1

Historical Approach to Chemical or Process Engineering

Today we live in a world of what Georges Friedmann calls Sunday drivers – people who have never opened the bonnets of their cars, people for whom functioning is not merely the function of things but also their mysery. (Baudrillard 2005)

Thus, in France, the development of chemical engineering education owes nothing to industrialists. (Grossetti 2004)

The industrialist utopia promised us that the development of the forces of production and the expansion of the economic sphere would liberate humanity from scarcity, injustice and misery […]. It means we must find a new utopia, for as long as we are the prisoners of the utopia collapsing around us, we will remain incapable of perceiving the potential for liberation offered by the changes happening now, or of turning them to our advantage by giving meaning to them. (Gorz 2011)

After Chapelier's Law, the 19th Century engineer set the manufacturing process in motion. It eradicates artisanal practice and the knowledge system that accompanies it. For the skills of companions, transmitted from master to disciple, teaching with intuition and sensitivity, it substitutes the rationalist approach of applied science. (Gaudin, quoted in André 2019, p. 65)

The scientification of processes comes from this desire for efficiency and the awareness of the implications of science integrated into the company's know-how. (Hers 1998)

Old technology imposes on new technology its own standards of economic valuation, developed by reference to its natural qualities, thereby introducing a kind of bias in the exercise of economic calculation. (Foray 1992)

The principle of reduction ignores that the whole has qualities, which are not found in the parts. (Wolf 2009)

Science is what the father teaches his son. Technology is what a son teaches his father. (Serres 2017)

It is science whose human ends are affirmed and systematically sought. The technician, the engineer in his current practice, does not use any truth that does not come from a particular science, but it is up to him to make an original synthesis of it. There is technique only where there is purpose. (Berger 1962)

What a technique lacks is not the ability to discover the solution to its problems, but the ability to generalize its solutions. (Canguilhem, quoted in André 2019, p. 93)

According to Isabelle Stengers (1989), chemists, throughout their history, have questioned their identity and their specificities with regard to physics… (Vinck 1999)

The more a commercial company gets media coverage, the more it must devote a significant part of its activity to the production of demand, by investing ever greater resources in attention-grabbing devices. (Citton 2014)

The individual serves the industrial system not by supplying it with savings and the resulting capital; he serves it by consuming its products. On no other matter, religious, political or moral, is he so elaborately and skillfully and expensively instructured. (Galbraith 1967)

Modeling is constructed as a point of view on the real. (Le Moigne 2013)

[In 1870] spiritually chemistry was a complicated physics with surprises. (Malisoff 1941)

1.1. Introduction

> The first is the invention of the distinction between the basic and applied sciences, a distinction that engineering sciences undoubtedly made the mistake of endorsing in the 19th Century, at a time of their extraordinary growth: they condemned themselves to being nothing more than ancillary sciences, humble servants in charge of applying knowledge developed elsewhere and by others: how could they participate in this formidable undertaking of invention rather than discovery, of construction rather than identification, of conception rather than analysis, which characterizes any scientific activity of elaboration of critical and prospective knowledge. (Le Moigne 1993)

Industrial chemistry, which was current at the beginning of the 19th Century, is a body of knowledge that corresponds to the control of the ways of obtaining a marketable product, raw materials and their supply methods, as well as the by-products, and even the economic and environmental performances that allow for profitable manufacturing. According to Bousquet, industrial chemistry is essentially descriptive in nature:

> Industrial chemistry is therefore a body of knowledge enabling the chemical engineer and/or researcher concerned in various capacities by the process industries to know which are:
>
> – the obtaining routes (which are most often unitary process or operation sequences);
>
> – the obtaining routes (which are most often sequences of raw materials;
>
> – the production routes (which are most often by-product chains and the economic and environmental performance that allow the production of chemical industry products. (Bousquet 2008)

> This new chemical industry was extremely profitable, but difficult to “drive”, as it was then called, and extremely polluting… But with the rise of modern chemistry, chemical manufacturers felt the need to protect their industry, which they said was a victim of obscurantism and prejudice when it was in their eyes the jewel of the French economy and, of course, harmless. It was under their pressure that the decree of 1810 on insalubrious establishments was adopted, the purpose of which was not [...] to protect public health, but to protect industry or, more precisely, to define precisely its rights and those of its neighbours. (Massard-Guilbaud 2004)

For Fressoz (2012), chemical manufacturers were well aware of the risks they posed to their workers and the environment as a whole. But they had chosen to consciously ignore it (Jarrige 2012):

> The safest way to be discredited is to claim that absolute security is offered, that a system is under control when it is not, in short, to idealize a situation. As soon as the people to whom this is addressed realize the slightest gap between discourse and reality, everything collapses. As we have seen, this is the explanation for many crises. These are crises of "disillusionment". (Hirsch, quoted in André 2019, p. 100)

Thus, in Paris and its suburbs (at the time), ammonia was produced in Saint-Denis and Vaugirard by treating animal waste from the capital with hydrochloric acid and calcium sulfate (local gypsum), producing particularly harmful foul odors (Barles *et al*. 2009). "Soda ash manufacturers have been forced to direct acid fumes into underground tunnels, or lose them in deep wells, so as not to burn crops, and inconvenience neighbours with clouds of muriatic acid fumes rising from their stoves" (Chaptal 2009). This has resulted in gains for some and a brand image that is still difficult for the chemical industry to get rid of. Indeed, according to Da Lage *et al*. (2008):

> Fear mobilizes both an individual dimension as an intimate experience, and a collective one, shared with others in the public space, because fears are socially staged. Thus, the more recurrent and the less recurrent fears provide information on the representations and values of our contemporaries. Moreover, our societies seem to be developing a kind of "fear addiction" in an aseptic universe. The search for thrills becomes the rule for an intensification of the relationship with the world or for self-assertion. From then on, we "play at being afraid". In this respect, fear constitutes a negative intangible resource, even if it only appears as such in a hollow.

For example, the Leblanc process, which was the result of the blockade of the French empire under Napoleon I and the effects of deforestation, made it possible to produce soda ash in the Marseille region. Sodium carbonate used to come from plant ash (algae or *Salsola soda* and other saltwort plants, like samphire) or wood combustion ash (rural application) or natural sodium carbonate deposits (e.g. Egyptian natron). "In 1783, the Academy of Sciences offered a price of 2,400 pounds to anyone who found a way to obtain sodium carbonate from sea salt. The solution was found in 1789 by the French chemist Nicolas Leblanc after a research project initiated in 1771." According to Wikipedia (2018), the industry was operational in 1791.

According to the same source and Perrin and Scharff (1993), the Leblanc process was based on the following three chemical reactions:

– hot sulfuric acid is mixed with sea salt to produce sodium sulfate and chlorine gas (often discharged into rivers) according to:

$$2\ NaCl + H_2SO_4 \rightarrow Na2SO4 + 2\ HCl \text{ (hot reaction)}$$

– reduction by charcoal mixed with sodium sulfate (θ > 950 °C, with, according to Guillet (1908), variable qualities depending on the distribution of heat in the furnaces, but consumption exceeding 0.5 kg of carbon per kg of sulfate):

$$Na_2SO_4 + 4C \rightarrow Na_2S + 4\ CO \text{ (toxic gas) and } Na_2SO_4 + 2C \rightarrow Na_2S + 2\ CO_2$$

– calcination of sodium sulfide to produce sodium carbonate (θ > 950 °C):

– $Na_2S + CaCO_3 \rightarrow Na_2CO_3 + CaS$

Calcium sulfide (CaS) was, at the start of the process, released into the environment and hydrochloric acid was, in France (but not in the United Kingdom), recovered. When reduced, this sulfide was used to produce sulfur. The sodium carbonate thus produced, soluble in water, can be recovered by washing with water and then evaporating the water. These various operations require a variety of equipment such as chemical reactors, mills, mixers, separators, contactors, purifiers (see, for example, Millet 2008), material transport, and storage. These elements will be described in chemical engineering as unit operations constituting, in a way, parts of a mechanic for the realization of a global process, applied to a given transformation. Indeed, in this example, we find most of the tools still in use in the chemical industry today. However, as a result of an inductive approach, the optimization of local processes in economic, environmental, etc. terms was not the priority. Moreover, the high cost of the product made it possible throughout the 19th Century to maintain rural activities based on processes for using ash from wood combustion.

With the Solvay process, this situation changes. Called the "ammonia-soda" process, it was developed in Belgium in 1863 (then in 1873 in Dombasle in Lorraine thanks to the simultaneous presence of sodium chloride and calcium carbonate) and is still used today. The process is simpler, less expensive than the Leblanc process and is at a pivotal time in industrial development in the Western world (Breton 2008). From this stability of production processes, a sometimes-doctrinal field could be deduced, why not certain forms of orthodoxy, considering as immutable the link between need and production: stability of methods, stability of demands from relays, stability of solutions. Moreover, a system that has proved its worth, of large size, "having a captive market, producing simple products that do not involve the implementation of complex products, will tend towards a bureaucratic operation characterized by a strong formalization of rules” (Alter 1999).

> Habit becomes […] a great thing, structuring individuals socially because it makes them forget themselves in the small, unimportant gesture: the more commonplace it is in everyday life, the more powerfully it is structuring. (Kaufmann 2001)

Figure 1.1, based on Guillet’s data (1908), shows a fourfold increase in French production between 1870 and 1900, illustrating the transition from a craft activity pushed to its limits to the emergence of a new industrial age (with current world production of 45 million tons of sodium bicarbonate/year, a factor of around 200 globally 1900, but a factor of only 4 for France alone! (Conso-Globe 2018)).

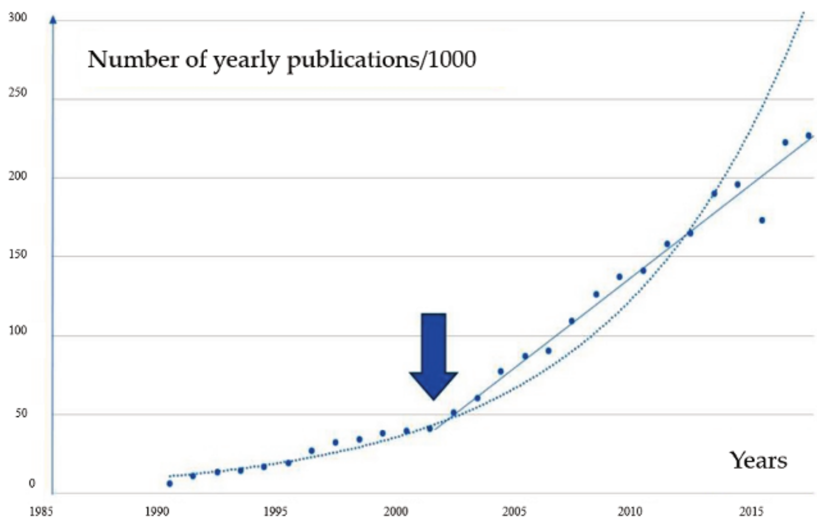


Figure 1.1. *Soda ash production between 1866 and 1902 in France*

This result is interesting in that it demonstrates, since the beginning of the 20th Century, a globalization of knowledge and processes for the transformation of matter and energy. With the chemical process defined, how can we develop competition between companies at the Western and then global level?

What can we think of this part of Lauth’s letter (1879):

> In the organization of our teaching, there is not even a school where a teacher who wanted to carry out this program could be a part of

> [transforming a scientific fact into a practical result]. Our chemical industries are increasingly taking on a scientific character; the factory is no more than a large laboratory in which victory will remain at the most learned.

Does university science obscure its evolution towards reasoned practice?

Grossetti (2004) reminds us, partly because of the aftermath of the 1870 war, that: "The creation in France between 1883 and 1914 of technical institutes in universities and the almost simultaneous development in the United States of technological universities are one of the steps in the institutionalization of research 'for engineers'." But it is in a country where environmental conformity is not celebrated that the concept of chemical engineering will emerge. MIT can serve as a model for a technological university, what Etzkowitz (2002) calls an "entrepreneurial university", whose creativity and depth of reflection allows research to be of interest to industry (knowledge commercialization).

In this pivotal period before the First World War, an 1896 document, quoted by Cameron (1982), tells us that:

> The change […] was sudden and violent. The great inventions were all made in a comparatively short space of time […]. In a little more than twenty years all the great inventions of Watt, Arkwright, and Boulton had been completed, steam had been applied to the new looms, and the modern factory system had begun.

This is what we can sense in the description of the manufacturing processes for soda ash. It goes without saying that the increase in productivity (see Figure 1.1) has been linked to mechanization, that is, the displacement of traditional operator skills by machines, Taylorism, and unhealthy conditions in new industrial cities (Usher 1920).

In practice, there is probably no scientific creation without the cooperation of a principle of profusion and freedom, imagination and disorder with respect to "received rules" and rigorous principles, methods, regulated ordering, criticism and robust validation. Both modes seem necessary and, of course, must "work" together, which can limit the efficiency of an overly closed strategy and lead to paradoxical injunctions for the "harmonious" functioning of research oriented towards technological development. Domains are emerging in a dynamic allowed by the unprecedented development of digital technology and the possibility of creating increasingly complex and sometimes customized objects and/or products (see Figure 1.2). They are an integral part of the industry 4.0 concept. For the time being, as suppliers of the material and energy needs of technology leaders, the mass process industries are rather behind compared to digital technologies. But without these ever-improving productions, is there a salvation for digital achievements?

