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The complexities of corporate science and technology development: the triple uncertainty analytical framework

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ABSTRACT
In this paper, we introduce an analytical framework – called the Triple Uncertainty (TU) – that casts strong doubt on both the existence of a linear path leading to organisational innovation and the alleged accuracy of most R&D performance metrics. This framework, grounded on both the analysis of field-data and actor-network theory underpinnings, emphasises the importance of a series of uncertainties that pervade the management of techno-scientific projects. According to the TU framework, the management of techno-scientific projects hinges on the choice of mode of organisational coordination. To illustrate this thesis, we analyse in this paper the managerial complexities of a techno-scientific R&D project at Tenaris (a world-leading manufacturer of steel-tubes) whose intended outcome is a computer simulation of a critical industrial process.

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Knowledge production as a non-linear process

A spectre haunts R&D literature. Since the days of Vannevar Bush's *Science: The Endless Frontier* ([1945] 1999), a linear measurable path seems to tacitly associate science and technology development and innovation – the actual generation of novel products or the improvement of processes, in classical Schumpeterian terms. Even though this spectral linear innovation model as such does not actually constitute a matter of academic concern anymore,[1] its premises can still be easily found (under the guise of theoretical infrastructures) in recent work of R&D management scholars.

The linear (tech-push) model of innovation separates – suggesting that this division is possible and non-problematical – techno-scientific knowledge production activities into (a) Basic Research, (b) Applied Research, (c) (Technology) Development, and (d) (Production and) Diffusion (Bush [1945] 1999). To some extent, linearity conveys certainty which is at odds with both the nature of R&D practice and science and technology development.

Dosi, Llerena, and Labini (2005) stated that some scholars transformed the aforementioned linear tech-push innovation model into another (no-less-linear) market-pull model. For instance, Von Hippel (1978, 1985) as well as other market-pull scholars merely reversed the direction of the linear steps to be followed: the lead-user R&D process starts with the lead-users contributions (i.e. the market insight) and also traces a linear path towards the industry.

Thus, it might be useful to ask what makes scholars from different fields speak of innovation as a linear process that can be divided into a sequence of phases. At first glance, the answer is simple: linearity favours or, to be more precise, simplifies (time and expenditure) measurement. A specific amount of successful or unsuccessful new products and a rate of change can be measured. Also, a

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frequency distribution can separate the population of users of a product into lead-users, early adopters and other less engaged users (Von Hippel 1978, 1985). Although these metrics convey measurable certainty, they also leave the (messy) organisational learning black-box unopened. Accuracy and reliability are not precisely synonyms (Mintzberg 1994; Weick and Sutcliffe 2001). Despite the widespread use of all these metrics, the question to what extent an organisation can profit from its techno-scientific R&D activities still remains unanswered.

Tenaris

Tenaris is a world-leading manufacturer and supplier of (seamless and welded) steel-tubes. The company also provides handling, stocking and distribution services for petrol, gas, and other pipeline installations. Tenaris is the largest company of the Techint Group in terms of revenue. The industrial plants of seamless steel-tubes of Tenaris are located in Argentina, Mexico, Italy, Japan, Canada, the United States, Venezuela, and Romania. According to company records, Tenaris produces more than six million tonnes a year of (welded and seamless) steel-tubes and its workforce amounts to 22,500 employees around the world (Source: http://www.tenaris.com/en/AboutUs.aspx, accessed date: 29 September 2010).

The Centre for Industrial Research

The CINI centre (stands for Centre for Industrial Research) is one of the main industrial R&D facilities of Tenaris. This centre is located in Campana, in the outskirts of Buenos Aires, Argentina. A considerable amount of Tenaris R&D initiatives – viz. new product development, the optimisation of existing products, and the optimisation and development of production processes – involve the CINI centre to some extent. CINI projects cover academic areas such as steel metallurgy, computational mechanics, fracture mechanics, and surface chemistry (tube coatings). In addition, the CINI centre literally connects the steel factory and techno-scientific networks.

Metal Forming is the CINI centre area in charge of the mathematical or computer simulations of factory processes. These simulations can predict the behaviour of critical industrial processes[2] (Figure 1).

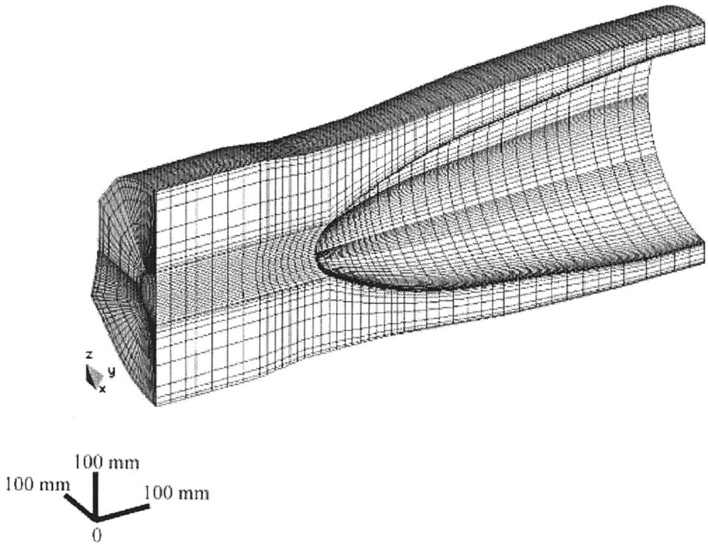
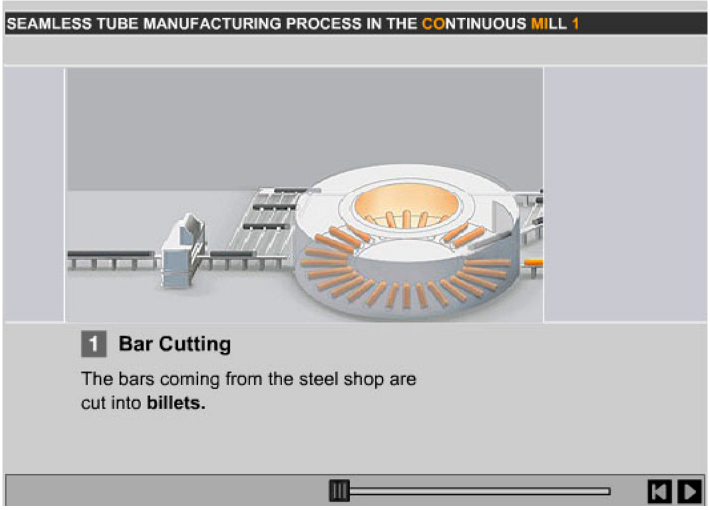


Figure 1. The FEM studies the behaviour of a continuum by dividing it into a mesh of cells. This figure depicts a half-pierced steel-tube (i.e. a stopped bar at the Mannesmann process). Source: Berazategui et al. (2006, 1130).

