permeability, reducibility) varied and practices generated localised knowledge.

Let us be more precise. In Dunkirk, the standard deviation of coal injections from tuyere to tuyere did not vary by more than 2%. In Fos, on the contrary, the variation in an equivalent blast furnace was between 2 and 5%. Such different practices were almost always due to the absence of any systematic effort to extract information from the workings of individual blast furnaces thereby creating generic knowledge. Each plant not only interpreted similar technical phenomena in different ways but used a variety of jargons and tools for the measurement of technical parameters. Even the methods adopted for the economic evaluation of operations differed across plants, leading to incommensurable data across the board due to the idiosyncrasy of the tools and evaluation methods particular to each unit.

Moreover, the heterogeneity of practices was also partly due to various more or less rational beliefs and emotions held by practitioners and their attitudes towards the exploration of specific paths: where some viewed a particular practice as the appropriate solution to a problem others treated it as impracticable. An example of this diversity relates to coke injection. Whereas in Fos sur Mer increasing the coal rate injection was viewed with fear and suspicion due to the prevailing belief that burden descent would be degraded if the coke rate exceeded 60–80 kg, in Dunkirk, during the mid-1980s, the coke rate increased continuously for a sustained period of time and by June 1985 had reached a monthly average of 143 kg:

> During the last decade coal injection in the blast furnace has become a standard practice and nowadays coal rates in the order of 190–200 kg/htm are achieved in routine operation on several blast furnaces. In France coal injection, first investigated in the early sixties, and then rapidly abandoned, gained renewed attention in the beginning of the eighties. Following the first industrial trials in Usinor in 1982, coal injection steadily developed from 1983 to 1989, reaching rapidly a level of 145 kg/htm in 1985. The barrier of coke less than 300 kg/htm was definitively broken in 1990 at BF 4 in D
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> (Van Crayelinghe, in Jollivet, 1999, p. 443)

In this context, it is also interesting to note that IRSID's predictions with respect to coal injections during the 1980s were not very accurate. Standard IRSID results concerning coal rate injection were notably in line with the practices prevailing in Fos sur Mer's practice: the recommendations stated that 60–80 kg had to be the limit. In this case, it was only due to the force of local practice and the success of high injection rates that eventually led to a reversal of earlier fears. So, during the 1980s practical experience informed scientific experimentation and provided best practice models rather than the reverse. This situation was to change in later years. Indeed the articulation and generalisation of knowledge inside Usinor was pushed through the will to create shared beliefs. For example, IRSID, which was meant to carry out fundamental research for all French firms in the steel industry, became, as a matter of fact, an integrated Usinor R&D centre. IRSID was therefore given the historic opportunity to collect the results of local experimentation and to bring them together thus becoming a large store of information that could help solve problems and co-ordinate practices.

Following these developments, IRSID was also increasingly enabled to engage in the task of comparing practices between different plants and therefore allowed to find shared measures of practice and scientific translations for local experiences. This process inevitably raised new questions in relation to the solution of local problems. Scientific experiments followed local ones for some time and IRSID for a while followed existing practices instead of trying to impose a shared vision around the blast furnace. By the end of the 1980s however, IRSID had a new part to play in the generation of abstract knowledge and in helping practitioners go beyond their local apprehensions and fears. This role was quite distinct from the one that had prevailed throughout the beginning of 1980s, which had seen IRSID as little more than a deposit of experiences and technologies.

### 3.2. Knowledge articulation in Usinor

In Usinor, knowledge was articulated through the launch of 'Xperdoc' in 1989. This established a common word-list and was aimed at creating a shared vocabulary among blast furnace experts. Shared semantics were seen as the first step in the process of harmonising different practices, beliefs and repertoires and were meant to constitute a common reference for the group. A team was set up to establish the relevant categories to be used in describing blast furnace related knowledge, which resulted in the identification of eight general themes.[7]

Following the thematic choice, the problem was decomposed further in an attempt to understand the causal links between technical events and the reasoning behind the blast furnace experts' actions. The resulting, rather consistent, Xperdoc, document provided a common interpretation of observed phenomena and highlighted the lack of understanding of a number of technical events. Xperdoc showed that no uniformity existed in the handling of the fluidisation process and any combustion problems that occurred. The reason for this was that actions taken by operators depended on the interpretation of a number of technical parameters, the identification of which depended entirely on the state of local knowledge. For example, in some plants it was thought that the complete combustion of coal particles and their transformation into carbon monoxide in a very limited area of the raceway was only possible if the coal was finely ground. In other plants, however, the same process was perceived to be too hazardous to be undertaken due to the possibility of dust explosions, despite the fact that such an event had never materialised.

The creation of this kind of "hand-book"[8] had the following objectives: firstly to bring the experts together by giving them the opportunity to meet ('Xperdoc' in this way gave them a chance to exchange views and discuss their practices) and secondly to lead to the mutual acknowledgement of different practices and help institute personal trust between experts.

'Xperdoc' shed a preliminary ray of light on habitual ways of carrying out tasks and on the different interpretations of blast furnace operation. Moreover, it produced a radical change in organisational memory and in the knowledge activated daily in the firm, by questioning old repertoires, especially due to the fact that it led to the compilation of the very first ICT document (in hypertext format and including a variety of texts, links and graphics), made available to all the different 'communities of practice'.