Indeed, what remains to be done to ensure our viability if not inventing new and increasingly sophisticated techniques to solve the problems created by the old ones as they arise? The principle of the achievement of freedom for all has been replaced by the direct influence of technologies and new habits on the interactions we have with each other and with nature.

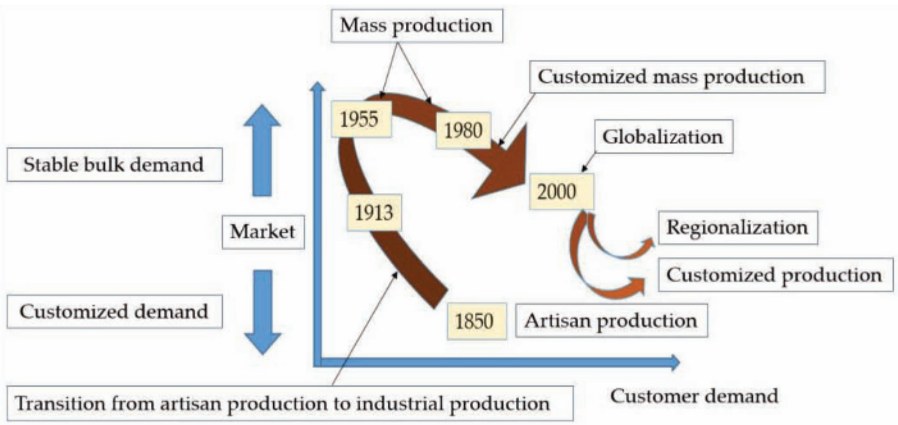


Figure 1.2. *Change in production methods of manufactured products*

1.2. The emergence of chemical engineering

> Recently, new disciplines have emerged from a synthesis of practical and theoretical interests. Thus, computer science was built from a machine and segments of older disciplines such as electrical engineering, psychology and philosophy. Materials science and other fields such as nanotechnology, which are on the list of key technologies of all nations, have emerged in the same way. (Leydesdorff and Etzkowitz, quoted in André 2019, p. 64)

The rapid development of the chemical industry at the end of the 19th Century and in the 20th Century triggered a need to standardize processes, to separate the body of these engineers from industrial chemists (and especially from "general" chemists) and from other engineering disciplines, such as mechanics. The main idea was to design optimized processes for the transformation of matter and energy from simplified elements. This allowed the transition from an efficient technology to an integration science with specific methodologies (Böhme *et al.* 1983), the basic building blocks of the domain that will be recalled in this book. This specialization, which was supposed to have disjointed knowledge from many other disciplines, first translated into technological know-how, has been transformed into an interdisciplinary field called chemical engineering, partly and through the creation of the journal of the American Institute of Chemical Engineers (AIChE). The nucleation was born, both at MIT and in England. Davies' book (1904) can serve as the English starting point for this new discipline (Furter 1980, 1982; van Antwerp 1980; Cohen 1996; DGCGB 2017).

For Divall *et al*. (2008), "originally, the term 'chemical engineering' (and its related terms, such as chemical engineer) was an *ad hoc* neologism based on a confusing relationship between its two supposed parent domains, chemistry and mechanical engineering". Andrew Abbott, quoted by these authors, would have considered that the emergence and development of science and technology fields cannot be understood in isolation from other emerging fields. Chemical engineering, because it is useful for industrial development, effectively competes with other fields of engineering sciences, such as mechanics and thermal engineering, but with interdependencies that are complicit with this new field, which has a specific pillar, the transformation of matter and energy.

However, from a rhetorical point of view, it is indeed a science which, through experimentation, leads to reproducible results (and, in this sense, meets the criteria of Thom 1986). Unlike sciences further from the transformation of matter, there is no applicable chemical engineering without matter, except that it is always possible to develop mathematical models involving the vectors of causality (see Figure 1.3). But, since the chemical synthesis that will be at the heart of the reactor (but not only there) does not always have a very high level of intimate knowledge (environmental effects, inhibitors, temperature sensitivity, etc.), the data applied in reality may not have all the right precision criteria desired, leading, using Thom's (1986) expression, to speak of "diffuse causalities". This situation has led to the autonomy of the domain, which, in reality, has only a cousin relationship with mechanics.

However, in the logic of a transformation of industrializable matter, there is only a partial place for process engineering, as it only very rarely intervenes in the first instance of this development (which for a long time conferred on it an image of a serving science, or even of a simple supporting technology). Figure 1.4 from Giroudière (2000) positions process engineering in this industrialization process (which generally lasts several years).

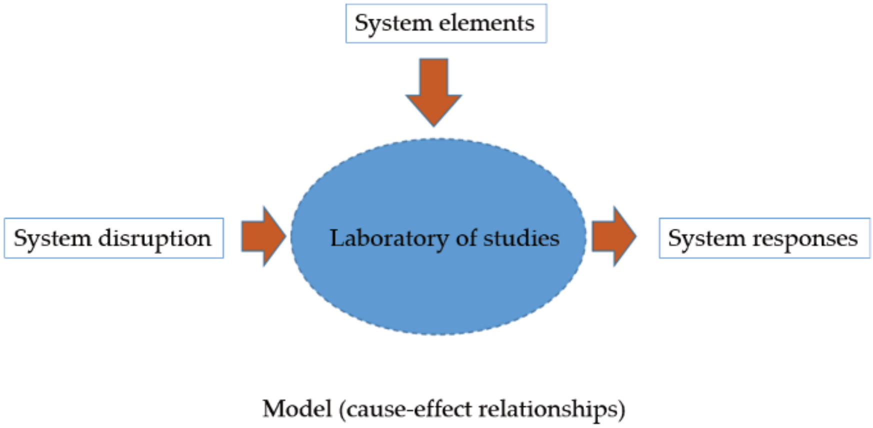


Figure 1.3. *Chemical engineering modeling*

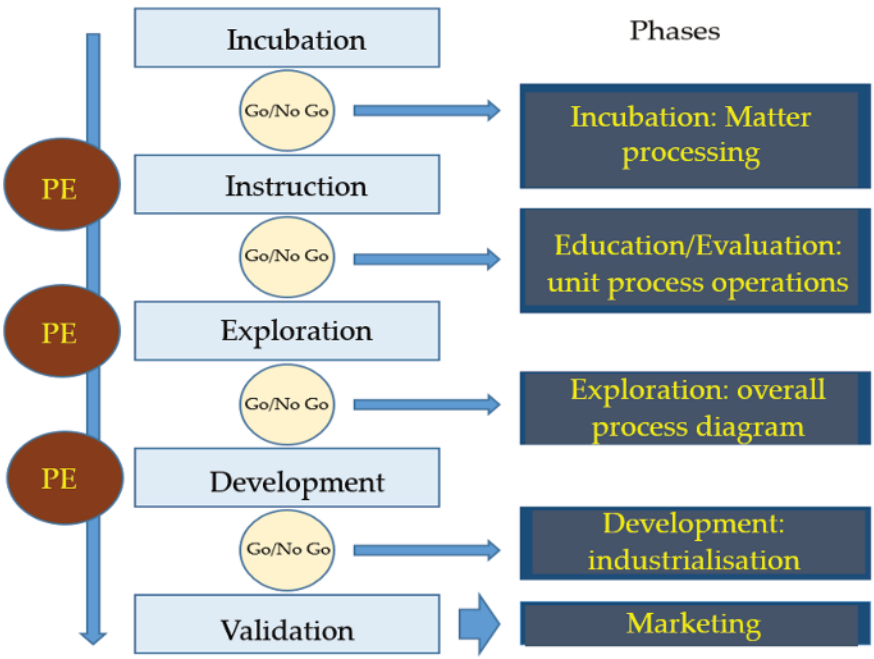


Figure 1.4. *Industrialization and process engineering approach*

At MIT in 1888, influenced by developments in German universities (with substantial financial support from domestic industry (Burhop and Lübbers 2010)) and a series of conferences on the operating practices of the British chemical industry, presented by George E. Davis at Manchester Technical School in the United Kingdom, Lewis M. Norton created the first chemical engineering program, by combining mechanical engineering with industrial chemistry. In 1891, MIT awarded seven bachelor's degrees in chemical engineering, the first of their kind to be awarded. After 1893, Frank H. Thorpe took over the course. "Outlines of Industrial Chemistry", published in 1898, is considered one of the first chemical engineering textbooks (Freshwater 1989, MIT ChemE 2018). However, from a historical point of view, it was the industrial need related to the First World War that imposed, through a much-increased demand, a certain standardization and better rationalization in processes, which has led to a preference for emerging knowledge in relation to the know-how of industrial chemical practitioners. This effect was further amplified after the Second World War, as evidenced by the reports of Bush (1945) and Steelman (1949).

As is often the case, a number of skills that were developed during these periods of high stress translate into recognition by society as a legitimate discipline for industrial development. However, this recognition in legitimacy has not been so easy, as each learned organization from chemistry to mechanics wishes to keep chemical engineering in its midst. There were a number of critical breaks, as happens in a quest for autonomy with a certain "societal corporatism" (Divall *et al.* 2008).

What has been the strength of the field since the beginning of the previous century is the integrative concept of unitary operation, which takes into account different elements, such as heat transfers, material and energy flows, various devices such as those related to evaporation, distillation, etc., which are applicable design elements (to varying degrees) for all chemical plants, whatever the product considered (see for example, the book by Walker *et al.* published in 1923). These bases have thus introduced a coherent order into chemical engineering, which makes it possible to affirm that unitary operations, by reducing the arbitrariness of the expert approach resulting from industrial chemistry, are very important characteristic elements, in that they have revolutionized chemical engineering since MIT at the very beginning of the 20th Century (Cohen 1996; Rosenberg 1998, pp. 168–191).

The concept of transport phenomenon, later, can be considered as a generalization based on partial differential conservation equations and their solutions in the presence of chemical transformation (Bird *et al.* 1960). These balance sheet equations of various origins have contributed to the unity of professionals, not only in the United States, but also more broadly (Churchill 2007).

Thus, chemical engineering has survived and prospered for more than 100 years, while other branches of engineering have disappeared. This survival is attributed by Churchill to the integrating factors defined below, with the risk of generalizations, simplifying concepts and dangerous analogies.

In a reductive way, chemical engineering could probably be described as starting from two pillars – unit operations (already well developed in the 1920s and 1930s) and transport phenomena (developed in the late 1950s) – and identifying chemical reaction engineering as a third pillar. It was built on autonomous knowledge relative to the science of the time because it did not provide the knowledge necessary to understand system dysfunctions. The pooling of knowledge within the framework of integration has thus resulted in the emergence of a scientific discipline, initially based on learning processes.

Figures 1.5 and 1.6, from Freund and Sundmacher (2008), illustrate what is meant by unitary operation associated with functional modules.

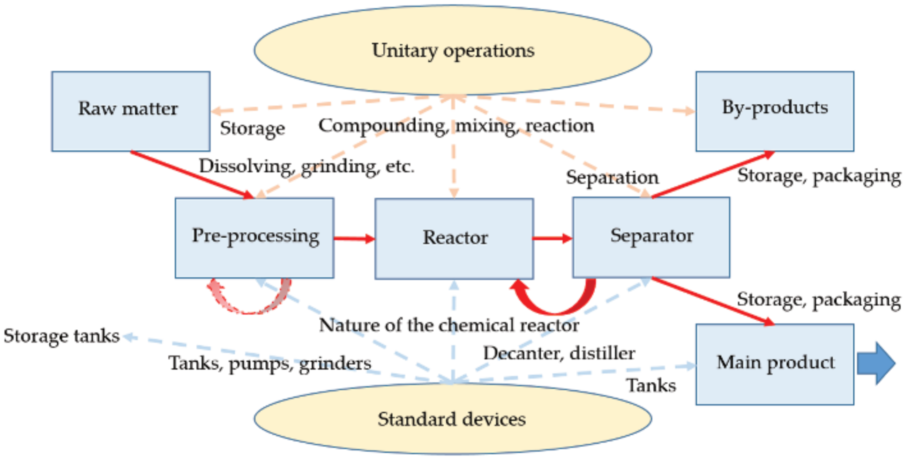


Figure 1.5. *Flowchart of a process combining several unit operations. For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*

However, the field is and remains broad. It is developing in many directions, and according to Costa *et al.* (2006), a consensual framework for this young discipline is not stabilized (see also (Voncken *et al*. 2004)). Moreover, according to Bousquet (2008): "Since 1987, and under the impetus of Jacques Villermaux, the concept of process engineering, which is none other than chemical engineering, has been established in France each time it is applied to material transformation process industries other than the chemical industry" (see also (Perkins 2002)).