The piercing (Mannesmann) process

Solid cylindrical bars cast in steel are manufactured out of selected metal scrap, sponge iron, and hot bricket iron. These solid cylinders are cut into billets (i.e. shorter sections of the long metal cylinders) during the second phase of the production process. In turn, the billets enter a 1250-degree Celsius rotary furnace. Once out of this furnace, a rust layer from the heating process is removed. The resulting hot billet is pierced by means of the Mannesmann process which turns solid cylindrical iron bars into a hollow shell (similar to a raw pipe) (Figures 2 and 3).

During the Mannesmann process, each billet is placed between two rolls which, simultaneously, squeeze and rotate the small solid steel-bar. The pressure exerted on the bar produces an internal

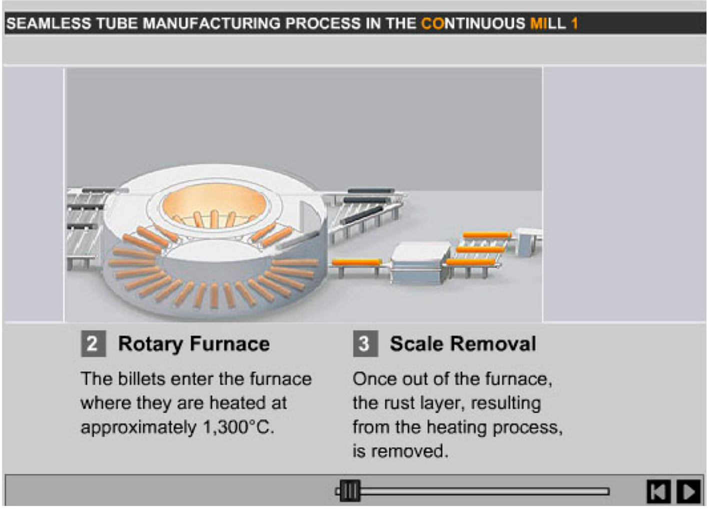


SEAMLESS TUBE MANUFACTURING PROCESS IN THE CONTINUOUS MILL 1

1 Bar Cutting

The bars coming from the steel shop are cut into **billets.**

Figure 2. Seamless tube manufacturing process. Source: http://www.tenaris.com/en/AboutUs/Prod_Proc_seamless.asp (accessed date: 2 January 2007).



SEAMLESS TUBE MANUFACTURING PROCESS IN THE CONTINUOUS MILL 1

2 Rotary Furnace

The billets enter the furnace where they are heated at approximately 1,300°C.

3 Scale Removal

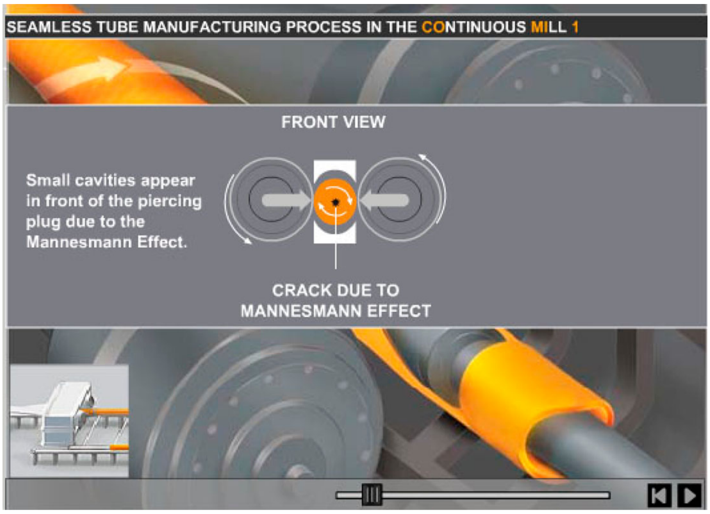
Once out of the furnace, the rust layer, resulting from the heating process, is removed.

Figure 3. Seamless tube manufacturing process. Source: http://www.tenaris.com/en/AboutUs/Prod_Proc_seamless.asp (accessed date: 2 January 2007).

crack (this mechanical process is known as the *Mannesmann Rotary Piercing Process*). This opening at the centre of the bar is formed in before the plug enters the bar as a group of CINI researchers noted in a recent publication (Berazategui et al. 2006). The plug is the end of a rotating spear (or 'piercer' according to the industry jargon) which penetrates into the steel-bar guiding this fracture. This spear does not actually produce the longitudinal hole inside the bar; it just guides a pre-existing hole shaping the internal surface of the future tube. Thus, while the piercer penetrates into the steel-bar, hot material flows along the surface of the plug transforming the billet into a smooth round hollow shell.