[7] Among themes included in the blast furnace description: gas distribution (survey of gas flow, gas reduction), burden (physical and chemical quality of burden as well as burden descent steadiness), walls (evolution of and inconsistencies in wall temperatures and thermal losses), permeability (determination of levels, evolution of stability in the different parts), tuyeres, hearth draining (differences between tapping holes, late slag, too low or high metal flow), hot metal theme and slag quality (alkali balance and analysis of inconsistencies), water leaks ($H_2$ utilisation and water tank level).

[8] Hatchuel and Weil deal with the same problem in the case of an expert system. Handbooks are usually the first stage in a longer process and are intended to transfer, translate and articulate current practices through a support instrument known to all contributors. For a more general discussion, see also Cowan and Foray (1997) and Cowan (2001).

### 3.3. Identification of 'best practices'

In 1987, the SACHEM initiative came to light mainly due to the efforts of a group of staff members who believed that artificial intelligence could help practitioners memorise a large part of the knowledge held by experts.[9] This idea was only implemented in 1990 under the supervision of Francis Mer, the company's senior manager, who was particularly interested in this new tool in his efforts to improve Usinor's productivity.

During the course of year, over a hundred artificial intelligence applications were tested in collaboration with IRSID. The implementation of artificial intelligence projects benefited from European subsidies and a 40-strong team spent 5 years working towards the creation of systems and their dissemination within the group. Following this first stage, 17 technical solutions were selected, among which the SACHEM project. This latter was first implemented in October 1996, following a long period of discussion within the company which focused mainly on the following crucial questions:

- What kinds of knowledge have to be articulated and stored?
- How should practices be selected?
- How can such practices be transposed into a new tool?
- How can losing tacit knowledge be avoided as the importance of articulated knowledge increases?

In order to identify the 'best practices' and key 'know-how', 13 experts were chosen among those who had co-operated in the compilation of 'Xperdoc'. Experts were selected according to know-how and location in order to ensure a fair representation of the various types of knowledge prevailing in the different plants (Fos sur Mer, Dunkirk, Hayange, etc.). The team worked with six "knowledge engineers" in order to extract the "core know-how" and articulate it (400 interviews were conducted).

This stage of the articulation process shed light on the different ways blast furnace experts solved problems and on the set of different solutions used within the company. For example, in injection practices fuel injection, coke injection and coal injection co-existed. Following this observation, practices were gradually harmonised during the past decade and now coal injection has not only become the norm in Usinor but has been fully routinised (Jollivet, 1999).

At the beginning of the SACHEM project, although injections were carried out in different ways in the plants, coal and coke injections predominated. However, the differences between plants did not end there. Coal injection itself can be effected with two different technological trajectories: pulverised coal injection (PCI) and granular coal injection (GCI).[10] In Hayange, GCI was judged to be economically more advantageous as the cost of coal preparation it required was deemed to be inferior to that required by PCI. In Fos sur Mer, on the other hand, following a long stint during which coal injection was viewed with some suspicion, coke injection and coal injection came to co-exist. During the 1980s, conventional wisdom changed again in Fos sur Mer as coal injection was perceived to increase equipment costs as compared to coke injection. The price difference between the two available technical solutions was deemed trivial and blast furnace operators turned away from the complicated coal injection. In Dunkirk, on the contrary, after a long adjustment period during the mid-1980s, PCI was adopted across the board following the development of a technique

[9] Three main reasons explain the process of articulation and codification in Usinor: (1) the need to create unified capabilities and articulated knowledge across the group and to channel all local knowledge into a common project in order to create shared semantics between experts ("to ensure that we are talking about the same thing"). (2) The firm made 98,000 employees redundant between 1977 and 1990 (mainly through a retirement policy). Following this period, the company hired very few new employees and therefore, the average age of the group's employee population rose dramatically (around 50% of Usinor's employees will have retired by 2010). In this context, the need to save existing collective knowledge became crucial, given that most of its human holders were soon to disappear! (3)The need to improve the quality of the process by introducing real time intervention, thus ensuring the rapid resolution of problems occurring during the early stages of metal fusion (the cost of guiding the blast furnace in a plant like Sollac (Fos sur Mer) represents 56% of the total costs of steel production).

[10] GCI requires the coal to be ground extremely finely (100%: $<5$ mm and 95%: $<2$ mm). The outcome of the process is also dependent on preparation and the hardness of the coal. Pulverised coal injection, on the other hand, requires even finer grinding (80%: $<74\,\mu$m).

involving the distribution of pulverised coal between the tuyeres.

During the mid-1980s, it became clear the PCI as carried out in Dunkirk was one of the "best solutions" to the combustion and fluidisation problems. The technique also proved to be the most cost effective as it reduced coke consumption and required less capital investment than additional coke ovens. To summarise briefly, practices relating to the combustion problem within the blast furnace arose largely out of individual learning experiences. Some plants thought of PCI as distinctly superior, while others continued experimenting on the combustion problem in line with the availability of different inputs. Given the empirical origin of the predominant patterns, deriving general principles proved difficult as different experiences and observations had led to a variety of beliefs. In this context, SACHEM attempted to respect diversity while offering generic knowledge that could contribute to a better understanding of the relevant technical principles. The collection of case studies that resulted from the project is an example of the diversity/universality principle prevailing in the company.