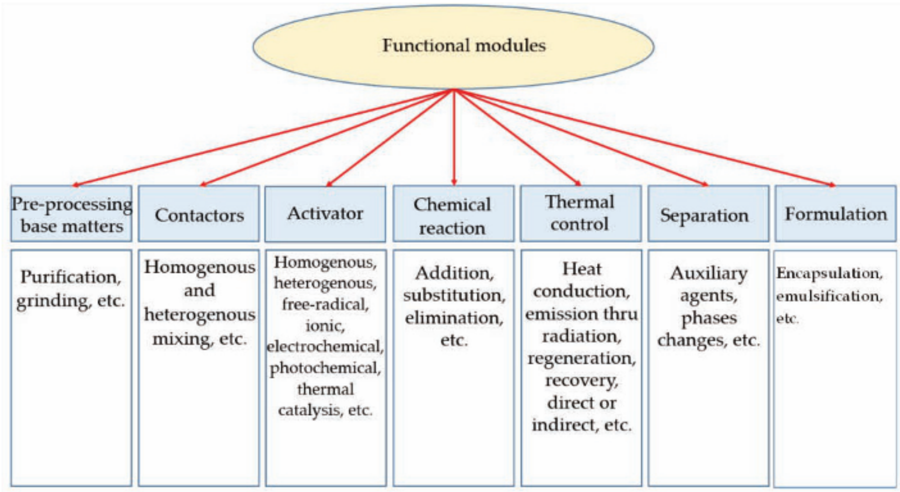


Figure 1.6. *Sequence of functional modules*

As we have understood, this is indeed an engineering science, close to technology and the applicability of methods; it therefore has no reason to be stable, always digging in the same place. But, at the same time, this situation may suggest that it is a somewhat "corrupted" science, drawing its research from frontier objects where chemical engineering techniques (or now processes) are used or, in a more conceptual way, exploring new fields of study directly related to the theme (for example, by studying situations where traditional chemical engineering paradigms are challenged, such as exploring non-linear systems, the effects of micro-fluidics in PE, etc.).

To paraphrase Grangier (1986), the stabilization of the domain first of all makes it possible to describe and, above all, to make people understand the meaning, the methods that allow experiments to be transcended and their possible limits to the rationalization introduced by the integrating concept of chemical or process engineering. Achievements are naturally found in training and research at the frontiers. In short, "to identify the presuppositions of a scientific practice, to establish the inventory of a system of concepts, to define the zones of indeterminacy, to recognize logical paths and extra-logical approaches: in this alone can an epistemology be constituted" (Grangier 1986). Chemical engineering has flourished because of several factors, including the more widespread and efficient use of balance equations and dimensionless numbers that constitute integrators that allow for analogical comparisons. However, for Churchill (2007), "many of the generalities, simplifying concepts, and analogies in current textbooks, handbooks, and even computer design packages are wrong or obsolete and should be deleted or noted to be only of historical interest. The radical changes that are currently afoot in chemical engineering and in the world in which it is currently practiced can be expected to make many more obsolete or irrelevant, thereby creating a need and/or opportunity for the formulation of new ones”. These aspects will therefore be discussed later in the book.

Before taking up this historical approach to examine how the discipline has spread outside of English-speaking countries, it seemed useful to recall some of the basic elements that characterize the field. In fact:

> Although increases in productivity as a result of the use of mechanical power and machinery were admitted, most accounts stressed the use of child labor, the displacement of traditional skills by machinery, and the unwholesome conditions of the new factory towns. For most of its history, for most people, the term industrial revolution has had a pejorative connotation. (Cameron 1982)

The rationalization of processes and the inclusion of working conditions in them have been decisive in this evolution. Giroudière (2008) recalls:

> The development phase, which is more substantial in terms of human and experimental resources, can vary from 1 year to more than 10 years for complex processes to be implemented. This phase will focus on the only chosen path. It includes the determination of the basic data necessary for the extrapolation of unit operations, the choice and design of chemical engineering equipment, integrating safety and environmental impact on the one hand, and operating principles on the other hand, and guaranteeing the product’s use properties.

It has therefore been a rather slow process of transformation, linked not only to cultural but also to financial aspects (but also to heavy conservatism in some countries).

1.2.1. *Balance equations*

According to Le Goff (1965), these equations can be grouped together in Table 1.1: in a system, it is a question of knowing different types of balance in the presence of a transformation of matter: matter, total energy, mechanical and thermal energy, balance of quantity of motion. These concepts will be further developed in the presentation of current chemical engineering training courses and will therefore not be developed further here (and go a little further than the concepts already introduced in 1904 by Davies in the United Kingdom).

Material balance
(output flow) – (input flow) + (accumulation rate in the volume) = (creation speed in the volume)
Mechanical energy balance
(increase in mechanical energy of the fluid as it passes through the system) + (mechanical energy dissipated in friction) = (mechanical energy supplied from outside by the machines)
Thermal energy balance
(increase in heat carried by the fluid as it passes through the system) + (heat transferred to the walls by conduction and radiation) = (heat produced in the system by exothermic reactions)
Movement quantity balance
(flow of movement quantity carried by the output flow) – (flow of quantity of movement provided by the input flow rate) + (quantity accumulation rate of movement in the volume) = (resulting from external forces)

Table 1.1. *Balance sheet equations in chemical engineering*

1.2.2. *Dimensionless numbers*

> Gazing at the myriad of different forms and rhythms, [we] contemplate patterns, relationships and telltale signs. How happy it would make us to come upon a clue or a formula that was a key to some unifying principle. In proportion we find a strategy to do this […]. (Hemenway 2008)

This is the identification of a dimensionless characteristic variable that eliminates or minimizes parametric dependence on other dimensionless variables. The objective is to transpose results from one scale to another, in particular (principle of similarity):

> To reproduce a process studied on a small scale (model) at the same scale as the industrial scale (prototype): we then proceed to an enlargement (scale-up).

> To predict the behavior of a process on an industrial scale (prototype) using tests conducted on small equipment (model); a scale-down is then performed. (Delaplace *et al*. 2014)

These numbers are not only the subject of chemical engineering specialists, but also of heating engineers, mechanics, etc., but their use already makes it possible to make the difference with industrial chemistry.

For example, the Reynolds number, Re, widely used in chemical engineering, is the ratio between inertial and viscous forces. It is expressed through the relationship:

$$Re = V.L/ \nu$$

with:

– V the characteristic velocity of the fluid [m/s];

– L the characteristic dimension[m];

– and ν the kinematic viscosity of the fluid [m2/s].

What is useful to the engineer is that the Re increase makes it possible to distinguish four main regimes: Stokes, laminar, transient, and turbulent. Even if the Re values can be considered as approximate (V and L may only represent an order of magnitude), it is already possible to access essential flow characteristics. Other dimensionless numbers are used and will be introduced during the course of the work:

> Disjunction and reduction are therefore the two main aspects of a simplification paradigm whereby scientific thought either dissociates itself from inseparable realities without being able to consider their link, or identifies them by reducing the most complex reality to the least complex reality. (Wolf 2009)

BUCKINGHAM'S THEOREM – *If we have n system variables, and k fundamental quantities (length, time, mass, etc.), we can define n-k numbers without independent dimensions that define the system (see for example (Seon 2018)).*

Table 1.2 presents, as illustrative examples, the main dimensionless numbers used in process engineering for material and energy transformation processes.

Name	Symbol	Expression	Meaning of the word
Biot material	Bi_M	$k_D L/D_e$	Material transfer at the interface/ material transfer within a particle
Thermal Biot	Bi_T	hL/λ_e	Heat transfer at the interface/heat transfer within a particle
Damköhler Criterion	Da	$kC_0^{n-1}\tau$	Space time/reaction characteristic time
Froude Criterion	Fr	N^2d/g	Inertia forces/gravity forces
Nusselt Criterion	Nu	hd_P/λ	Heat transfer by convection/heat transfer by conduction
Peclet Criterion	Pe	uL/D	Material transfer by convection/ material transfer by diffusion
Prandtl Criterion	Pr	$\mu C_p/\lambda$	Motion diffusion/heat diffusion
Reynolds Criterion	Re	$\rho ud/\mu$	Inertia forces/viscosity forces
Schmidt Criterion	Sc	$\mu/(\rho D)$	Motion diffusion/material diffusion
Sherwood Criterion	Sh	$k_D d_P/D$	Material transfer by convection/ material transfer by diffusion
Prater Criterion	β	$D_e(-\Delta_r H)C/(\lambda_e T)$	Temperature gradient within a catalyst particle
Thiele Criterion	φ	$[(rL^2)/(D_e C)]^{0.5}$	Chemical reaction/material transfer by diffusion within a particle

Table 1.2. *Examples of the main dimensionless numbers used in process engineering for material and energy transformation processes*

Name	Symbol	SI unit
Acceleration of gravity	g	$m.s^{-2}$
Calorific capacity	C_p	$J.kg^{-1}.K^{-1}$
Reaction heat	$\Delta_r H$	J.mol-1
Material transfer coefficient	k_D	$m.s^{-1}$
Heat transfer coefficient	h	$W.m^{-2}.K^{-1}$
Characteristic length	L	m
Diffusion coefficient	D	$m^2.s^{-1}$
Effective diffusion coefficient within a particle	De	$m^2.s^{-1}$
Thermal conductivity	λ	$W.m^{-1}.K^{-1}$
Effective thermal conductivity within a particle	λ_e	$W.m^{-1}.K^{-1}$
Kinetic constant	k	According to the order of reaction
Concentration	C	$mol.m^{-3}$
Characteristic dimension	d, d_p	m
Characteristic dimension of a particle	$L = V_{Particle}/A_{Particle}$	m
Density mass	ρ	$kg.m^{-3}$
Reaction order	n	-
Space time	τ	s
Temperature	T	K
Viscosity of the fluid	μ	Pa.s
Flow velocity	u	$m.s^{-1}$
Kinetic rate	r	$mol.m^{-3}.s^{-1}$
Stirring speed	N	s^{-1}

Table 1.3. *Representative examples of dimensionless numbers used in PE*

1.3. Diffusion of chemical engineering in France

In France, and, in particular, in Lorraine after the disaster of the 1870 war, it was necessary to show our German neighbors that the country intended to develop economically. It was on this basis, between this date and the beginning of the First World War, that technical institutes were created (a little like in Germany!). Thus, thanks to the dynamism of academics such as Ernest Bichat and Albin Haller, with substantial financial support from Ernest Solvay, the city and the State (one million francs at the time!), the Chemical Institute (now the École nationale supérieure des industries chimiques) was created in Nancy in 1887. In the minds of the promoters, it was a question of introducing more science into industrial production to improve the competitiveness of French companies, particularly in the face of German competition (with a new border located less than 30 km from Nancy). Following a donation of 100,000 francs to launch his projects, Haller presented his ideas on the relationship between "science and industry" at a conference organized by the Société Industrielle de l'Est (Birck and Rollet 2015). The aim was to introduce to France scientific disciplinary specialities that are not present in the country, such as electrochemistry, with the task of linking the academy to industry (if only through joint and paid expertise).

It was at this point, as has been pointed out, that in English speaking countries chemical engineering was created from industrial chemistry and the emergence of new engineering sciences such as mechanics or thermal engineering. At MIT, in Boston, the idea of an "entrepreneurial" university was born in the same period, with a more proactive approach than in France, which, like Germany, continued to develop its skills in industrial chemistry. At MIT:

> Filtration, sedimentation, grinding, distillation or electrolysis are examples [studied in chemical engineering]. A process is then the sequence of several of these operations. Rather than studying each process separately, it seems more interesting to the proponents of chemical engineering to develop and teach these basic elements directly with the objective of extrapolation to an industrial scale. (Grossetti 2004)

It was only after the Second World War that French (provincial) engineering schools began to focus on chemical engineering, in Toulouse with Joseph Cathala (who had worked in the United Kingdom) and in Nancy with Maurice Letort and Pierre Donzelot (who would have slowed down the Toulouse project). Maurice Brulfer, a former member of the Institut de Nancy and president of the Union des industries chimiques at that time, strongly supported the development of chemical engineering (perhaps a little more in Nancy). Pierre le Goff, an eminently creative and enterprising character, was one of the first chemical engineering teachers in the school that is now called ENSIC.

Instead of having a complementarity, a fruitful partnership with Toulouse, the domain is not emerging under the best conditions in France. This situation, with the success of process engineering having become so legitimate that it is now taught in chemical engineering schools, is now considered to be a thing of the past. However, this short history reveals a ruptured functioning (an import of chemical engineering) linked to forms of follow-up culturally rooted in the subconcious of decision-makers. But that’s another story.

Today, process engineering research units and French engineering schools have a qualification that is appreciated by manufacturers. But tomorrow?

1.4. Training in chemical engineering

> An engineer is a person who has successfully completed a long theoretical and practical higher education, scientific, technical and technological, capable of responding within a given time with the material and financial means defined, to an industrial problem that will suffer an economic sanction. (Roby 2014)

Jacob Bigelow, at the beginning of the 19th Century (1829) was at the origin of the English language system of engineering training (see MIT). In France, this also served as an engineering training model designed as a “problem solver” (Forest et Faucheux, 2013). According to Grossetti and Detrez (2000), this activity of decomposition into specific processes (unit operations), largely distinct from the use they allow, is part of the basic corpus of specialized chemical engineering training and/or processes. Extrapolation is thus allowed, as indicated in section 1.1, without the creativity part being significantly affected.

According to Forest and Faucheux (2013), “this relative concealment of design in the curriculum is harmful because engineering schools have clearly favored the Platonic reason model (Le Moigne 2002) and abandoned the ingenious reason model”. The creative and innovative aspects (incremental and disruptive), based on an adventure pedagogy, are today only very imperfectly part of the training of a chemical engineering specialist, which is, as we can understand, the heart of this book, because the need to change which was valid a few decades ago is becoming even more acute.