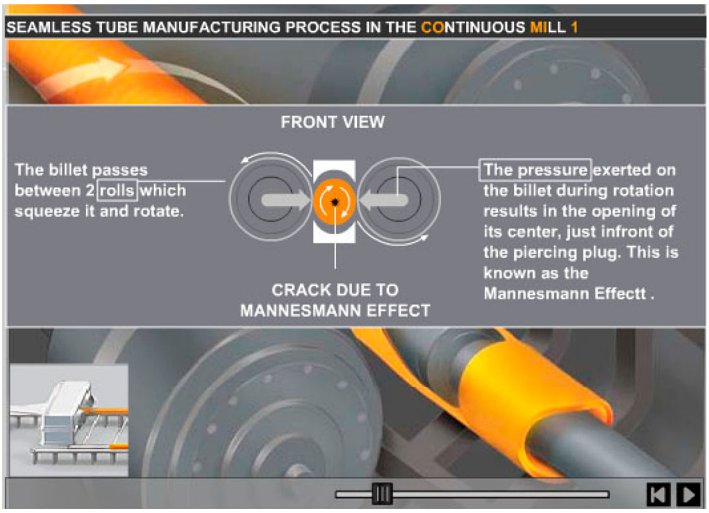
The fact that most of the future mechanical properties of a seamless steel-tube depend on this industrial process stresses the importance of being able to accurately predict the behaviour of the steel during the piercing process (Figures 4–8).

Figure 4. The Mannesmann rotary piercing process. Source: http://www.tenaris.com/en/AboutUs/Prod_Proc_seamless.asp (accessed date: 2 January 2007).



Small cavities appear in front of the piercing plug due to the Mannesmann Effect.

Figure 5. The Mannesmann rotary piercing process. Source: http://www.tenaris.com/en/AboutUs/Prod_Proc_seamless.asp (accessed date: 2 January 2007).



SEAMLESS TUBE MANUFACTURING PROCESS IN THE CONTINUOUS MILL 1

FRONT VIEW

The billet passes between 2 rolls which squeeze it and rotate.

The pressure exerted on the billet during rotation results in the opening of its center, just infront of the piercing plug. This is known as the Mannesmann Effectt .

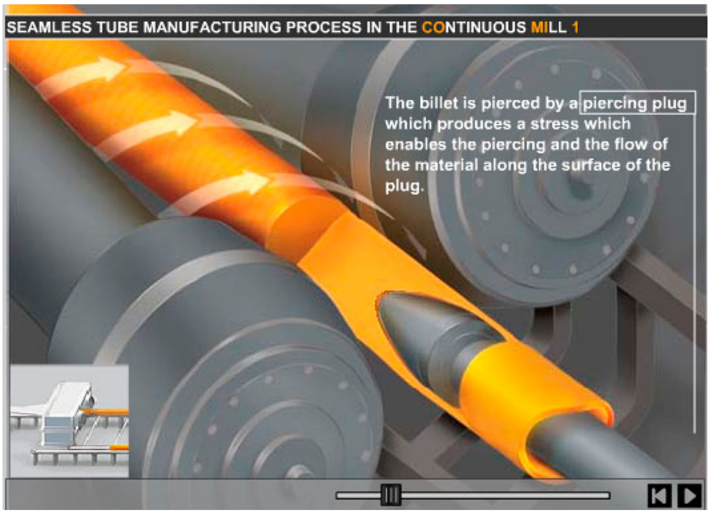
CRACK DUE TO MANNESMANN EFFECT

Figure 6. The Mannesmann rotary piercing process. Source: http://www.tenaris.com/en/AboutUs/Prod_Proc_seamless.asp (accessed date: 2 January 2007).

Methods

Field setting

The first research question guiding this study was *what type of management practice is required to co-ordinate techno-scientific developments?* The identification of three corporate networks involved in R&D at Tenaris and the major relevance of different types of uncertainties were the main results of this preliminary stage. The first research question was later re-phrased into *what type of translation processes (i.e. circulation and transformation*; Latour 2005, 106–109) *do the R&D ideas, the projects, and the fully fledged developments of a highly qualified techno-scientific research centre have to undergo to make a contribution to the emergence of organisational dynamic capabilities?* During the first exploratory phases of this study, the data collection comprised:



SEAMLESS TUBE MANUFACTURING PROCESS IN THE CONTINUOUS MILL 1

The billet is pierced by a piercing plug which produces a stress which enables the piercing and the flow of the material along the surface of the plug.

Figure 7. The Mannesmann rotary piercing process. Source: http://www.tenaris.com/en/AboutUs/Prod_Proc_seamless.asp (accessed date: 2 January 2007).

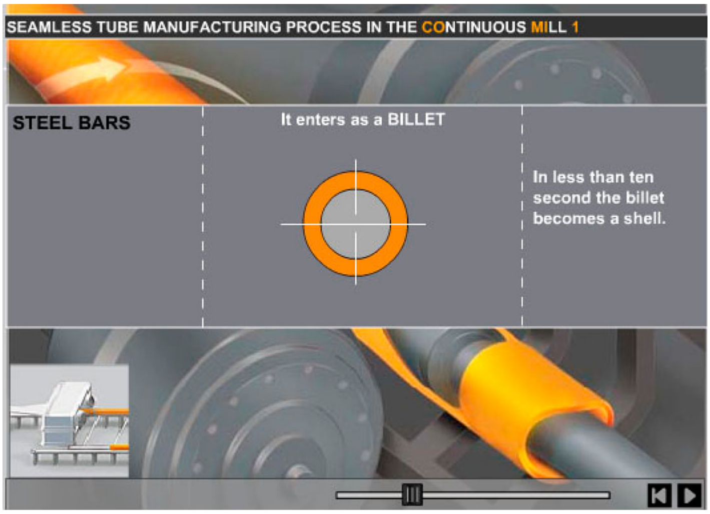


Figure 8. The Mannesmann rotary piercing process. Source: http://www.tenaris.com/en/AboutUs/Prod_Proc_seamless.asp (accessed date: 2 January 2007).

- Narrative interviews with (a) the CINI researchers working on the computational simulation of the piercing process, (b) the potential users of this simulation, (c) CINI researchers working on two other development-projects, and (d) relevant informants for this study who do not belong to Tenaris (ranging from science scholars to researchers who studied either Tenaris or the CINI centre).
- Additional data from: (a) Tenaris institutional material and (b) non-academic publications on Tenaris and the CINI centre.
- A guided visit to the Tenaris industrial plant in Campana, Argentina.
- Attendance to a series of academic seminars of the CINI researchers.