A further step in the attempt to understand expert know-how was taken by the creation of an interpretative model called General Expert Analysis (GEA). Blast furnace experts based GEA on a collection of representative case studies depicting the rules of conduct adopted in the face of technical problems. For example, a particular expert described his interpretation of the gas distribution occurring during a PCI, another depicted the way he understood gas distribution when GCI was used and a third expert explained in great detail the causal links between gas distribution and their effects on the tuyeres. The purpose of this collection of case studies was to put together a detailed set of rules on blast furnace operation and to cover as many aspects of the blast furnace process as possible. In practice, the rules derived in this way were sometimes incomplete or only partially true. In order to extend and complete the process of mapping qualitative knowledge more extensively, a method called Cased-Based Reasoning (CBR) was adopted.[11]

The intention in running GEA was to begin by working on the validated case studies only to progressively validate or definitively invalidate the rest. This preliminary work took 10 months (from September 1991 to June 1992) and allowed the identification of key and daily activated know-how. It also allowed the delineation of a perimeter of expertise and the relevant results were diffused among the experts. The process of disclosure itself saw a further selection of accumulated knowledge, as two important conditions had to be fulfilled before knowledge could be selected, validated and eventually codified.

First, knowledge had to be generic, that is to say, it had to be sufficiently broad to remain meaningful once it had been dissociated from its local context and specific use. Variety amongst experts and their associated expertise, which stemmed from different plants, helped identify these broader strands of knowledge. Secondly, the knowledge had to be identified and acknowledged as being 'true' by all the experts involved (i.e. it had to be deemed both useful to and usable by operators before it was codified). Consequently, at this stage, parts of pre-existing knowledge were lost while others were given increased emphasis (validation reinforces the parts collectively judged as crucial to the detriment of those deemed too tacit or local to be selected).

### *3.4. Selection and validation of 'best practices'*

As we saw with the GEA, one of the problems associated with this methodology is the potential reinforcement of existing and diffused know-how through adaptation. For example, the suggested gas distribution method following a decrease in the burden was based

[11] The latter worked by analogy, providing conclusions based on an initial premise, and relied on the similarity principle to discover new causal links by putting together different pieces of knowledge that shared a number of dependence relations. The main aim of this tool was to complete the chain of human reasoning derived from the initial case studies that had, in the meantime, been validated or at least partially validated. The process resulted in some additional pieces of knowledge, although it should be emphasised that the CBR was not intended to create new ways of solving problems but simply to make new connections between the set of existing solutions to common technical phenomena. Three types of case studies were observed in this context: (1) case studies that had been validated and confirmed by the blast furnace experts; (2) case studies that had been suggested by some experts but had only been partially validated; (3) case studies on new situations that had yet to be confirmed by other experts. For a technical discussion on the similarity principle and the dependence relation, see Salotti (1992).

on coal-based injection, because this was considered to be both a universal and a confirmed practice. More specifically, gas distribution and its evolution were first considered during PCI. In order to include GCI in this story, the generic knowledge, gained through observation and analysis of PCI related practices, was adapted for GCI which required a different gas distribution, another fluidisation process and a more stable model for the permeability of the tuyeres. This kind of adaptation was frequent and, was also applied to coke injection (notably in Fos sur mer). In practice, this meant that general models had to be adapted in order to take account of local specificities (arising from such things as differences in the number of tuyeres or in the oven inputs that changed from one plant to another). As a result, the dissemination of the SACHEM outcomes had to be done in stages. Fos sur Mer and Dunkirk (1996 and 1997) were the pioneering plants, followed by Hayange in Lorraine (between 1998 and 1999).

The selected know-how was classified and indexed between April 1992 and May 1995. During this stage, called Detailed Expert Analysis (DEA), key concepts and their articulation were registered in order to introduce consistent problem solving. For example, 150 potential blast furnace anomalies were identified and classified according to their position in the steel making process (quality, gas, wall, temperature decline, permeability, etc.). On the basis of this knowledge, specific problems (such as an unusual temperature increase) could be identified systematically, operators alerted and specific recommendations made on the actions to be implemented (the system also involved the fitting of 450 alarms and a number of different warnings).

Following the process of translating words into codes, the stage of knowledge acknowledgement and validation was launched. Blast furnace experts had to recognise their codified know-how, which had been radically transformed by computation. This stage was crucial, as it allowed experts to verify whether the codes did in fact represent what they had intended to articulate in the first place. Knowledge validation was a long and difficult stage as consensus had to be reached before it was concluded. Individual meetings, which saw experts having one-to-one discussions with