And yet, for Gaston Berger (1962), the engineer’s activity is based on “science whose human ends are affirmed and systematically sought. The technician, the engineer in his current practice, does not use any truth that does not come from a particular science, but it is up to him to make an original synthesis of it. There is technique only where there is purpose". "Action that is as reasonable and lucid as possible, applied to the pursuit of human ends: this is the true definition of technology. Engineering does not suppress technology: it uses it or improves it" (Berger 1964). It is good that there is a general question asked by decision-makers and that it is necessary to find optimized means to achieve it (Bhaskar *et al*. 2000), putting the "process" engineer in an expert position to deal with problems that are now classic. On this basis, it is indeed the "toolbox" of chemical engineering that has been and continues to be the subject of sustained attention from educators (and this is what has constituted the success of this young discipline). According to Karpik (2010), three types of product exist:

> – *standard* products, goods that are part of the normal functioning of the market;
>
> – *differentiated* products that are characterized by their heterogeneity;
>
> – singularities, which, unlike the other two, are not taken into account by economic theory.
>
> These unique products stand out for the multidimensional nature of their qualities, their immeasurability and the radical uncertainty as to their future value for the consumer.

In the prospective analysis proposed to the reader, it is shown that humanity faces a number of difficulties – including environmental ones, according to Hoffmann (2000), and the All Saints' Ceiling Rule, cited by Ayache (2018) – that require a specific perspective from specialists in the transformation of matter and energy (but not only these specialists).

In this field, the future can be the "child" of the past. Future developments may be based on the current dynamics of research and engineering developments, organizations and concepts, knowledge of emerging needs expressed, new opportunities arising from major scientific advances, and finally the availability of personnel and financial resources:

> Unless adequate technological forecasting studies are undertaken to enable us to relate development options to resources and requirements, our achievements may fall short of our needs, and a degrading environment and quality of life may force us into costly crash programs. (National Research Council of the USA 1971)

To quote Berger (1964) again:

> Each invention allows us to solve old problems, but in fact new ones appear immediately, in another field. We are caught in a movement that, far from slowing down, is accelerating. Let's not expect to make any effort and then rest. Our very progress requires us to look further.

The acceleration of Kondratieff's cycles and the emergence of new demands therefore require revisiting PE training to dynamically anticipate needs. By giving the floor to Germinet (1997), the point is confirmed:

> Challenges for engineers: they must know how to do, in other words, capitalize on experiences and rules to be designers and specialists. They must also know how to understand, solve puzzles, find a solution to a problem, if they want to be able to assert their authority. Finally, they must be able to combine by experimenting, innovating and acting as project managers.

According to Roby (2014), "the engineer himself is produced by the school in order to reproduce according to its idea of industrial needs. It is seen as a factor of production, not as an innovative and disruptive seed that poses the real problems (relevance) without care (impertinence)". There are therefore strong elements that campaign for a reinvention of PE training (National Academies 2005).

In addition, "New Public Management" is defined by Drechsler in 2005 as:

> the transfer of business and market principles and management techniques from the private into the public sector, symbiotic with and based on a neo-liberal understanding of State and economy, The goal, therefore, is a slim-lined, minimal state in which any public activity is decreased and, if at all, exercised according to business principles of efficiency.

This paradigm is reflected in the strengthening of links between research centers in the public domain and industry, which allows the possibility of developing training in research–higher education relations (see also (Gingras *et al*. 2001, Heil 2010) and Article 25-1 of Act No. 99-587 of July 12, 1999 on innovation and research).

Among the more traditional changes desired in particular by Costa *et al*. (2006), several trends (actually observed since then) seem necessary for the proper development of the discipline:

– expansion of the body of knowledge associated with the discipline (Mashelkar 1995; Wintermantel 1999a, 1999b; Wesselingh 2001; Favre *et al.* 2002);

– adoption of a multidimensional approach to products and processes (Villermaux 1995; Wintermantel 1999a, 1999b; Charpentier 2002; Grossmann 2003; Li and Kwauk 2003, 2004; Charpentier and McKenna 2004; Wei 2004a, 2004b);

– green chemical engineering, supporting the chemical industry of the future (Churchill 2007; Charpentier 2016; UNIDO 2018);

– changes in scale (e.g. (Davis 2009));

– emergence of chemical engineering (product engineering) as a well-established field of teaching and research.

In 2006, Byrne, in proposing the general model for chemical engineering training, defined a body of educational "doctrine" for most specialized training in the field, with the study of transport phenomena (transfer of heat, mass, and quantity of movement) coupled, or not, with the transformation of matter and energy, with modules associated with safety and environmental constraints, as well as certain automatic control and modeling processes, sometimes with economic studies (see Figure 1.7).

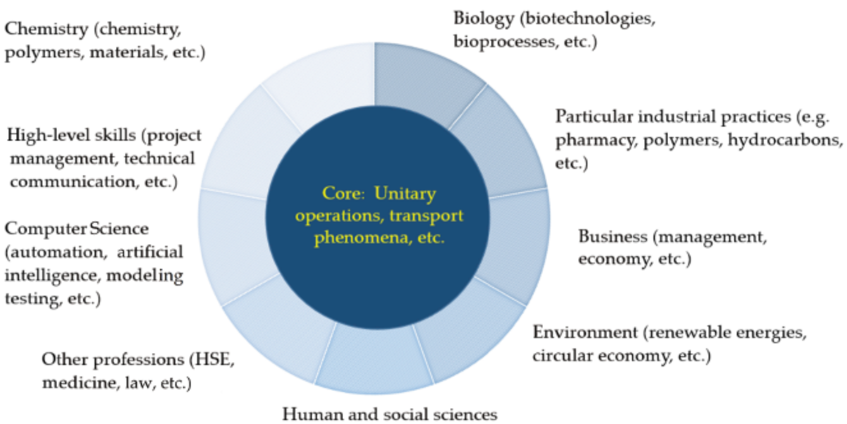


Figure 1.7. *Generic (optimistic) model of chemical engineering training courses (HSE: Hygiene, safety and environment). For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*

1.5. A question of image?

In this chapter, it has been possible to show how chemical engineering, which has become process engineering, has emerged in the technical society. But, as it is a somewhat "portmanteau" concept, difficult to explain easily to a (French, at least) politician, it was necessary to carry out perception surveys among different audiences on this topic of engineering science in the transformation of matter and energy.

Figure 1.8 answers the question for the general population (with no filter).

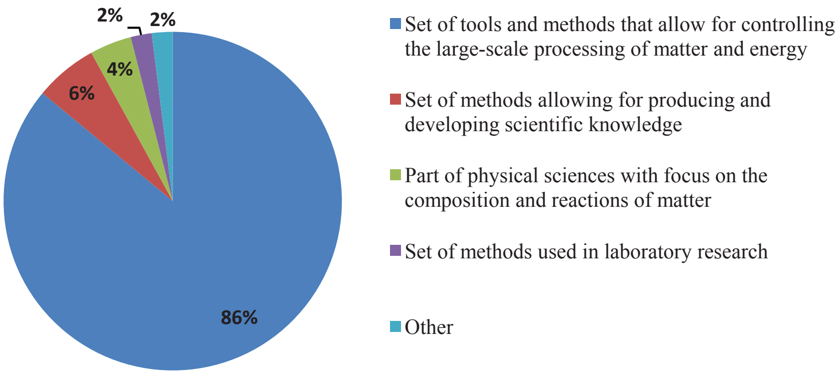
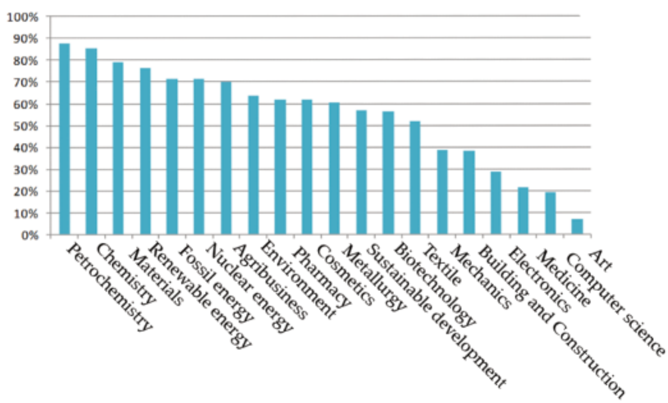


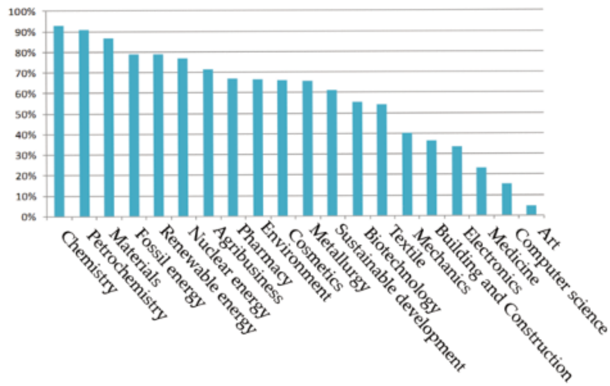
Figure 1.8. *Answer to the question: "what is chemical engineering?". For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*

There is therefore a good understanding of what the term "chemical engineering" means to the public. Another set of questions was asked to targeted populations about, not what CE is to them, but what the jobs of engineers trained in the field are. The results are shown in Figure 1.9.

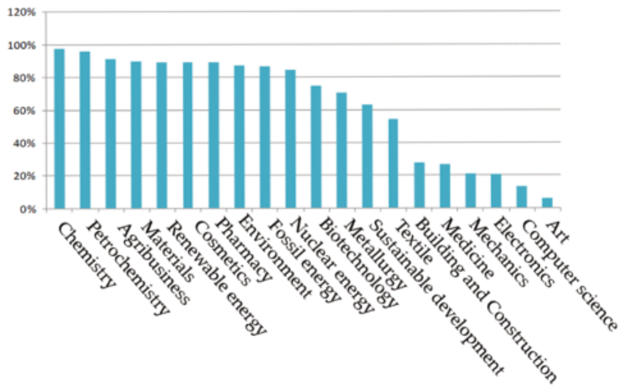


(i) General Population

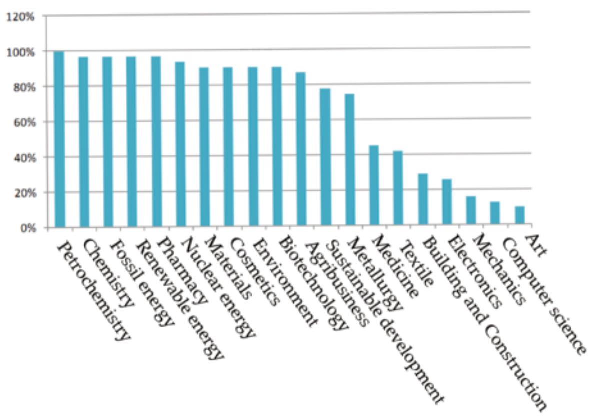
Figure 1.9a. *Perception of jobs in different professional branches: possibility of several choices*



(ii) Students not involved in PE

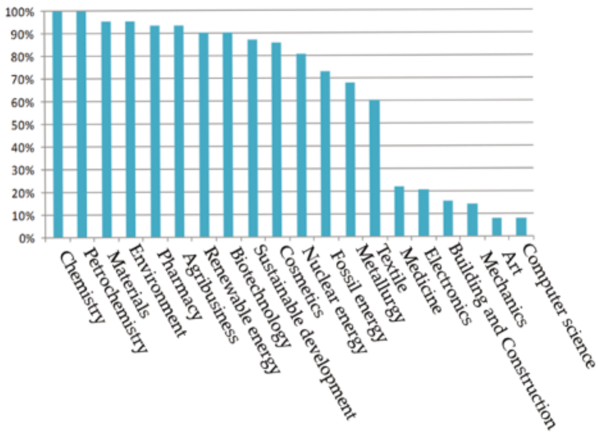


(iii) PE students



(iv) PE engineers

Figure 1.9b. *Perception of jobs in different professional branches: possibility of several choices (continued)*

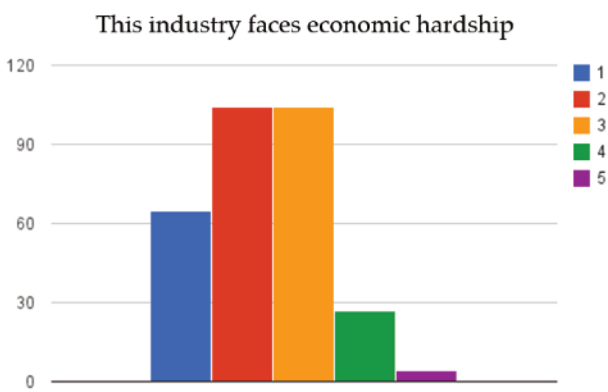


(v) PE teachers

Figure 1.9c. *Perception of jobs in different professional branches: possibility of several choices (continued)*

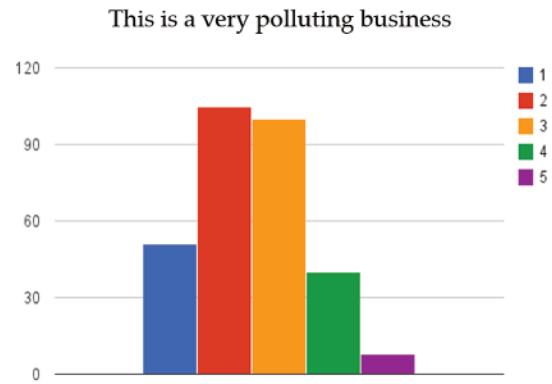
What we can see is that, even if PE is difficult to characterize in detail, whatever the population concerned, there is a fairly good agreement on the main destination of engineers trained in PE with reality (OIC 2016).

As we continued our investigation, we asked respondents what they thought of the general activities related to PE. The results are shown in Figure 1.10.