After the first phase of this study, it was decided to focus the analysis on the Mannesmann simulation development-project. This interest on the development of the piercing model came from (a) the fact that many relevant informants of the company classified this project as ‘strategic’, (b) the fact that the project will have no direct market output, (c) the fact that this project is embedded in a corporate research programme, and (d) the fact that a number of uncertainties have to be taken into account in order to manage this project.

Since uncertainty became a major issue of consideration with regard to Tenaris R&D managerial aesthetics, the final research question of this study aimed at identifying and characterising the *sources of uncertainty* involved in techno-scientific R&D management.

Data analysis and interpretation

All the transcripts from the interviews with CINI researchers, potential users of the simulation, and decision-makers were transcribed in full and discursively analysed (Czarniawska 1997, 1998; Grant et al. 2004) and codified using the software ATLASti. Approximately, 12 hours of recorded interviews were analysed.

Even though three organisational networks are going to be presented in this paper, it is worth clarifying that most of the data collection and analysis drew on the interviews with members of the strategic (R&D decision-makers) and the techno-scientific networks (CINI researchers). Two potential users of this simulation were interviewed as well. Since these potential users are not in charge of the development of this project and the simulation of the piercing process is still an unfinished project, only little data from these last interviews was of use to the writing of this paper.

Both the three networks analysed in this paper and the passage points between them are described in linear fashion. The circulation of R&D initiatives within the Triple Uncertainty (TU) can vary from clockwise to anti-clockwise depending on the specific project we want to analyse. Since the order of the written text is linear, it will be up to the reader to understand the winding order of the proposed analytical framework.

As all the interviews and most of the analysed documents are in Spanish, all the quoted excerpts were translated into English. The preservation of the original meaning was privileged rather than a word-by-word correspondence between languages.

The triple uncertainty

It is worth clarifying that, in addition to field-data, the theoretical insight of the translation process (Callon 1981, 1986) lies at the heart of the TU. In contrast to the traditional diffusion (linear) process (Latour 1987), which usually takes the results of a project and the agency of the so-called inventor as the relevant departure points to address innovation, uncertainty is part and parcel of the less predictable translation process. A quick glimpse into seminal science and technology studies can highlight that uncertainty pervaded, for instance, the failure of the researchers to predict the anchorage of the scallops at St. Brieuc Bay (Callon 1986), the difficulties to black-box the diesel engine (Latour 1987), the configuration of insiders and outsiders in knowledge networks (Latour 1991), and the emergence of Portuguese heterogeneous (*avant-la-lettre*) engineers who were able to co-ordinate and stabilise (to some extent) an entire network of long-distance navigation (Law 1986). Since no social group can be regarded as a passive agent and development-projects have to undergo a number of transformations in order to become a black box, the strength of any development-project hinges on the uncertain set of associations that holds the network together. As Latour (1987, 142) states, we are 'never quite sure which association is going to hold and which one will give way'.

The TU, at degree zero, is a descriptive analytical framework of three networks (and the passage points between them; Serres 1991) involved in the dynamics of R&D management at Tenaris. These networks are (a) the R&D strategic network, (b) the techno-scientific network, and (c) the industrial plant one. These three networks do not constitute clear-cut bounded regions (Mol and Law 1994): far more important than the predictable sequential path of development-projects is the interactive journey across these three networks (Callon and Laredo 1992; Van de Ven et al. 2008) following the shifting alliances and the different forms of network coordination between heterogeneous actors. Having specified the non-linear trajectory of this journey, it is worth to highlight the importance of feedback signals (Kline and Rosenberg 1986) as well as feedbacks and feed-forward loops (Rip and Schot 2002) between the three networks. According to this line of enquiry, knowledge is not a homogeneous well-defined commodity that flows unchallenged from the organisational strategists through the R&D lab towards the industrial but ideas that needs to be constantly re-designed in order to be of use to its internal users. Even though the TU permits to differentiate these networks to some extent, the management of the Mannesmann simulation and organisational learning strongly hinges on network coordination (*qua* collective minding; Weick and Roberts 2001; and distributed cognition; Hutchins 1995). Thus, akin to the actor-network perspective, collective minding addresses a structuring process (cf. Latour's assembling; Latour 2005) instead of departing from a ready-made structure of three networks.

By and large, decision-makers pertain to the strategic network, CINI researchers to the techno-scientific network and industrial plant workers to the industrial network. However, a number of cross-border ontologies can be found at Tenaris. For instance, there is a decision-maker who has also been engaged in the writing of scientific papers on the piercing simulation, and there is also an industrial plant worker who collects day-to-day data for the improvement of the piercing

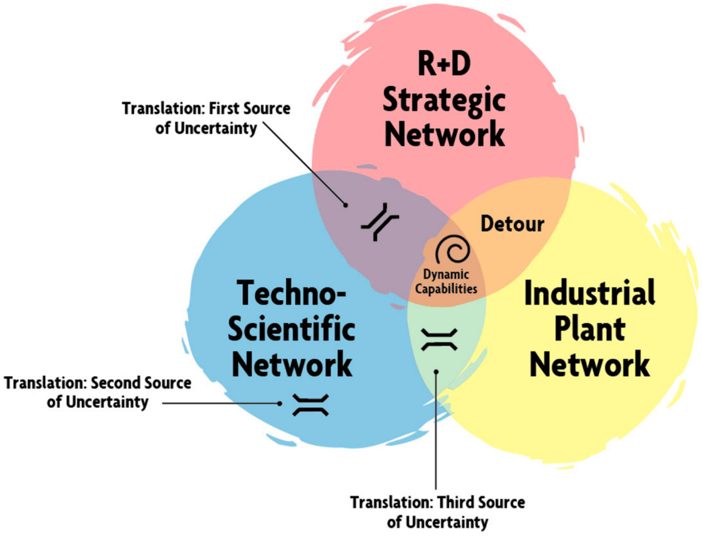


Figure 9. The networks of the TU.

simulation. Thus, the same actor can play more than one role within the three networks of the TU. In addition, network coordination hinges on a number of boundary objects (Star and Griesemer 1989) and obligatory passage points (Callon 1981, 1986) that can be found at the intersections of the three networks (Figure 9).