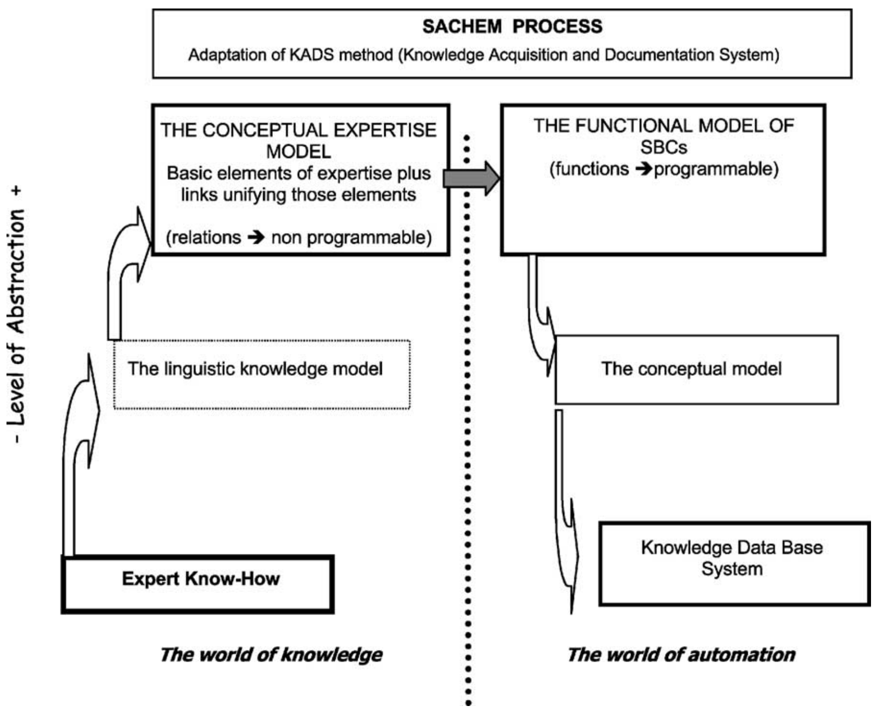


Fig. 1. The SACHEM methodology.

Table 1
A summary of the different stages of the SACHEM project

| Years | Main objectives | Technical name of the sub-project and process of knowledge's transformation |
|---|---|---|
| 1989 | Shared vocabulary among blast furnace experts | Xperdoc (first stage of knowledge articulation) |
| 1990 | Exploration of various opportunities provided by artificial intelligence<br>Choice of the SACHEM methodology | |
| 1991–1992 | Delimitation of the blast furnace expertise with representative case studies | General Expert Analysis (second stage of knowledge articulation) |
| 1992–1995 | Selection of core know-how<br>Encoding process and validation by blast furnace experts | Detailed Expert Analysis (codification) |
| 1996 | SACHEM implementation in Usinor | SACHEM |

knowledge engineers, and a collective one, including all the experts, took place. Local know-how had been radically transformed as the "knowledge engineers" had changed the way experts represented their own expertise. As it happened, parts of the general knowledge codified in the expert system had ceased to be meaningful to some of the experts. For this reason, the knowledge engineers designed a linguistic model (in natural language) in order to translate the code. The experts were thus able to recognise their own expertise and acknowledge it collectively. Similarly to the interpretative model, which had translated the experts' articulated knowledge into codes, the linguistic model converted codes into words. Different models had to be created because different levels of abstraction and local knowledge were required depending on their use. This methodology is depicted in the following table (Fig. 1), which also shows the "break" introduced by knowledge automation.[12]

The main stages of the SACHEM project are summarised in the Table 1.

## 4. Cognitive and organisational consequences of the SACHEM project

The consequences of articulation and codification were very important because actual knowledge content changed drastically, forcing some blast furnace experts to modify long standing beliefs and their customary interpretations of technical phenomena. The creation of generic knowledge forced all the people affected by this process to "translate" the codes in order to make sense of the codified knowledge. The company also allowed the experts to play an active role in the adaptation and update of the system in order to improve its daily performance.

SACHEM also led to a reconsideration of traditional automatisms embodied in old repertoires: following a degree of revision of pre-existing beliefs, these were reactivated and generated further new insights for the company. As routines changed, organisational memory in Usinor was transformed due to the creation of different forms of memories and levels of activation. Let us examine these aspects in some more detail.

### 4.1. *Deep transformation of the content of knowledge*

Articulation and codification entails a radical change in knowledge because it involves the selection of parts of all available know-how. Moreover, it affects the content of knowledge, as, in practice, traditional expertise anchored in an expert's routines is live. A first transformation occurs when experts put their practices and parts of their tacit know-how into words. This 'explicitation' creates articulated knowledge, which entails a first selection of know-how. Parts of know-how are too dependent on practices prevailing in local plants: these cannot be articulated and resist extraction because of their ambiguity and fragility (deeply tacit knowledge and personal judgement may

[12] For another description of a similar knowledge recognition and validation process used in the implementation of a knowledge based system, see de Jongh et al. (1994). More specific and technical details about Knowledge Acquisition and Documentation Systems (KADS) can be found in a recent article by Shabolt (1998).

defy codification by virtue of being too personal). For example, a particular tapping perturbation that occurs during hearth draining involving substantial metal flow was described by one of the blast furnace experts but was judged too idiosyncratic and failed to be acknowledged by another one. This knowledge was first classified as a new situation in need of validation only to be rejected at a later stage as it was deemed that this kind of tapping perturbation was never encountered during the working of the system.