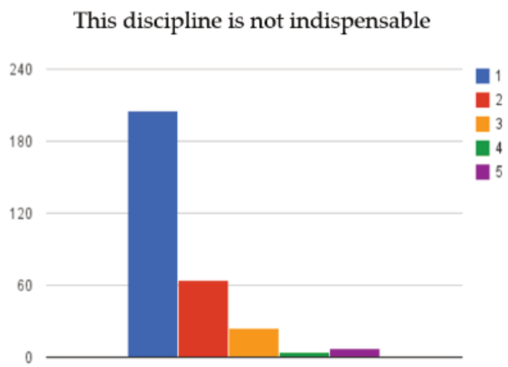


(i)

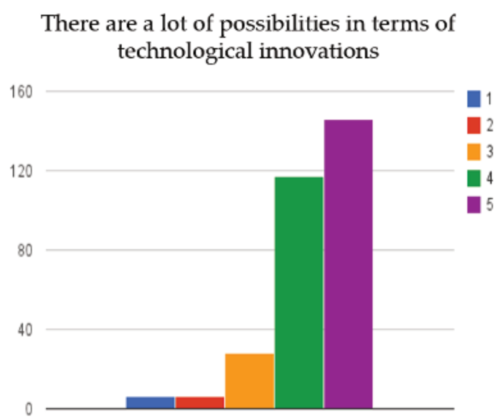
Figure 1.10a. *Perception of the material processing industries. Agreement with the statement on a scale from 1–5, with 1 (blue, on the left) strongly disagreeing, and 5 (purple, on the right) strongly agreeing. For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*



(ii)



(iii)



(iv)

Figure 1.10b. *Perception of the material processing industries. Agreement with the statement on a scale from 1–5, with 1 (blue, on the left) strongly disagreeing, and 5 (purple, on the right) strongly agreeing (continued). For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*

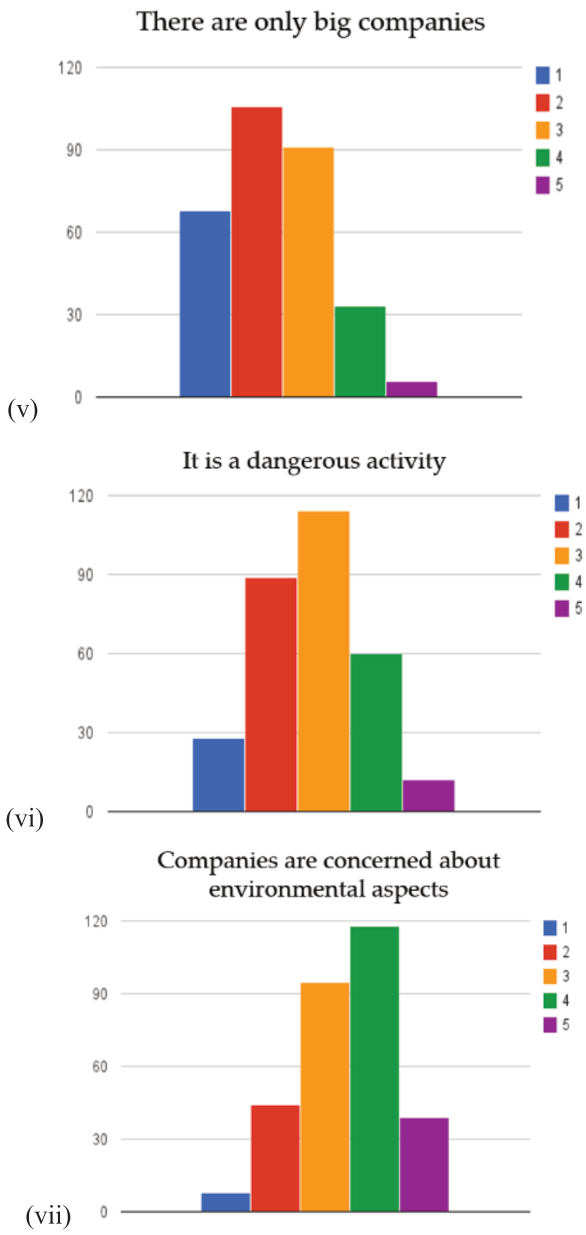
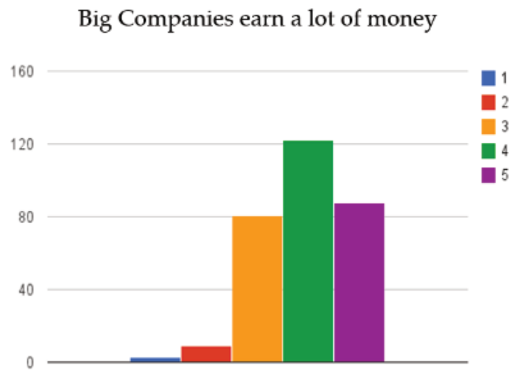


Figure 1.10c. *Perception of the material processing industries. Agreement with the statement on a scale from 1–5, with 1 (blue, on the left) strongly disagreeing, and 5 (purple, on the right) strongly agreeing (continued). For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*



(viii)

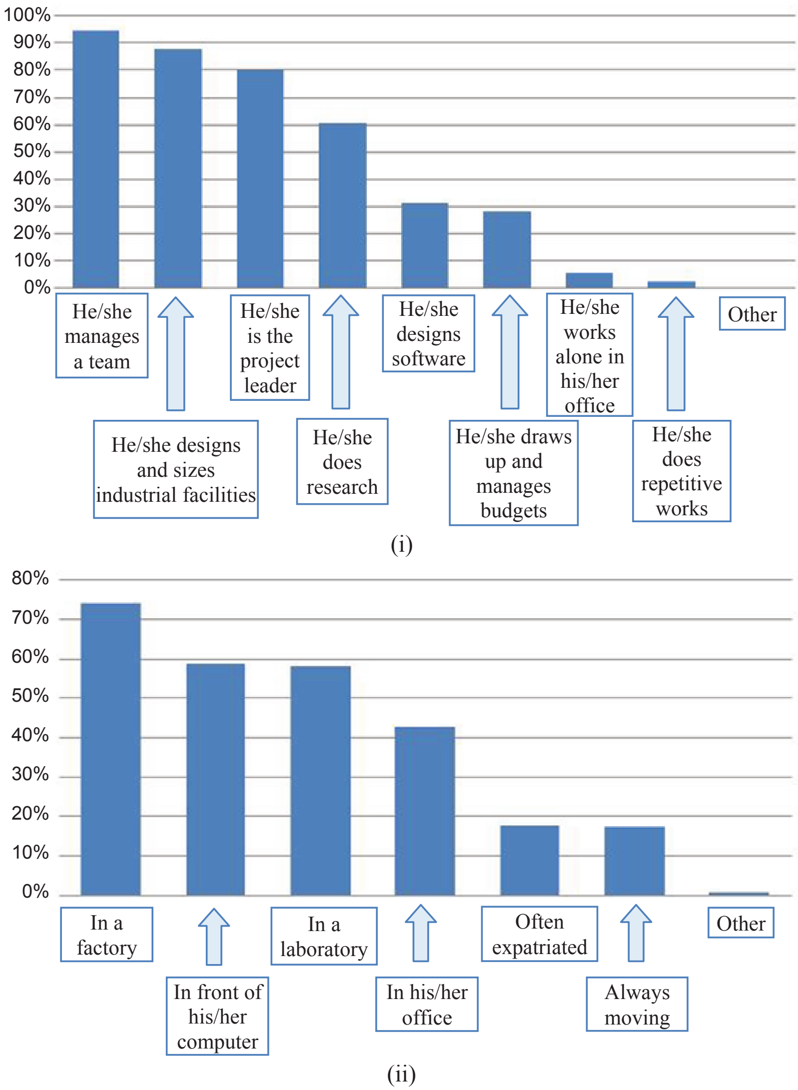
Figure 1.10d. *Perception of the material processing industries. Agreement with the statement on a scale from 1–5, with 1 (blue, on the left) strongly disagreeing, and 5 (purple, on the right) strongly agreeing (continued). For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*

While some errors can be identified, the brand image of the business is quite satisfactory. Among the remarks, in Figure 1.10a(i), the material and energy processing sector, considered to be in moderate economic difficulty, is in fact still growing, but not with the same performance as the digital sector; the deteriorated image of chemistry is shown in Figure 1.10b(ii), while companies respect environmental constraints. The Seveso disaster and some other accidents maintain, via the media, this vision of polluting chemistry; with regard to Figure 1.10b(iii), the respondents consider the interest of material and energy production well, while for the public, these operations are hidden; there is a very favorable view in terms of innovations in Figure 1.10b(iv), while the purpose of this book is to push for strengthening this aspect; Figure 1.10c(v) is interesting in that the opinion sees rather medium-sized companies, which in terms of plants is generally validated, but they are often linked to international groups; the answers are ambiguous in Figure 1.10c(vi) with regard to risks, whereas the chemical industry has a very low accident rate at work (much lower than the construction sector); given the deteriorated image of chemistry and regulation, companies are concerned about environmental aspects, as shown in Figure 1.10c(vii); finally, the opinion on the ability of industrial groups to earn a lot of money is interesting, no doubt because the transformation of matter is associated with energy (Figure 1.10d(viiii)):

> Because it essentially consists of transforming, modifying, and synthesizing elements, chemistry is considered fundamentally unnatural, associated with an aseptic and "dehumanized" imagination. Chemistry as a science is emerging in people's minds as the positive and "purest" side of chemistry, while industry forms its negative side. There are therefore two perceptions of chemistry in the collective imagination:

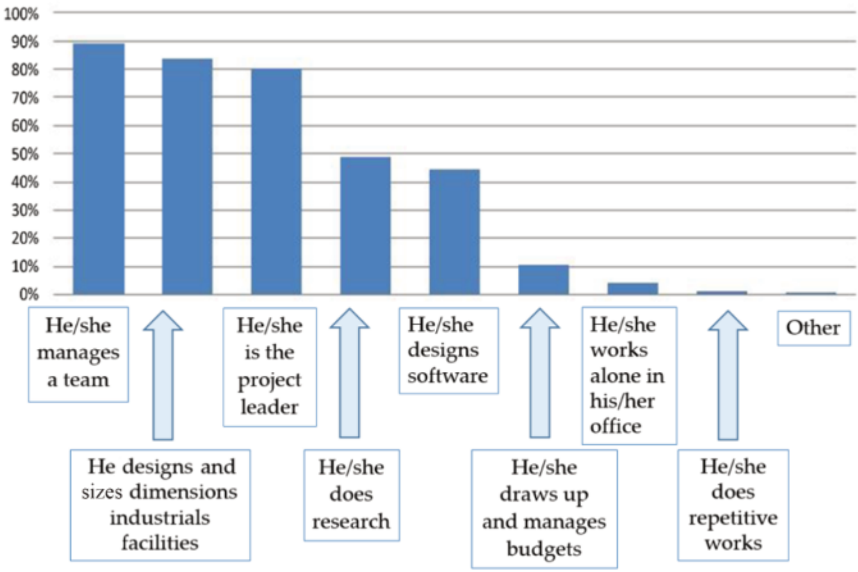
one that worries or frightens, on the one hand, and one that convinces and gives hope, on the other. (UIC 2018)

Third, we wanted to know what the respondents thought about the profession of process engineer. The result of the consultation is shown in Figure 1.11.

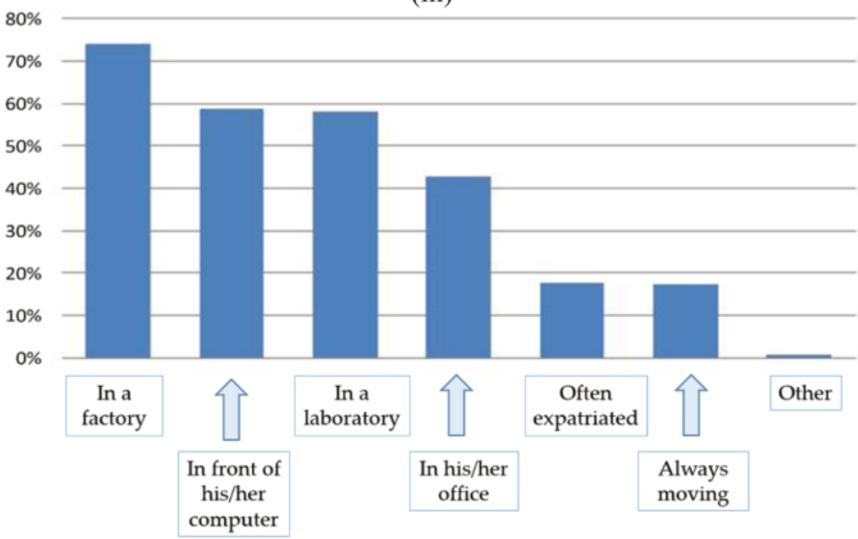


Figures (i) and (ii) refer to persons not related to PE

Figure 1.11a. *Perception of PE engineers' jobs*



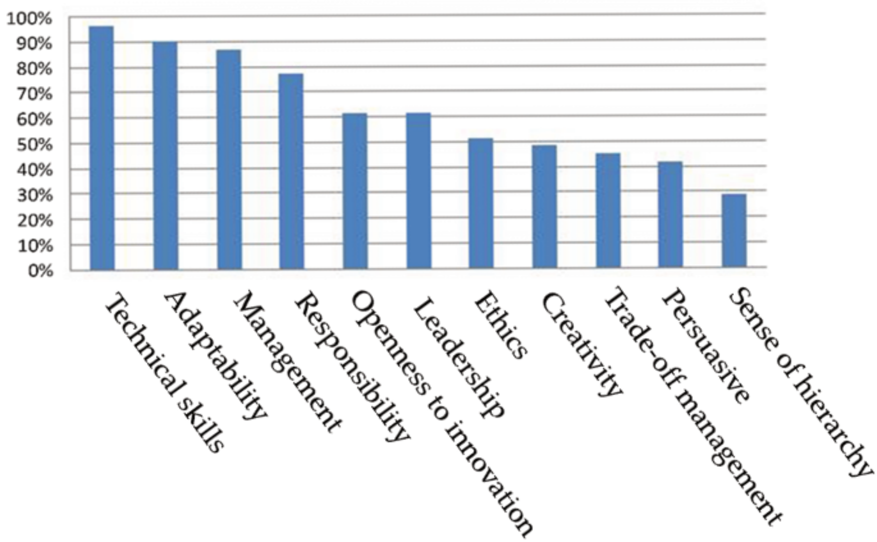
(iii)