In the specific case of the simulation of the piercing process, although a reasonable degree of consensus could be verified – across networks – in connection with the strategic intent behind this simulation, the nature of the final technological outcome and the potential organisational capabilities stemming from this development project still constitute matter of great organisational debate. It is worth to clarify that from the beginning of this R&D project, Tenaris R&D decision-makers never envisaged this simulation to run on line with the steel-tubes production orders (as an industrial plant managerial device). Industrial work is usually hectic and it will be too much of a hassle for the operators to handle a 500,000 degrees of freedom simulation in conjunction with their day-to-day industrial duties. While sketching this simulation accuracy (a clear picture of the dynamics of) the plastic deformation of the steel during the Mannesmann process was privileged rather than operational on line support for the steel-tube industrial process. Although the outcome of the simulation can be of great use to the industrial plant (e.g. for the set-up phase of the machines, order planning activities, and designing a new product with a rare type of steel), industrial plant users will only be able to use a limited (abridged) graphic inter-phase of the results of the simulation (e.g. a set of coloured maps where the user can change only a limited range of parameters). From the first seminal idea, it was always stipulated that running this simulation (once stabilised) will always require the CINI researchers input in order to construct these graphic inter-phases (or coloured maps).

The notion of 'uncertainty' involved in the TU analytical framework at the very least stand for: (i) the often contested meaning/s of a specific development project between networks with regard to, for instance, strategic importance, academic depth, and potential industrial benefits, (ii) the science in the making/ready-made science dyad (Latour 1987) across networks (e.g. one of the tangible products of the piercing simulation are maps that are often used to ground industrial plant network decisions but, at the same time and as noted above, the industrial plant network will never become an autonomous user of this simulation), and (iii) the fact that passage points between networks always entail some sort of transformation of the circulating object: strategic insight need to be transformed into clear-cut projects and computer code needs to be transformed into coloured maps in order to gain access into the industrial plant network.

It is worth noting that a deep awareness of the three sources of uncertainty of the TU does not turn, for instance, the outcome of R&D investment any more predictable. The TU does not prescribe any set of steps to be followed in the vein of a best practice. Nothing can eradicate uncertainty; there is actually no remedy for this condition. Nevertheless, *the TU can contribute to better understand a series of tensions involved in the management of techno-scientific R&D projects*.

Last but not least, not all the R&D initiatives at Tenaris stem from science and technology development, that is, there is also a possible passage point connecting the R&D strategic network and the industrial plant one. This 'detour' from science and technology development is not going to be analysed in this article.

The R&D strategic network

'Strategic' here stands for (R&D) organisational 'politics' (Figure 10). Therefore, the strategic network elaborates an R&D political order by problematising – and sometimes, solving – a number of organisational tensions. Even though the strategic network elaborates the R&D agenda, the network building effort (Van de Ven et al. 2008) for any development-project does not necessarily begin within the strategic network.

Most of the interviewed respondents agreed to label the computer simulation of the piercing process as 'strategic'. A considerable part of the 'strategic' character of this project stems from the fact that all the Tenaris industrial plants around the world use a similar piercing technology. It is

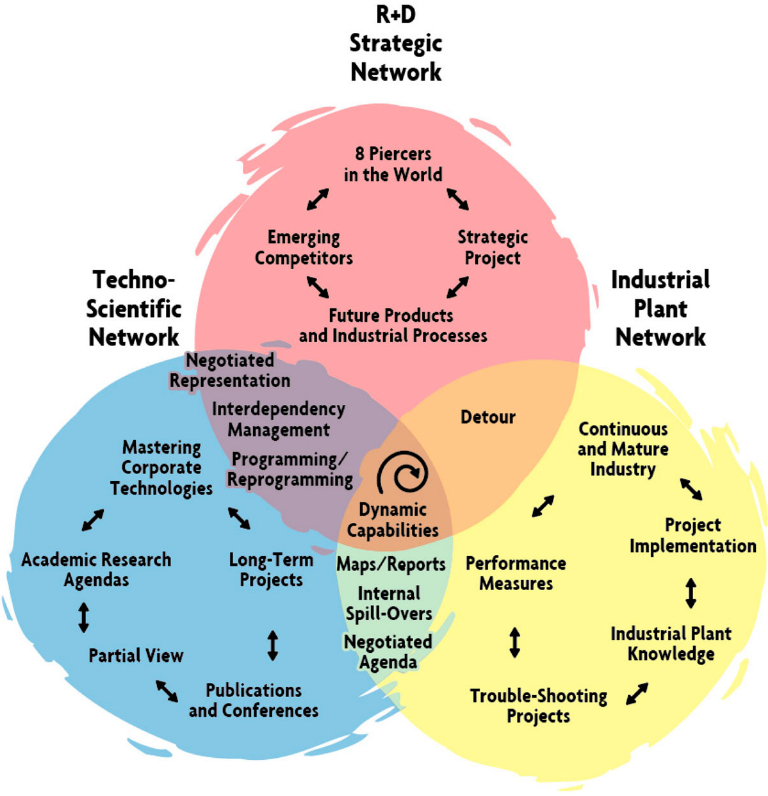


Figure 10. The TU.

envisaged that by changing the input data, this simulation will be able to unproblematically travel from the Argentinian plant to Dalmine and Mexico. In fact, the Techint Group CEO often highlights the importance to simulate the Mannesmann process. In the following excerpt, an important R&D decision-maker of the CINI centre comments on the views of the CEO.

> One of his [the CEO's] arguments stresses that: […] 'We have seven or eight *piercers* around the world, it can't be the case that we don't have a [computer] model [to predict the behaviour of this process].' This [development of a common model] encompasses all the different piercers at Tenaris.

Hence, Tenaris decision-makers at the strategic network agreed that being able to simulate the piercing process of geographically distant plants which have been constructed at different times but following similar architectonical and technical principles constitutes the main potential advantage of investing in this type of development-project.

Furthermore, according to a CINI decision-maker, considering that, at present, most of the Tenaris plants work 24 hours, 7 days a week 'using the plant as a laboratory is just madness'. Therefore, the nature of a continuous industry working at the top level of the installed capacity enhances the organisational importance of an accurate predictor of the piercing process.