A second transformation takes place when articulated knowledge is turned into a code, as technicians in the area it affects have their own ways of representing and selecting knowledge: parts of knowledge may be deemed useful simply because of the nature of particular technical parameters embedded in the expert system. In other words, the nature of the container is far from being neutral and can in fact change the knowledge content itself by including unnecessary bits of know-how while excluding others. Consequently, the outcome is not a simple translation of existing knowledge into code but also a reformulation produced by the knowledge engineers and validated by the experts. Each stage of the transformation, which takes place in the handover from live expertise and activated knowledge to the memory of an outsider and from one outsider to another, entails a change in the preserved knowledge. This is neither a perfect equivalent nor a total substitute of the knowledge carried in the different memories. For example, the survey of hot metal and slag quality provided by the expert system lacked crucial information on the balance of alkalis. As a result, conclusions reached on the alkali problem and the causal links between fluidisation and burden decrease had to be re-codified because many recommendations were of limited use due to a lack of proper understanding of the links between the alkali balance and fluidisation during the encoding process.

Following codification, the container further transforms knowledge content because each language has its very own ways of representing things (Hatchuel and Weil, 1992). Repeated transmission through a variety of languages will always involve some losses as codes differ radically across languages. Moreover, articulation and codification are in a way unpredictable because they are largely based on individuals' willingness to participate in a process that is likely to depart from their initial experience (most implemented codes differ substantially from the original individual representations of particular technical problems). This is precisely the reason why the translation into natural language and the validation by experts that took place following the codification process was crucial to the SACHEM project: it prevented experts from feeling they lost their original know-how once they had passed it on to the knowledge engineer.

### 4.2. Revision of prior beliefs and reinforcement of empirical know-how

An important contribution of the SACHEM project was that it brought about a change in the way operators and experts themselves understood the blast furnace process. As we have already emphasised, the blast furnace experts' know-how is generally empirical and has not yet been captured in its entirety by a scientific model. Implementation of the SACHEM codes meant that some parts of pre-existing know-how were validated and acknowledged, whereas other prior beliefs were discussed and collectively rejected. In this way, the newly validated know-how, a subset of that previously employed, in itself contributed to the improvement of the company's empirical knowledge.

For example, before SACHEM was set up, a phenomenon called 'fluidisation', involving an increase in temperature above the ores was often observed. This was connected to the suspension of coke iron ore and limestone flux and was associated with a fall in different ores. In the 'Fos sur Mer' plant, two beliefs prevailed about this phenomenon:

Belief 1: Experts believed that fluidisation never occurred in 'Fos sur Mer'.

Belief 2: When descending ores and fluidisation were detected, experts did not associate it with fluidisation and the temperature increase was attributed to a different phenomenon.

After SACHEM came into use, prior beliefs were revised, notably:

Belief 1: Fluidisation did take place in 'Fos sur Mer'.

Belief 2: When fluidisation occurred, fluidisation had preceded the descent of ores by an hour.

In practice, the system provided a robust tool against which empirical know-how could be tested in order to improve and generalise it. As the process unfolded, prior beliefs were gradually redefined: what had been known to be true started appearing to be only partially so (especially through the discovery of new causal links between technical events). The causal links connecting separate technical events, which used to be tacit and intuitive, were tested and systematically proven. In this way, the articulation process led to more robust beliefs and unquestionable know-how within the firm by changing the experts' and operators' local cognitive representations. The SACHEM project also led to the creation of generic knowledge and even to some scientific breakthroughs because some of the new knowledge paved the way to new insights for IRSID.

### 4.3. Discovery of new routes for R&D and efficiency gains

Another important element leading to blast furnace efficiency gains was the increased importance attributed to the development of new research based on the improved understanding of the causal links between technical events: "instead of relying purely on trial-and-error to find what may work, the tendency is to attempt to understand the principles governing the behaviour of objects and structures, to 'observe' phenomena and test hypotheses with sophisticated instruments, and to stimulate processes on computers" (Arora and Gambardella, 1994, p. 523). In Usinor, SACHEM provided more exhaustive information on the characteristics of certain technical phenomena but also mathematical models that could help understand parts of the "black box".[13] Although the creation of a single global model has yet to be achieved, partial models have paved the way for the discovery of new routes in R&D and have helped compare the new knowledge between different industries facing similar technical situations. Let us discuss these aspects in some more detail.

The existence of an expert system that provided validated information on the behaviour of the burden and on fluidisation was an important element underlying IRSID's decision to take the process a step further and model some of the data gathered by SACHEM. Indeed, the expert system afforded a clearer overall picture of the different practices coexisting in the company and also provided exhaustive information on the different kinds of pulverisation. Different profiles of oxidation-condensation were registered and the information collected gave some insights into the part played by alkalis in reducing degradation in the mineral burden. The research that was carried out on the basis of these observations is a good example of a new route to R&D. A number of industrial trials on burden behaviour have now been performed (in co-operation with researchers from Berlin University), in an attempt to reduce alkali load circulation thereby improving blast furnace stability and productivity. The mechanics of burden reduction (fine generation) in the presence of alkalis have now been fully characterised for a variety of materials that can be loaded into a blast furnace (sinter, iron ores, pellets). Tests have been carried out with different quantities of alkalis in order to identify the weight fraction of fines generated following an abrasion test (the results have highlighted the catalytic effect potassium has in reducing iron oxides in all tested materials). IRSID is now planning to introduce this new information into current routines affecting the daily performance of the burden across all the Usinor plants, especially for blast furnaces still using coke pulverisation.