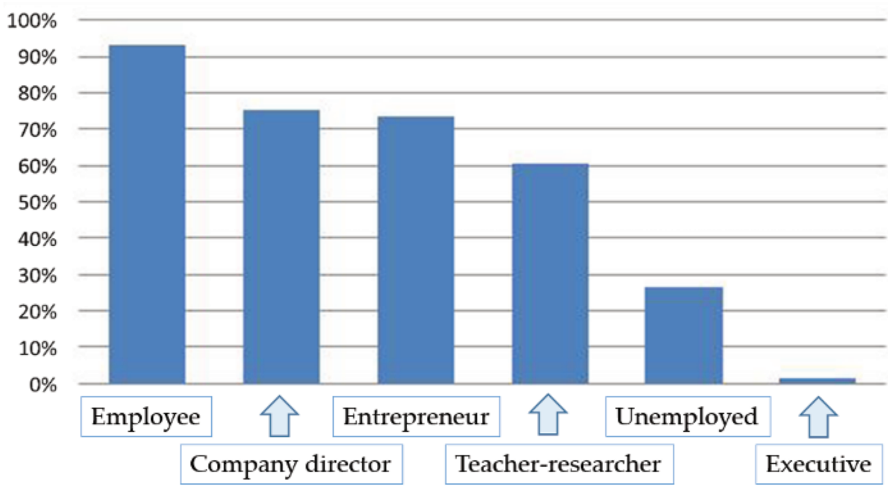
(iv)

Figures iii and iv refer to students not involved in PE.

Figure 1.11b. *Perception of PE engineers' jobs (continued)*



(v)



(vi)

Figures v and vi are the responses of people involved in PE (the last one indicating the profile of the respondents).

Figure 1.11c. *Perception of PE engineers' jobs (continued)*

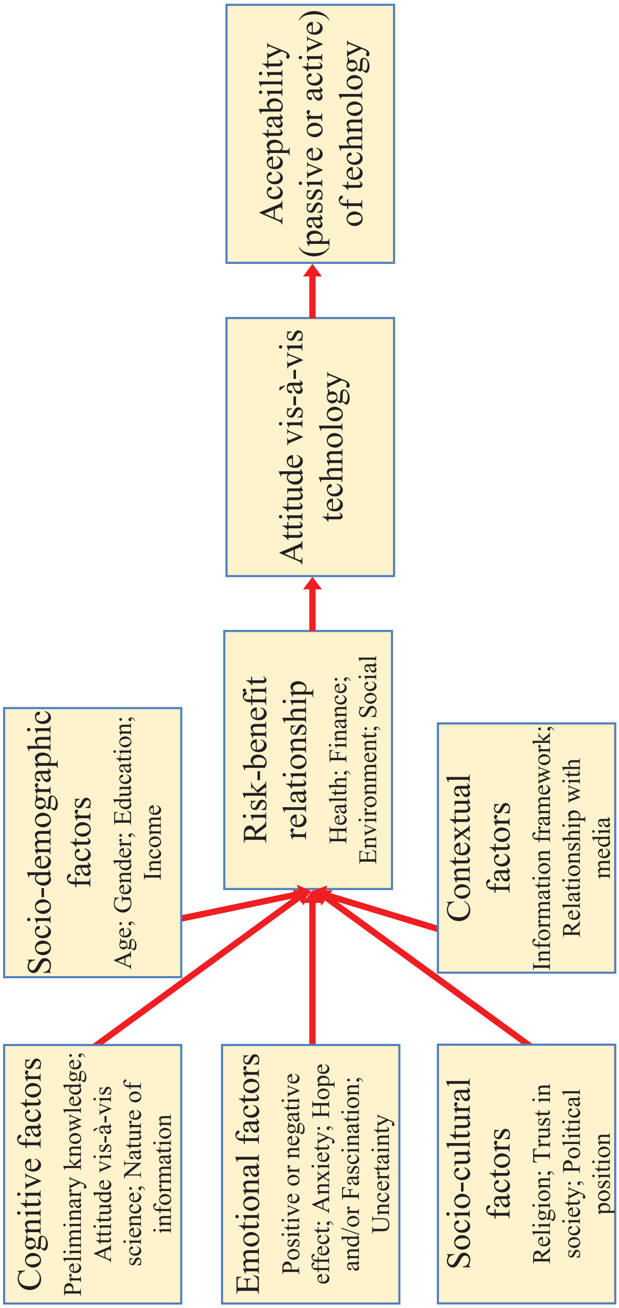


Figure 1.12. *Factors affecting the acceptability of a technology (example of nanotechnologies)*

This spectrum of skills, seen from outside or from the experience of specialists in the field, illustrates the variety of activities and ways of serving the mission. They are consistent with most engineering activities in OECD countries.

NOTE.– By transferring to the PE domain, what Pillai and Bezbaruah (2017) published on the social perception and attitude aspects of nanoparticles and nanotechnologies, Figure 1.12 highlights the different parameters to be considered, in order to have an understanding of the desirability (and rejection) of a technology. In the case of the PE, which is largely invisible to the lay public, the image is neither negative nor positive at the bottom, which is not quite the case for chemistry (see also Cobb and Macoubrie 2004; Burri and Bellucci 2008; Berube *et al.* 2011).

1.6. Placement of engineers with a degree from French grandes écoles

It is difficult to have information and/or statistics on the placement of process engineering graduates at a European level, but the latest data we have collected, at the informal level of the European Chemical Engineering Federation[1], show that the labor market is doing well, and that young people from European training courses with a Bachelor's degree in process engineering (currently!) have no difficulty finding their first job. Moreover, in France, PE engineering schools are fairly well-placed in the hierarchy of schools, as indicated in the recent report of the *Usine Nouvelle* (2019). We are in the presence of a *student's market*, but for how long?

At the National School of Chemical Industries (ENSIC), the latest survey[2] conducted by the *Conférence des grandes écoles* and the *Fédération Gay-Lussac* (pioneering network of engineering schools) in 2018 confirms these trends: young graduates are easily integrated into industry. More specifically, more than half of engineering students (51%) found their first job before graduation, and almost a quarter (22%) within two months. The average time to access employment is 1.2 months, and almost all new hires (97%) have a managerial position, most of them on permanent contracts (85%).

On average, six months after graduation (some students graduate in September, others in December, as a result of curriculum extensions), only 6% of students in the 2018 class (which had 140) are still looking for work. In addition, 76% are in professional activities, 10% in thesis (this proportion is indicative of the good health of the market, the number of engineers continuing in thesis increases when

1 https://efce.info/.

2 https://ensic.univ-lorraine.fr/sites/ensic.univlorraine.fr/files/users/pdf/metiers-carrieres/placement_2018_promos2013-2014-2015-2015-2016-2017.pdf.

proposals decrease), 3% in pursuit of studies (same trends as for thesis prosecutions), and 4% in voluntary work.

The positions held are still in the traditional professions of process engineers: production and operations (29%), research and development (24%), studies and consulting (12%), or technical assistance (7%). Similarly, the sectors of activity remain those that traditionally hire process engineers: chemical industry (23%), consulting firms and design offices (16%), energy (12%), agri-food industry (5%) with an increase in jobs in the pharmaceutical industry (24%). Finally, as regards geographical distribution, 19% work in the Île-de-France region, 64% in the provinces, and 17% abroad. Average annual gross salaries vary from nearly €42k in France to nearly €53k abroad.

At the National School of Engineers in Chemical and Technological Arts (ENSIACET), the data show the same trends for[3] the two departments of chemical and process engineering: more than half of the graduates of the CE (50%) and PE (58%) departments had signed a contract before leaving school, and 17% of them within the following two months. Most contracts remain permanent contracts (72%) in large companies (with more than 80% of jobs are in companies with more than 50 employees).

The functions of young graduate engineers also include research and development (25% in CE and 13% in PE), studies and consulting (18% in CE and 28% in PE), production (16% in CE and 13% in PE), and technical assistance (8% and 9% for both departments). The sectors of activity seem identical to those of ENSIC students: chemical industries (34% in CE and 21% in PE), consulting and engineering (22% CE and 26% PE) energy (6% CE and 13% PE) and environment or agri-food (10% CE and 7% PE). There is also no major difference in the geographical distribution of graduates from these two ENSIACET departments: 27% work in the Île de France region and 24% abroad. On the other hand, average annual salaries seem a little lower, from €33 to €35k. Perhaps the figures are not discounted, or given in net salaries?

Finally, at the National Superior Engineering School of Industrial Technologies (ENSGTI), the data on the hiring of graduates[4] remain the same: 2.3 months of average time to find a first job, 95% on permanent contracts and 75% in management positions. The professions occupied by graduates of the ENSGTI's "Processes" course also concern studies and consulting (29%), research and development (15%) and production (14%). The sectors of activity also fall within the same fields, except for the chemical industries: design office (28%), energy

3 http://www.ensiacet.fr/fr/relations-industrielles/emplois-et-carrieres/observatoire-premier-emploi.html.

4 https://ensgti.univ-pau.fr/entreprise/insertion-professionnelle/.

(30%), agri-food (5%) or eco-industries (10%). The average salary is of the same order of magnitude as for ENSIACET graduates, equal to €32k per year.

This first comparison of the three main engineering schools in chemical engineering and process engineering in France shows that young graduates do not have any major difficulty in finding their first job, and that the functions performed and the sectors of activity are indeed those targeted by the training.

More generally, the latest analysis of the employment of engineers (IESF, 29th National Survey of Engineers, 2018) confirms the trends observed in chemical and process engineering: an unemployment rate much lower than the national average (3.4% compared to 8.9%), down between 2016 and 2017, as well as a better integration of the latest promotions. These observations also show an increase in recruitment rates for all engineers – particularly in the agri-food, pharmaceutical, and energy industries, and even difficulties in recruiting in some areas, such as engineering companies.

About 93% of salaried engineers are on permanent contracts and 96% have executive status. Then there are 16% who work abroad, and the highest expatriation rates are in the extractive industries (35%), chemical industries (21%), and pharmaceutical industries (31%). Engineers are mainly engaged in research and development (32%) and production (20%). The average salary at the time of hiring is €34k gross per year. The statistics of the three chemical engineering schools in France are consistent with these latest data.

Non-engineering scientists (master's and/or doctoral graduates) seem to be slightly more affected by unemployment (5.1% compared to 3.4% for engineers). They are less numerous in industry and service companies, as well as in large companies. They are also more present in administration and research, as well as in the public sector. Their salaries increase slightly less than those of engineers over the course of their careers. However, these latter statistics have been obtained from a relatively smaller number of staff than the total non-engineering scientific population.

It is difficult to obtain such statistics at a European level. The few published studies concern both the fields of chemistry and chemical engineering (Salzer *et al.* 2015) and are not very recent. At the American level, the DataUSA[5] sites and the Bureau of Labor Statistics[6] show that chemical engineering engineers work in the chemical industry (35.5%), the pharmaceutical industry (17.4%), and refining (11.8%), for an average salary (all ages combined) of $105k per year. Growth

5 https://datausa.io/profile/soc/172041/.

6 https://www.bls.gov/ooh/architecture-and-engineering/chemical-engineers.htm.

estimates are 7.5%, slightly higher than the national average of 7.4%. The activities of American chemical or process engineers include technology in Figure 1.13, communication, management, complex problem solving and training.