First source of uncertainty: which are the lines of techno-scientific enquiry to be explored?

Within the intersection between the strategic network and the techno-scientific one, an obligatory passage point (Callon 1986; Serres 1991) can be found. A number of feedbacks and feed-forwards loops (Rip and Schot 2002) can take place at this junction of the TU. Unlike resource allocation techniques (in the vein of neoclassical economics), this source of uncertainty addresses how the interplay between the R&D political insight referred above and the R&D capabilities of the techno-scientific network can be translated (i.e. circulate and transform) into a number of lines of science and technology enquiry and fully fledged projects, that is, researchers do not work with strategic imperatives but with time-schedules, lab assignments, a series of tests to be performed, and so on and so forth. In the case of the piercing simulation, the aforementioned strategic insight literally met the academic interest of a few CINI researchers who were able to pursue well-regarded academic careers based on metal forming research. It is fair to point out that not all the projects and lines of enquiry of the CINI centre are equally attractive to the researchers. For instance, intellectual property protected research will find it extremely difficult to be granted company authorisation in order to get published in academic forums.

Therefore, the conformation of the ensuing R&D project portfolio requires stabilised versions of research plans, allocated resources (e.g. some projects of the CINI centre entailed building laboratories and buying equipment) time-schedules, organisational priorities, and criteria to demarcate research areas. Once stabilised, the R&D project portfolio plays the role of an obligatory passage point. Project activities of the techno-scientific network have to stick to this fixed external environment of a project (Vissac Charles 1996).

While talking about the non-linear path of science and technology developments and the difficulties to frame projects into a timeline, an R&D decision-maker pointed out:

> The problem of this industry is that you always have to stick to a time-schedule. Having done that, you have to be sensible … […] I mean, in the industry you schedule everything, which doesn't exclude re-scheduling. [*Laughs*] No, no, no, I am being serious. I am serious. I mean, it doesn't exclude … [We have] sensible people: you can re-schedule but you can never say that you don't know when you are going to finish.

This excerpt identifies one of the main difficulties to 'frame' R&D ideas into corporate vocabulary. Another major difficulty to co-ordinate a business agenda vis-à-vis a series of techno-scientific projects stems from the forking and interrupted paths of science and technology developments. More often than not, the expected results bear little or no resemblance to the actual results of R&D projects. Any R&D academic initiative of the CINI researchers will have to undergo decision-makers validation. Hence, the beginning of the TU winding path can also be found within the boundaries of the techno-scientific network.

Balancing a science and technology project portfolio entails a thorough management of the potential, and often hidden, *knowledge interdependencies* between projects. For instance, having successfully implemented a 'furnace project' – the results of this project standardise the temperature of the outgoing billets from the rotary furnace – a few years ago permitted to simplify the development of the piercing process simulation by eliminating input data variety. Thanks to the furnace project, all the incoming billets enter the Mannesmann process at exactly the same temperature. The TU highlights the importance of *interdependency management* – innovations are the result of a complex knowledge patchwork or assemblage (Mol 2002; Law 2004) and not the outcome of a single project as R&D mainstream literature seems to suggest. The furnace project results can serve as a boundary object for a series of other R&D initiatives, that is, even though these other projects do not have anything to do with thermal equation development, R&D project portfolio planning has to take into account the emergency of these boundary objects which have the potential to coordinate distant academic worlds (Vissac Charles 1996). This insight strongly contradicts the clear-cut distinction that separates project failure from success.

Only occasionally can a CINI project produce a fully fledged product. Rather, interdependency management emphasises the fact that each project is only a *contributing factor* to improve an industrial process or to devise a new product. In particular, the simulation of the piercing process project will neither improve this process nor devise any new products per se. Nevertheless, a stabilised simulation of the Mannesmann process can contribute to facilitate the development of new products and their ramp-up phases.

Finally, more often than not, techno-scientific work that would not probably pass publication standards (this is not the case with the piercing simulation) can prove to be extremely useful to develop organisational dynamic capabilities by easily travelling from a specific network to the rest of the TU. Likewise, sometimes, a major scientific development or a highly qualified article in a prestigious journal can be of no use whatsoever to the strategic and the industrial networks. *This apparent paradox lies at the heart of the passage point between the strategic and the techno-scientific networks*.

The techno-scientific network

Most of the time, the lines of R&D enquiry are tied to the academic careers of the CINI researchers. Therefore, personal academic projects have to comply to some extent with corporate ones. For instance, the main topics of the Ph.D. theses of three of the heads of the CINI technological areas were agreed with the company management.

By and large, CINI researchers portray themselves more as academics than corporate members. While interviewed about their work to model the piercing process, two researchers of the CINI claimed to be 'researchers who don't use canned software'. This self-perception statement hints the insight of Tenaris R&D policy. As one of them pointed out,

> That's the most important question: 'why didn't you search for a year to choose the best available software [to simulate the piercing process]. You buy it and … That's it!' I think that's the great debate. We neither bought canned software in this area nor in Fluids … And the great debate is if you are going to have a research centre with researchers or with canned software users. […] I've been to [a steel company in Brazil] and they don't even dream about this. The guys over there use canned software: they know much more about the results they want to get than about the mathematics behind the results, which they don't really care about. Works like a black-box: 'I throw the data in and then … ' They're [i.e., the Brazilians] actually good at assessing if the results they obtain are good or not.

This scientific expertise of the CINI researchers is in line with the organisational R&D aesthetics of Tenaris and the Techint Group, that is, being able to understand at a corporate level the intricacies of the techno-scientific developments the company funds.