More generally, the data collected by SACHEM have helped create new ways of understanding blast furnaces and have also led to the development of new mathematical models. As we saw earlier, the validity of measurements is crucial in any attempt to move away from a trial-and-error process and for monitoring the burden. SACHEM provides frequent and reliable measurements with which to observe and analyse the process in operation. These on-line measurements of the material trajectories in bell-less top charges are now carried out with impact sensors situated inside the furnace. Two years ago, IRSID created a comparative mathematical model of the deposition of coke and sinter layers thus helping improve the accuracy of burden distribution control. Similarly, Irsid has recently produced mathematical models of the gas found within the burden. One of these, "NeuroGaz", is complementary to earlier models because the control of burden

[13] Its methodology is protected by a patent and some part of it is licensed in other industries.

Table 2
SACHEM efficiency and performances in Fos sur Mer

| | Mean shutdown time equivalent, per month | Yearly production capacity saving | Gain on the PCI | Gain on the iron quality | Gain on the BF life duration | Productivity increment |
|---|---|---|---|---|---|---|
| Without SACHEM | 19 h | | | | | |
| With SACHEM | 14 h | 30000 THM or 2.5 days | | Sigma = 0.003 | 1–14 years | |
| Direct value (in US$/THM) | | 0.20 | 0.90 | 0.20 | 0.40 | 0.30 |

*Source*: Usinor, December 2002.

distribution has a clear influence on the desired distribution of gas.[14]

These models have been applied in different plants, such as Fos sur Mer, Dunkirk and Hayange, in order to guide blast furnace control. Moreover, new insights for R&D policy have provided by sectors that go well beyond the steel industry thus increasing the degree of generality of their application. For example, the thermodynamic properties of the Fe–Zn–O system, which helped understand the operating conditions of the chemical evolution and mineralogy of dust, came from the field of marine aerosols whereas other chemical reactions have been interpreted using models imported from the nuclear industry.

In terms of efficiency, the global evaluation of SACHEM has shown that operational routines do improve if reliable data are at hand. The decrease in the number of accidents has had an important effect in diminishing monthly shutdown periods, has improved the quality of iron by reducing its silicon content and has also increased the lifespan of blast furnaces. In 2002, in Fos sur Mer the total measured return on investment came to around US$ 2 per metric ton of hot metal (THM). The improvement of productivity in Fos sur Mer is summarised in the following table.

### *4.4. The co-evolution of tacit and codified Knowledge*

The emergence of generic and scientific knowledge might lead one to conclude that tacit knowledge has all but disappeared in the plants. It is in fact true that some forms of tacit knowledge are no longer activated on a daily basis. For example, sensorial know-how used to describe the quality of the metal during fusion and for the prediction of its future granularity fell out of use in Usinor following the introduction of SACHEM. This kind of know-how was progressively abandoned during the 1980s, due to the automation of the casting process and the introduction of sensors that replaced sensorial activity with actual data. Computers, tools and data memorised by SACHEM also changed the personal nature of knowledge dissemination, which used to take place through the expert–pupil relation (apprenticeship system) (Table 2).

This, however, does not mean that tacit knowledge is no longer activated in the company. Although some forms of tacit knowledge have been replaced by data, other pieces of tacit or abstract knowledge, such as judgement and intuition used in the observation and detection of problems, are still required and remain necessary. SACHEM does not simply run on set technical parameters but depends vitally on the social co-operation of the blast furnace experts, the main knowledge repositories.

The system's recommendations, which result from its own interpretation of the data (especially the identification of causal links between different events), and the operators' ultimate decisions are still compared and scrutinised in a continuous attempt to capture existing knowledge and disseminate it. The gaps between the system's recommendations and the operators' decisions are systematically deconstructed in order to detect divergences. This kind of analysis allows the database to be enriched and updated. Parts of the tacit know-how that were not articulated and were considered insignificant during the second stage of the articulation process are now gradually

[14] NeuroGaz studies the coherence of temperature and gas analysis measurements projected on a generic instrumentation in real time. Data are validated through the operation of 14 artificial neural networks created in order to qualify the 10 functions of geometric analysis. The data are obtained from chemical and temperature sensors, distributed along a fixed or a sliding probe at the top of the blast furnace.

incorporated into the system. This mostly applies to knowledge that had originally been classified under a "to be confirmed" heading and was deemed to be idiosyncratic (e.g. referred to only by one blast furnace expert). Although some of this information has been gradually discarded, other disclosures, which over time proved to be robust and valid, have now been encoded. For example, a description of the gas distribution within a particular blast furnace and the evolution of irregular peak characteristics described by an expert (these were too chaotic to be captured by some of the experts) was eventually validated following a number of collective discussions and the production of quantitative data on the fluidisation process.