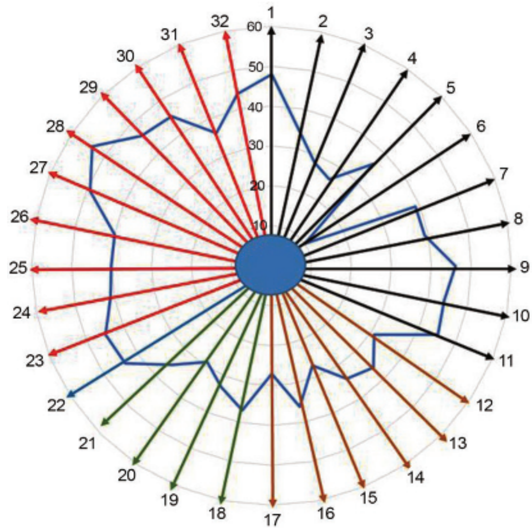


Figure 1.13. *Activities of PE engineers (Salzer et al. 2015). For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*

COMMENT ON FIGURE 1.13.– *This figure details the skills expected of American engineers. These include the importance of science, mathematics, critical thinking, communication in general, solving complex systems, decision-making... and continuing education. Notions that are easy to teach, all in all! 1) operations analysis; 2) technology design; 3) equipment selection; 4) programming; 5) monitoring; 6) operation and control of operations; 7) equipment maintenance; 8) repair, quality control analysis, 9) judgment and decision-making; 10) system analysis; 11) system evaluation; 12) social perception; 13) coordination; 14) persuasion; 15) negotiation; 16) teaching; 17) service orientation; 18) time management; 19) financial resource management; 20) material resource management; 21) personal resource management; 22) complex problem solving; 23) written comprehension; 24) active listening; 25) expression; 26) writing; 27) mathematics; 28) critical thinking; 29) science; 30) active learning; 31) learning strategies; 32) control. Arrows: black (technologies); brown (communication); green (management); blue (problem solving); red (training).*

1.7. The PE engineer role

> Anyone possessing it does not say, for instance: "Here this or that has happened, will happen, must happen". He uses his imagination and

> says: "Here such and such might, should or ought to happen". And if he is told that something is the way it is, then he thinks: "Well, it could probably just as easily be some other way". So the sense of possibility might be defined outright as the capacity to think how everything could 'just as easily be', and to attach no more importance to what is than to what is not. It will be seen that the consequences of such a creative disposition may be remarkable, and unfortunately they not infrequently make the things that other people admire appear wrong and the things that other people prohibit permissible, ox even make both appear a matter of indifference. Such possibilitarians live, it is said, within a finer web, a web of hazy imaginings, fantasy and the subjunctive mood. If children show this tendency, it is vigorously driven out of them and in their presence such people are referred to as crackbrains, dreamers, weaklings, know-alls, and carpers and cavillers. (Musil 1930/2011)

Figure 1.14 from Gosh (2015) recalls the areas of competence of process engineers.

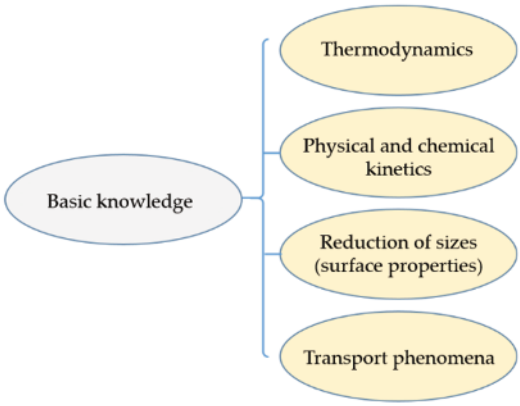


Figure 1.14. *Reminders on the basics of process engineering*

1.7.1. *Incremental changes*

> Normals are the only ones who are willing to leave things as they are; they limit themselves to the present and settle there without regret or hope. (Pigasse 2014)

Current training combined with continuing education enables technological engineers to play a leading role in the development of the material and energy processing industries. A number of specific comments that are presented in Figure 1.15 incorporate other qualities/skills completed in Figure 1.16.

Figure 1.15. *Skills needed in the training of engineers (According to Bensah* et al. *2011). For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*

COMMENT ON FIGURE 1.15.– *1) Establishment of a curriculum profile; 2) implementation of semester modules; 3) development of module outlines; 4) development of modules (courses) based on competency standards; 5) development of functional competencies; 6) development of generic competencies.*

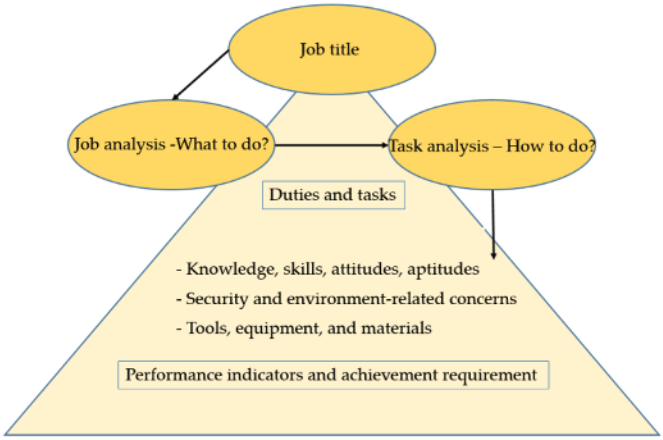


Figure 1.16. *Qualities and skills (see Bensah, Ahiekpor, and Boateng 2011)*

While engineering education has long focused on acquiring know-how through the provision of solidly proven and verifiable data (Grelon 1988; Maldonaldo and Gomez-Cruz 2012; Roby 2014), this historical situation changed significantly after the Second World War with the rise of innovation and techno-science (Etzkowitz 2008). Moreover, if only for brand image and communication policies, many schools have opened up training to new disciplines such as human biology, humanities and social sciences, economics, etc. The realistic argument is that the contribution of these disciplines combined with basic knowledge makes it possible to convey the complexity of the real world (Veltz 2007).

Supervising the production forces of Taylorian industry until recently, the engineer in charge of a project becomes a "boss" of a micro-enterprise, requiring autonomy, a sense of team leadership, listening, adaptability, etc. It is time for cooperation. According to Germinet (1997), a company is not approached by the "general", but by the individual. When hiring, a young manager should demonstrate technical competence, observation skills, conceptualization skills and, if possible, assertiveness by demonstrating general integration skills.

These different skills will have to be integrated into a new context in which citizens should/can play an enhanced role to take into account the major trends that will be widely discussed in Chapter 5 (Sörnik and Kleibrink 2015; Hill and Lawton 2018), leading to new skills that engineers will need to overcome the demands (needs) of the economy in the future, with more radical technological developments in which science and information technology will have to take a key role (see Table 1.4 from Boston Consulting Group 2015)).

Emerging Megatrends	Challenges and opportunities for Europe in 2030
Middle Class Growth: Opportunities and Risks	1) The working population will decrease by 21 million operators 2) Radical changes in working conditions will require new job ergonomics, organizational structures and leadership style
Research "Blue sky"	1) Development of the convergence of disciplines, with a significant contribution from research in biology 2) Research focused mainly on new generation robotics and studies on the human brain
Disruptive technologies and disruptive business models	1) Growth will be based on breakthrough discoveries but also on the innovation of the economic model 2) The innovation business model will be driven by the development of social networks, including suppliers, producers, customers, end users, and employees
Complex systems: integration and (in)stability	1) Unfortunate events can occur on the periphery of stakeholder networks and lead to disruptions in the production system 2) But the resilient system can be restored
Digital society: power, communication	1) Content can be accessible on demand and produced by the users themselves 2) Mass communication through horizontal networks with virtual and real-time interactive exchanges will give individuals new ways to exchange and produce

Table 1.4. *Reminders on the major trends in the current socio-economic situation that will need to be taken into account*

At the same time, what we are seeing is a “brain drain” of scientists within Europe, leading to the creation of hubs of excellence, and therefore naturally to a specialization of knowledge in certain parts of the Union (Van den Wende 2015), from which a specific attraction for students and specialized training also specific flows. To convince of the current trends, Figure 1.17 (European Parliamentary Research Service 2015) illustrates the differences in funding for tertiary education in Europe.

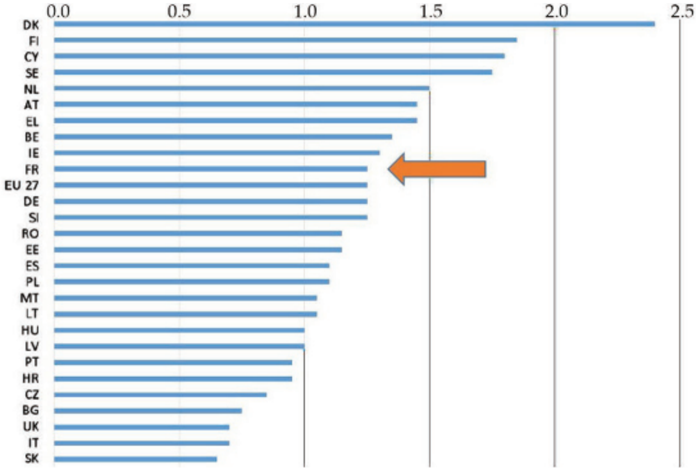


Figure 1.17. *Differences between financing academics in Europe (% of GDP)*

An OECD analysis (2015), presented in Table 1.5, also highlights measurable differences in the distribution of university education in science and technology (STEM) across the countries concerned, partly in association with their involvement in secondary industry (more so than in the tertiary sector).

Country	STEM (%)	HSS (%)	Other (%)
China	40	60	0
India	35	53	12
Germany	28	51	21
United Kingdom	22	40	38
France	18	74	8
USA	15	67	18
Brazil	11	72	17

Table 1.5. *Differences between the percentage of STEM training in different countries (other areas may include medicine, health and/or agriculture) – HSS for “humanities and social sciences”*

Finally, the National Science Foundation (NSF 2015), recalls the great diversity of jobs based on initial training. Following its 2014 report and after meetings with experts, this organization is developing, in the same reference, ideas for the future of the science, technology, engineering and mathematics (STEGMA) workforce. The main ideas that emerged from the NSF's work are as follows:

– in STEGMA, the workforce is quite large and essential for innovation and competitiveness, defined as subcategories of the workforce. For each subcategory, career opportunities can vary considerably by employment sector, industry, or region;

– the knowledge and skills related to jobs in the sectors covered by STEGMA make it possible to build dynamic bridges to fill shortages in other sectors. This approach invites policy makers to focus on ways to increase labor productivity. For example, what are the respective roles of governments, educational institutions and employers in activating and strengthening these bridges?

– the activation and strengthening of bridges between jobs in the sectors covered by STEGMA and those in other sectors is essential to increase the prosperity and competitiveness of individuals and the nation. The country must ensure that all individuals have access to high quality education. It should also encourage the participation of groups traditionally under-represented in the STEGMA sectors (e.g. minorities and women). This will allow the country to benefit from the capabilities of all its people and ensure that they can fully participate in a knowledge-based economy and become globally competitive.

1.7.2. *Open-mindedness*

To adapt to the growing complexity of his profession and environment, the engineer of tomorrow will have to strengthen his general culture and his interpersonal skills without compromising on the excellence of his technical knowledge. Developments include confirmation of the central role of innovation, increased internationalization, plus the emergence of societal concerns such as sustainable development or ethics, strengthening of services, etc. All these developments are transforming the industry and will revolutionize the engineering profession in the 21st Century. Their priority? Be more generalist than ever. Of course, they will always rely on irreproachable technical and scientific knowledge. But math experts will also have to take care of their interpersonal skills. A recent global study, conducted by six universities (including MIT) and funded by the German automotive supplier Continental, encouraged engineering schools to give more attention to this behavioral dimension. The most advanced are working on it. Cultivating team spirit and adaptability, developing one's ethical sense, working on one's creativity, but also strengthening one's general culture to better understand one's interlocutors, regardless of their geographical or disciplinary origin: these are some of the key skills that the engineer of tomorrow will have to master (Fauvel 2007). Stanford in the USA in the same way directly supports the development of entrepreneurship (Standford 2015). Table 1.6, taken from the World Economic Forum (2015), illustrates the trends seen by this organization to promote employment by relying on openings that emerge from traditional training.

Ages concerned	Considerations
Between 15 and 55 years old	Encourage employees to cooperate with public authorities and educational institutions in designing curricula and providing formal education and technical training.
Between 15 and 55 years old	Adapt education and vocational training to the specific needs of regions and industry, taking into account local perceptions and socio-economic contexts.
Between 20 and 60 years old	Promote the acquisition of essential employability skills *through* formal education through experiential learning for students, including internships, employee relations and field trips.
Between 20 and 60 years old	Establish a clear framework for vocational training that is linked to academic education and includes transferable standards and qualifications.
After 25 years	Expand the organization's training opportunities throughout the value chain and provide incentives for suppliers and distributors to participate in training.
After 25 years	Redirect workers according to the changing needs of the industry and combine training with placement services.
After 25 years	Promote lifelong learning through flexible training modules and programs with transferable qualifications.

Table 1.6. *Complements to training courses to promote employment*

1.7.3. *Between conformity and creativity*

> The French are always late, because they have trouble changing their minds, even in the face of changing facts. (Lenglet 2014)
>
> When we are faced with a holistic reality, we use subterfuge. (Friedman 2018)

More thought should be given to the consequences of our aversion to risk, our immoderate taste for safety and signposted career paths, royal roads in senior administration and income-generating positions in large groups. In fact, we pay a very high price for the devaluation of the entrepreneur's image in French society. Yes, we have a problem of culture, or rather of economic inculture. The French understand nothing about the entrepreneur's motivations, which are too quickly associated with the lure of profit. A century ago, the economist Schumpeter wrote very accurate sentences about the deep psychology of the entrepreneur. He is above all driven by an immoderate taste for innovation, the desire to shake up the established order, the fight against conformism, the ability to overcome resistance, to convince and lead his employees to new horizons.

The entrepreneur is an adventurer and a creator. Let us even dare to say that the entrepreneur is a transgressor who takes a malicious pleasure in changing the rules of the game. France, that of elitist competitions and the learning of conformity, is sorely lacking. Our *grandes écoles* or higher education establishments, because they have the ambition to attract and train the best, have their share of responsibility. Both in their selection and in their programs, they do not sufficiently value imagination, creativity, originality and the taste of risk. The risk, the real risk, is when it comes, for example, to fight with one's back to the wall to create a company and jobs, or to save a company and its employees' jobs.