This particular R&D aesthetics was also translated into the corporate management of the working hours. CINI researchers are allowed to work up to an 80 per cent of their working hours in academic (personal) research-agendas. As a CINI decision-maker noted,

> It's a complex issue. I am sure that if I tell them tomorrow 'well, guys, private [research] agendas are over and now we'll transform ourselves into a company which measures time thoroughly … Like in Engineering … In Engineering every day you enter [the place] you write down how did you use your eight or ten daily hours. You state that in a card.' If we move towards a control of that kind, I know that, of all the people we have here, 20 or 30% will leave. Then, you think 'well, that 20 or 30% is not going to be taken from the base [of the structure]; it's [actually] going to be the upper crust of our research team … '

In addition, CINI researchers work is often scheduled taking into account publication and conference dates. Also, a small proportion of the CINI researchers belong to CONICET (the Argentinian Research Council). Therefore, company duties can sometimes be in tension with the regular academic assessments the researchers have to face.

Second source of uncertainty: are the development projects going to produce any results?

The messy process (Law 2004) surrounding most science and technology developments is often at odds with the neat standards of the industrial world. Therefore, successive versions of this computer model aimed at the stabilisation of a black-box in order to be of use to the Tenaris industrial plants. Each provisional version of this simulation offers a technological *partial view* (cf. Latour's oligopticon as opposed to the megalomaniac all-seeing panopticon; Latour 2005). For instance, the current shape of the CINI model is able to simulate the plastic deformation of the steel during the piercing process but it remains unable to predict the wear of the tools involved in the piercing process. A coefficient that compares the amount of piercing plugs used in the process and the amount of semi-elaborated tubes is an important metric to assess plant performance. An accurate wear estimation of the piercing plug constitutes an important issue in both the business and the industrial-plant agendas. As one of the researchers in charge of the simulation of the piercing process pointed out,

> In our [computational] model, we represented best the physics of the plastic deformation of the material [using the FEM simulation]; however, what is going on, for instance, at the tribological level … What is going on in the inter-phases … [the border of the cells of the FEM mesh]. We roughly modelled that: let's say, it's a complex process and we used a simple model for that. […] Basically, to measure how the plug wears … In the model the tools don't wear. It [i.e., the computational model] doesn't include a wear model and if I have to incorporate that, the model will turn quite difficult. It will be extremely difficult to do it …

Annually agreed agenda meetings with R&D decision-makers construct both the evolving shape and predictable power of this type of simulation as well as the envisaged regime of utilisation of these developments. To begin with, R&D developments can be regarded as the outcome of successive phases of a *negotiated order of representation* akin to the interactive vein of the chain-linked innovation model (Kline and Rosenberg 1986). Therefore, all the three R&D networks of the TU actually construct the aforementioned *partial view* of a computer simulation out of continuous negotiation.

As noted in a previous excerpt, the neat corporate phases of development of a project do not actually echo the very nature of science and technology work. Although modelling the wear of the plug constitutes a relevant issue in both the business and the industrial agendas, the incorporation of such element into the simulation seems to be impossible given the development path the CINI researchers took in agreement with the company management.

Most of the annual academic milestones of the simulation of the Mannesmann process can be found in the articles the CINI researchers published (Dvorkin et al. 1997; Cavaliere, Goldschmit, and Dvorkin 2001; Berazategui et al. 2006).[3] Successive associations and substitutions of theoretical and empirical modelling 'approximations' (viz. theoretical developments, experimental results and tests)[4] were required to travel from one academic milestone into another. Given the progressive association of eclectic 'approximations' to this industrial phenomenon, the piercing simulation can be regarded as a knowledge patchwork (Law 2004). The management of this second source of uncertainty aims at the progressive stabilisation of this evolving patchwork of modelling approximations.

Third source of uncertainty: how will it be possible to implement projects grounded on techno-scientific research?

Many possible implementations (i.e. interactions with the final users) stem from a techno-scientific project. A CINI researcher mentioned that the interaction with the potential users of the piercing simulation evolved from the standard reports – the most conventional means to coordinate developers and users. A researcher characterised the inter-departmental relationship with the potential users at the plant.

> We generally give them maps, then in that map (which resembles topographical maps) the variables are painted using a colour-scale. They can say 'if what is going on here interests me I can densify the scale to see more here and less there'. Well, they can do that type of analysis on their own. We are beyond the 'report era'; reports stay [only] as managerial reports but not as reports of technical results.

This interactive loop (Kline and Rosenberg 1986) involving the CINI researchers and the industrial plant-engineers produce maps (grounded on plant-data) which can be of use to better understand the behaviour of the piercing process. It is worth noting that, even though plant-engineers praise the industrial potential of the Mannesmann simulation, at the time being, the Mannesmann simulation is still regarded as an unfinished project. This computer model is yet to be stabilised in order to be of use to a continuous industry. The coloured maps can be regarded as a preliminary attempt to black-box (Latour 1987) this simulation by transforming plant people into configured users (Woolgar et al. 1998).

At this stage of development, the computer model of the piercing process deals with no less than half-a-million degrees of freedom that needs to be resolved in an approximate way. Therefore, running the simulation on a computer can be extremely time-consuming. In order to enrol plant users into this technology, a new equipment was purchased to speed up the researcher-user interaction. Hence, simulation results can better match the hectic rhythm of the industrial plant.

This second passage – between the techno-scientific and the industrial-plant networks – states that *a major techno-scientific achievement* (i.e. a relevant advancement in a knowledge field) *does not necessarily entail a major industrial achievement and vice-versa*. For instance, many academic achievements surrounding the construction and assemblage of the Mannesmann simulation (e.g. the aforementioned academic papers) might not produce a potential reduction in the amount of scrapped tubes.[5]

The industrial-plant network

Having sketched most of the TU we can still ponder, what will be the main contribution of this piercing simulation into the industrial world? As previously noted, the mechanical properties of a seamless tube partially depend on the chances to be able to accurately predict or simulate the behaviour of the piercing process.

Grounding plant management (e.g. the set-up of the machines and the trial and error tests mentioned of the excerpt) on any predictor – even a weak one – of the piercing process behaviour is better than using past industrial records and factory heuristics. In addition, being able to determine the exact location of the original hole-formation (the Mannesmann Effect) has an impact on the industrial working conditions and the lifetime of the piercing tool (the spear) involved in the process.