Updates of this kind are formalised in an annual meeting with the operators, foremen and experts. Experts play a crucial role in this context as they formalise and systematise the results of the divergence analysis of users (operators). The constant activation of human skills is important because the expert system is unable to deal with new situations and solve novel problems. Its abilities are limited by its existing, previously articulated, knowledge. In the absence of integration of new pieces of knowledge and of their codification, the system would, in the long run, become outdated.

### *4.5. Different levels of knowledge activation inside Usinor*

SACHEM is able to collect systematic data (with the aid of over 1000 sensors placed inside the blast furnace), to interpret and to qualify them. The system continuously compares the collected information against a reference situation and can make certain predictions, detecting problems and recommendations to operators. It affords a global vision in real time, a selection of interesting indicators and some solutions. Operators retain a certain amount of autonomy in decision-making, as they are able to ask the system to provide explanations on a number of the phenomena it detects. The system has been set up in such a way as to avoid automatic guidance, which would risk reducing operators to a passive role and thereby undermine their ability to solve problems. The problem of excessive data production is further avoided by the introduction of a number of different access levels to the data. The system thus only provides data that are strictly related to a particular problem or moment in time. In practice, the system has a number of different organisational memories, some short, some long, some centralised and some decentralised.

The access levels do not entirely solve the potential for "cognitive overload" (the constant exposure

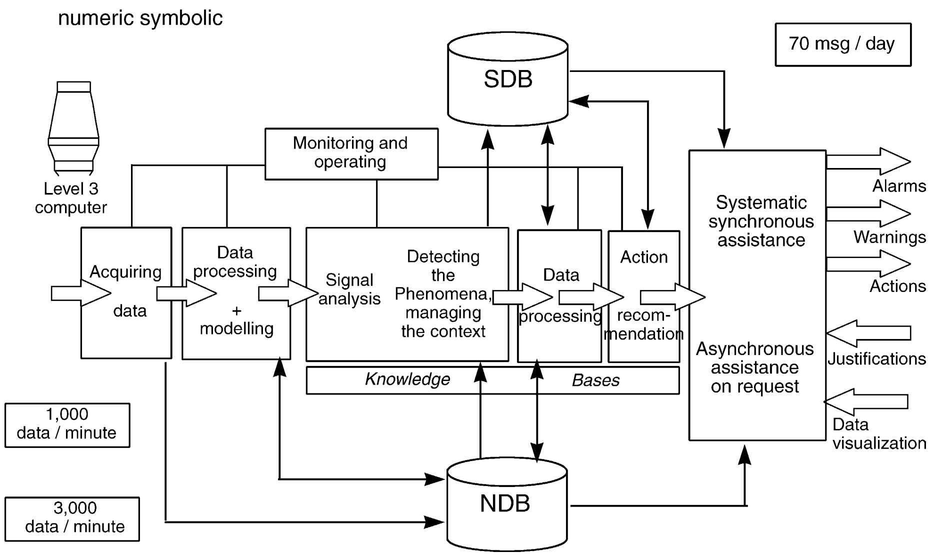


Fig. 2. The different levels of SACHEM activation.

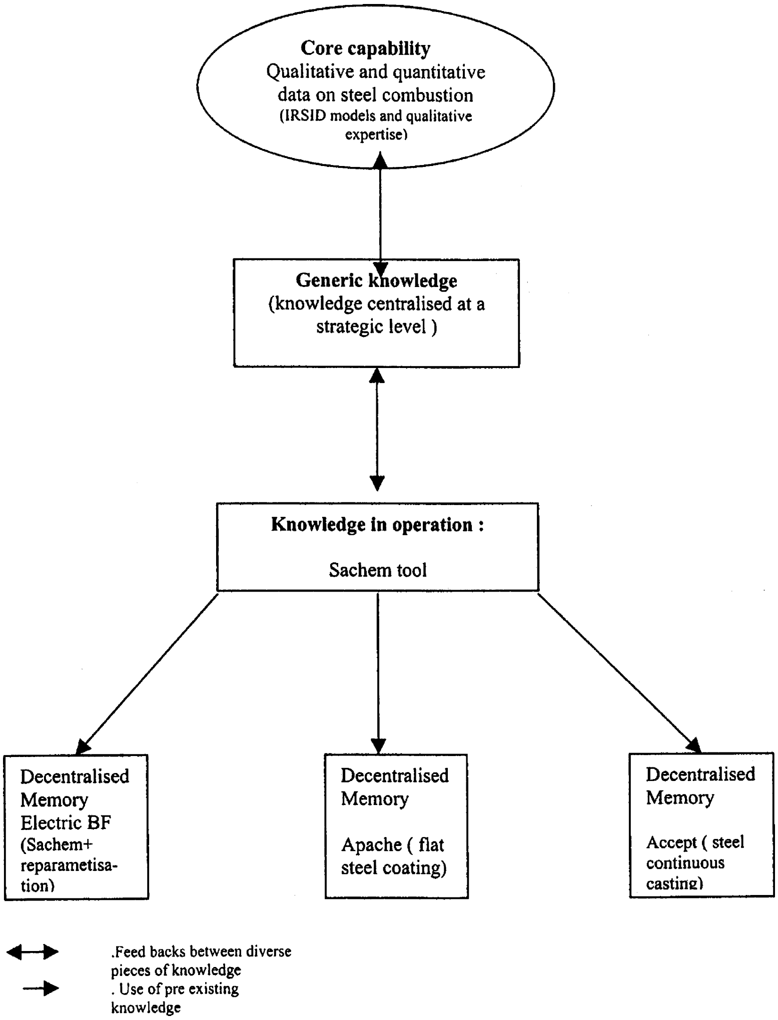


Fig. 3. Centralised and decentralised memories in Usinor.

to a flood of data, much of which is likely to be redundant) for the operators and other SACHEM users. As a result, off-line analysis has been introduced in order to afford explanations for the processes and descriptions of the detailed technical characteristics observed. Off-line data can produce preliminary representations of phenomena and some intermediary results. Moreover, a signalisation process has been introduced to provide qualitative and quantitative data in "user-friendly" format (i.e. accessible to a large part of users) and 450 warnings or alarms have been set up in order to produce a qualitative description of various processes (such as an increase in gas distribution on the wall, a low cast iron temperature or a high level of slag index). Recommendations produced by system can only be activated by an operator (he or she can agree or disagree with the recommendation and act accordingly).[15] To summarise briefly, the expert system collects different sets of data before making any recommendation and the intermediary results of

[15] Some suggest that the expertise rule used in SACHEM is captured by the following statement: "If a decrease in the quantity of air present in a nozzle is signaled and within two hours an increase, sufficient to compensate the previous decline, is also signaled, then this nozzle is suffering from a blast furnace nozzle punctual passage block" (Cauvin et al., 2002).

this process are given to operators in order to help trigger a human reaction. The alarms prevent the system from becoming a mere “cognitive prosthesis” and have been designed to induce human reaction and the constant activation of human know-how. The system can be activated with or without deliberation depending on the context and on the operator’s personal engagement. The description of the system and the architecture of SACHEM is illustrated in the following table (Fig. 2).

A further opportunity to act on the basis of the generic information provided by SACHEM exists at the company’s corporate level. In practice, a whole set of different ontological levels co-exist with different organisational memories. Thus, at the highest level we find the centralised memory arising out of the work of the different communities of practice and IRSID, whereas at the intermediate levels SACHEM’s general knowledge can be redeployed to create a variety of decentralised memories (applicable to the electric blast furnace or to the casting process among other things). These decentralised memories (Apache and Accept) were introduced at the end of 1999 and have benefited directly from pre-existing generic knowledge collected for SACHEM and relating to the steel process (for example, some descriptions of the fluidisation process are very useful in the determination of steel quality and the description of granularity during casting). A representation of the centralised and decentralised levels is provided by the following table (see Fig. 3).

## 5. Conclusion

In our view, the articulation and codification of knowledge in the French steel industry is a manifestation of a new behaviour, driven by the willingness to capture value from knowledge assets, to improve understanding of the knowledge associated with the workings of the blast furnace and to increase the furnace’s productivity and reliability. The firm has benefited from this transfer of knowledge and has, in the last few years, improved its productivity, increased operator reactivity, seen a global improvement in casting quality and a decrease in steel making related incidents. From a long-term perspective, the creation of strategic assets involving the memorisation of most of the company’s know-how is difficult to evaluate in simple monetary terms. The creation of ‘generic knowledge’ is also a strategy of ‘knowledge disclosure’, which prevents the company from losing crucial technical know-how and helps improve its capabilities at different business levels.

In Usinor’s case, experts have now ceased to be the only disseminators of knowledge and have a new part to play in the update and maintenance of existing organisational knowledge. The organisational consequences of this process are not neutral, of course, as they create centralised and decentralised memories, parts of which could be tradable outside the firm. In other words, capabilities have changed: they are now less dependent on the human holders and are anchored to the organisation and its shareholders.

Social context and managerial input play an active role in changing the content of knowledge. Participation, which is essential to the creation of a new representation of the blast furnace, involves renouncing old beliefs (concerning technical events such as fluidisation), once prevalent among different ‘communities of practice’ but also the discovery of new routes for R&D policy. The system relies substantially on the permanent combination of local and generic knowledge for its improvement, as parts of it are revised and updated by adding newly identified causal links between technical events. Tacit knowledge remains essential by preventing the rapid fossilisation of the company’s know-how. As we have seen, entire strands of knowledge, which originally were deemed to defy articulation, have been articulated over time as new causal links between technical events have been discovered. New pieces of knowledge have also been redefined thus increasing the meaningfulness of pre-existing codified knowledge. This tends to prove that the problem of articulation and codification is not likely to diminish over time. Moreover, the likelihood declines further if we consider that translation into different languages in itself transforms the actual knowledge content.

The organisational context provides additional feedback for the general knowledge produced because human beings and machines are not substitutes but complements. This also implies the existence of a new trade-off between local and codified knowledge, as some of the tacit knowledge embedded in the company disappears, while new forms of that knowledge gain currency. This new trade-off is also a route to new associations that lead to a further enhancement of existing empirical know-how and to new insights into the workings of this industry. Consequently, knowledge repertoires and organisational routines are activated differently because new beliefs and new insights have been triggered and new automatisms at individual and collective levels have been implemented.

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