By and large, three different industrial results stem from the Mannesmann process. Provided that the hole-formation starts too early (before the plug enters the blank-tube) the inner material of the blank-tube can rust. These defective tubes are often scrapped. On the other hand, if the hole-formation starts too late the plug can suffer accelerated wear (the plug would be actually penetrating

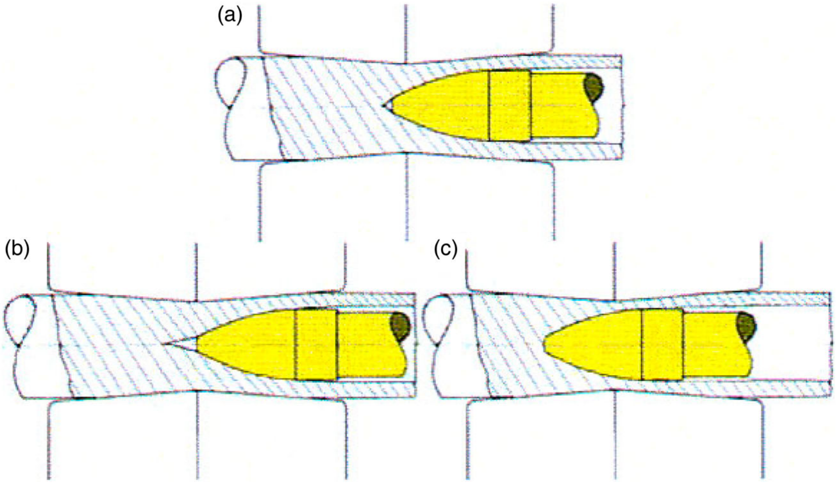


Figure 11. The importance of the Mannesmann process. Source: Ceretti, Giardini, and Brisotto (2004, 2).

into a steel-bar with no internal fracture). As noted in Figure 11, the 'optimal working conditions' of the last quotation refers to the 'type a' tubes only.

One of the interviewed potential users of the piercing simulation (the most involved with the project) was only in charge of collecting data through semi-elaborated scrapped tubes. These scrapped tubes are thoroughly measured in order to progressively assess the accuracy of the simulation. At the time being, the potential users of the simulation ignore the current status of the simulation although they are aware of some of the potential organisational advantages stemming from this project.

Inside the black-box of knowledge production

Unlike most of the perspectives reviewed in the first section of this article, the TU emphasises the importance of de-centred collective minding (Weick and Roberts 2001; Cooren 2004) and distributed cognition (Hutchins 1995) in order to come to grips with the winding path that leads to techno-scientific developments involving heterogeneous organisational actors (Callon and Laredo 1992). Although the analysed simulation has not been implemented yet and, therefore, little user interaction (the industrial plant network) has been incorporated into this development project, a few conclusions can be drawn from the analysis. The real value of the piercing model simulation cannot be assessed correctly at this early stage of the progressive implementation process – only the previously mentioned coloured maps account for a tangible outcome of this simulation so far. Even though little measurable economic impact comes from this simulation at this stage of development, Tenaris supported (in both financial and political terms) this project over the years since most of the company interviewees still believe that this simulation might engender a new generation of dynamic capabilities.

According to the TU insight, learning stands for joint co-ordinated action (Cooren 2004) and involves a few organisational networks and a series of relevant feedbacks between them (Kline and Rosenberg 1986). No network actually masters the TU or controls its results. Since network coordination became an issue of utmost importance to deal with the uncertain R&D landscape, a number of obligatory passage points and boundary objects (Vissac Charles 1996), for example, an R&D project portfolio or specific equipment that improves and modifies the developer/user interaction, play a stabilising role with regard to network co-ordination. Thus, dynamic capabilities are the outcome of network interaction than the direct result of building the best R&D centre, and hiring the best R&D decision-makers or the best industrial implementators. The TU actually permits to trace R&D knowledge production processes by following the circulation of a development-project through the three networks.

The TU signals that R&D management has to take into account (a) hidden academic and process interdependencies between development-projects, (b) the heterogeneous and difficult to measure contributions (evolving partial views) of these projects, (c) the uncertain (and non-linear) development paths of these projects, (d) the blurred boundaries separating techno-scientific failure from success, (e) the required co-ordination among three different agendas, and (f) the co-existence of science and technology knowledge vis-à-vis other types of knowledge (industrial and business knowledge in our research study). Most of these considerations seem to suggest that a vast uncontrollable distance separates techno-scientific knowledge production from the emergence of corporate dynamic capabilities or, the more vivid, new product and processes. However, it is still worth to pay the price.

Notes

1. The article of Godin (2006) 'The Linear Model of Innovation: The Historical Construction of an Analytical Framework' is one of the very few articles which recently addressed the issue. Also, the Argentinian journal *Redes* (14) published an entire Dossier devoted to the linear model in 1999.
2. The FEM (Finite Element Method) is the analytical tool the CINI researchers used to simulate, for instance, steel deformation. By using the FEM (widely known for car-crash simulations), a steel bar can be divided into a mesh of small cells. This computer technique analyses in-depth the behaviour of each cell while deformation takes place.

   Thanks to the FEM, it is possible to conclude from a specific deformation of a material the type of force or tension that was exerted on such material.
3. The simulation of the CINI researchers belongs to the numerical methods field. The CINI computational model evolved from a two-dimensional model into a three-dimensional one and uses an Eulerian innovative approach to study deformation.
4. Although it was tempting to call 'theories', these lines of enquiry to simulate a process, the CINI researchers corrected this other terminology in a couple of opportunities. The researchers called them 'modelling approximations'. These approximations combine, at the very least, raw theory (mainly physics), experimental results (e.g. tests on semi-elaborated bars), mathematical or numerical ways of modelling (like the FEM) and tests on a small-scale replica of the industrial piercer (called 'experimental simulator'). All these modelling approximations contribute somehow to ground and improve the simulation of the industrial process.
5. As part of this negotiated order of representation, one of the CINI researchers pointed out that sometimes he finds it difficult to explain to plant-engineers his anxieties and academic interests. At the industrial plant, there are a great deal of processes that 'technologically work', although no one really knows why. It was actually difficult for him to problematise an issue that no one at the plant considered as problematic.

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