The teaching of elite streams must further stimulate the capacity to innovate and create. He must value the qualities of intuition related to our emotional intelligence as much as the qualities of rational deduction. And why not encourage boldness, even impertinence, rather than conformity? And then, our *grandes écoles* should confront students with their particular responsibilities to preserve the national interest (Faibis 2011, 2014; Hachtable 2012):

> Demonstration is the systematic way of moving from the acquired to the new, and it ensures that, if the acquired is valid, the new one is also valid: it therefore gives conditional certainty. Euclid's demonstrations are still valid, as are Bourbaki's; it is the cement of mathematical constructions. (Kahane 1994)

In France, the common base of knowledge and skills lists a set of knowledge, skills and attitudes that every engineering student must master at the end of their training. This set mainly revolves around the transmission of knowledge – organized into disciplines – and critical thinking (although we can be pleased to see areas targeting "methods and tools for learning" (Taddei 2010). As a very French specificity, our critical thinking training is now necessary, but not sufficient. It is only one component of what we call 21st Century skills: critical thinking, communication, creativity and cooperation. We should therefore focus our efforts on other skills, in particular creativity (defined as the ability to imagine or achieve something new, original). With the author of Creating Innovators (Wagner 2012), it can be argued that teaching creativity is no longer an option, but an essential component of education. Indeed, while the emphasis was placed on the assimilation of a sum of knowledge in the past, what matters today for a student is not what he knows, but what he does with what he knows. Simply put, our industrial age educational paradigm is now obsolete because we live in a post-industrial world.

Moreover, according to Maldonaldo and Gomez-Cruz (2012), the increasing complexity of engineering requires changes in training and skills to be able to explore “border problems” in a flexible way; then his mastery of complexity sciences becomes an asset in international competition. However, it should be noted that in the fields of material and energy transformation, there are old processes (e.g. soda ash) as well as innovative processes in fine chemistry. There is therefore a wide spectrum of activities that must avoid any reductionism in the strategic choices of process engineering courses.

Moreover, in this post-industrial world, engineering students must, more than ever, learn to innovate, take risks and fail. As Paul Tough (2013) points out, error is an important element in the success of the learning process, as is the ability to persevere. He emphasizes the importance of seven attitudes that every student must cultivate, such as perseverance, curiosity, discipline and self-control. Therefore, creativity should be at the center of the learning process. More experimentation and playful moments are essential, which certainly requires moving away from our culture of memorization and written tests to move towards diverse learning situations. We need to put in place times when student-engineers are engaged learners who use their knowledge as a tool to solve problems in a creative and collaborative way. Figure 1.18, taken from Deloitte (2015), highlights the different criteria to be respected for value creation, a virtuous chain in which the engineer must take its full dimension.

But at the same time, as Hegedus (2005) points out, they will have to continue to master traditional knowledge. The example of chemical reaction engineering shows four types of reactive systems that depend on the nature of the transformation reactions of the material. Almost certainly, the knowledge dedicated to these operations should continue (Figure 1.19 on the next page). See also (Dudukovic 2010; Dudukovic and Mills 2015).

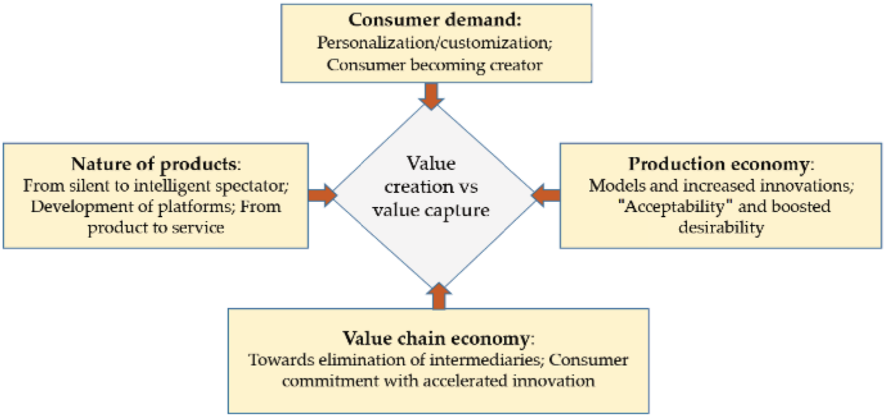


Figure 1.18. *Value chain*

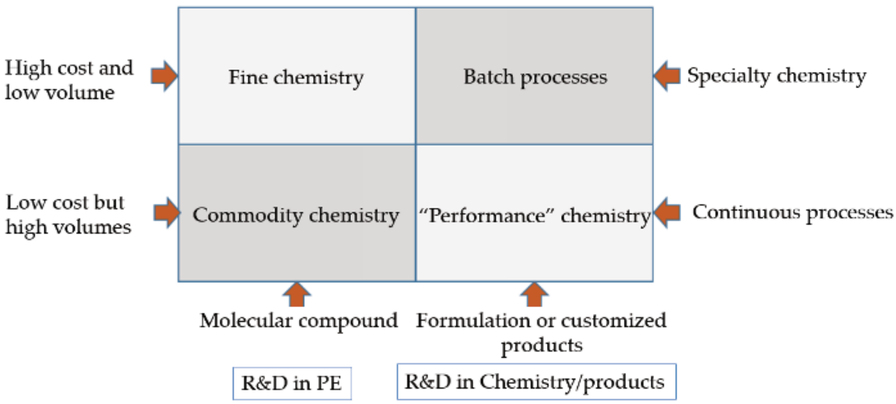


Figure 1.19. *Stability of chemical reactor selection modes according to the nature of the transformations considered*

1.8. A sociological approach to future students

What do we think of this statement: *The children now love luxury; they have bad manners, contempt for authority; they show disrespect for elders and love chatter in place of exercise. Children are now tyrants*? Socrates is the author. Or this one: *When fathers get used to letting their children do what they want, when teachers tremble in front of their pupils and prefer to flatter them, when finally young*

> *people despise the laws because they no longer recognize, above them, the authority of nothing or anyone, then it is there, in all beauty and youth, the beginning of tyranny.* It is from Plato, in 347 BCE. Conclusion: The question of 'differences' between generations is not a new one. (Richer 2018)

If only because of the considerable development of branches of National Institute of Information and Communication Technology (NICT), it is no longer possible to link men and women together as was done in the past. This simple observation leads to the necessary changes in pedagogical terms that need to be clarified. Economic, political and technological transformations and globalization, as well as the accelerated development and dissemination of knowledge in all fields of human activity, are making it increasingly difficult for knowledge to monopolize. For example, Figure 1.20, taken from EUA Publications 2015, shows the integration of internationalization processes into training and education in European universities.

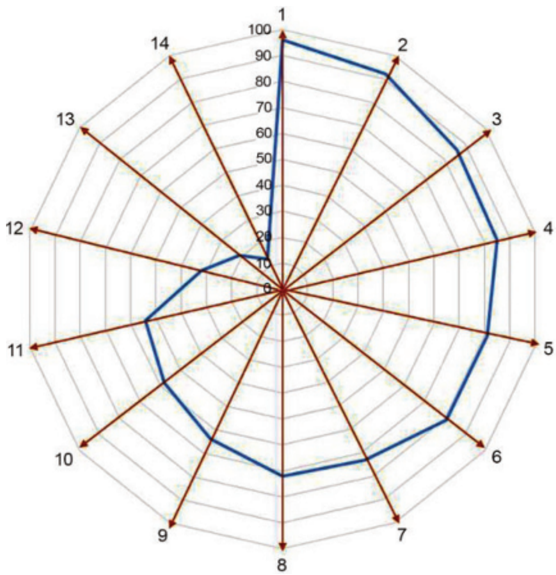


Figure 1.20. *Integration of internationalization processes into training and teaching in European universities (%). For a color version of this figure, see www.iste.co.uk/schaer/process1.zip*

COMMENT ON FIGURE 1.20.– *This figure highlights the different modalities of internationalization of student programs: 1) student exchanges; 2) teacher exchanges; 3) professional placement/student internships; 4) participation in international advanced education networks; 5) strategic partnership with selected* *foreign institutions; 6) curriculum taught in English; 7) international marketing; 8) summer schools; 9) internationalization in the country of origin; 10) international student recruitment campaigns; 11) capacity-building projects with partners in developing countries; 12) curriculum taught in a language other than English; 13) MOOC – Massive Online Open Course and other online training; 14) campus abroad.*

The advent of ICTs marks a revolution in the production and dissemination of knowledge, on a scale equivalent to that brought about by the arrival of writing and printing. Historically, knowledge was carried by teachers, by masters, but new actors are now intervening. Knowledge is now available when and where it is wanted, and this leads to a whole new relationship with knowledge among the new generations, which challenges institutions and methodologies. The teacher-student relationship is profoundly altered by the possibilities offered by ICT (Tubella 2015).

However, the hypertextualisation of the Net, broadband and search engines have accustomed us to the immediacy and availability of information. We can no longer wait and we get angry when we don't find the online information we are looking for. However, some believe that it is increasingly difficult to focus on topics that require analysis and understanding. NICTs not only change our habits, but also make us adopt new ways of thinking and permanently change the way our brains work (Neerdael 2014).

1.8.1. *Heterogeneity of the university framework*

The university's ability to form an institutional framework therefore depends essentially on the social actors, their will and strategies; it is therefore a weak, non-directive and very heterogeneous "institution". According to Georges Felouzis (2001), this conclusion sheds light on the root causes of the university crisis, understood as its competition with the *grandes écoles*, and its failure in terms of elite training. The increasing heterogeneity of the academic world, its increasing submission to the capacities of its agents to transcend the lack of managers, makes it highly vulnerable to institutions that are on the contrary characterized by a strong ability to offer students a normative environment (see the comparisons made between Finland, Denmark, Ireland, the Netherlands and Switzerland in (MEC 2015)). It is the democratization of higher education, in a context of unequal allocations of resources between the different parties, that is directly at stake. There is therefore a need to reform the university system in order to give the institution the means to carry out its democratization mission: one of the approaches proposed is that of university colleges, renamed here "medium universities", specifically dedicated to the first cycle, in a context of real care for students, both in terms of material resources (places, resources, supervision) and adapted teaching methods.

But the elitist principle persists, which translates into social origins that represent only a very imperfect representation of the population in the fields of engineering.

1.8.2. *Cultural developments*

We differentiate between technology, behavior and lifestyles. Lifestyles are transmitted from generation to generation through oral communication, as well as through the people around them. Cultural change is the transmission of culture through society. This is achieved through oral communication, the social environment and different behaviors. This change has always existed, but the process has become more complex over time. According to Malinowski (2004), cultural change gives the notion of "culture" a very broad meaning. Culture encompasses all social phenomena, it is an "organic unit"; by studying the culture of a population, we study institutions and their interactions. Around the rise of ICT, changes and developments related to their multiple and complex uses are developing. However, the world is experiencing a technological force and a steady development of digital cultures, which is the source of new socio-economic and cultural regulation: social cohesion, mobility, ICT and professional activities, multimedia in mobiles and security, data protection are among the problems to be taken into consideration (Licoppe 2009). It deals with the development of mobile devices, the emergence of a "utopia of communication" and a paradigm, "new mobilities" that are associated with forms of feedback, but also with rapid access to knowledge external to pedagogues alone. These different elements are shown in Figure 1.21, taken from Bauer and Erdogan (2015).

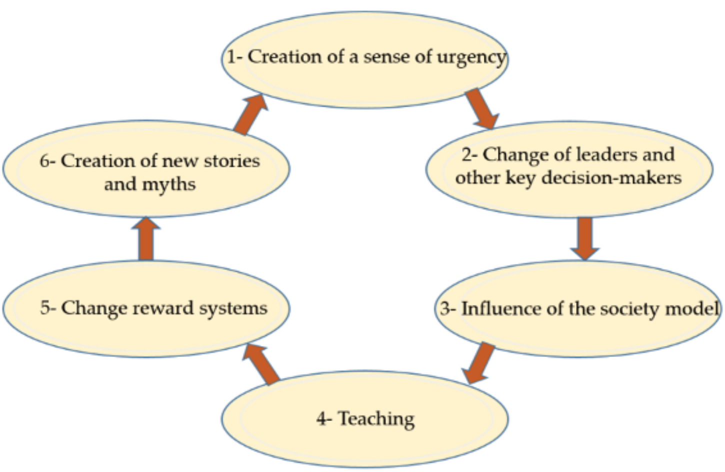


Figure 1.21. *Elements of cultural change*

Information and communication technologies tend to reconfigure the daily life of the younger generations. Having grown up in a digital environment, they are inventing a new culture with its specific codes and a metamorphosis of human relations (Lardellier 2006): the development of widespread entertainment, but an essential development of a knowledge society (Vryzas and Tsitouridou 2011). Education is a complex operation that aims to adapt culture to the needs of its members, and its members to the needs of culture and society. This operation is therefore not neutral because it has economic and social consequences.

Nevertheless, there are still obstacles (and this is undoubtedly normal) to the diffusion of information and communication technologies in classrooms, as indicated in the recent report of the Comité de Valorisation de l'Enseignement du Québec-Canada (2015), which highlights agreements and disagreements on the use of these "new" technologies (see Table 1.7). If most teachers use them, there may be tensions about implementation in the "field".

Question	Strongly agree	Agree	Disagree	Strongly agree	Don't know	N/A
A colleague who uses devices for non-teaching purposes bothers me	20.7	19.9	26.7	29.2	0.8	0
When I use a digital camera in class I feel like I'm disturbing the teacher	8.8	25.6	32.2	20.8	6.1	6.6
Ditto but oriented towards colleagues	5.6	14.5	37.5	31.4	4.4	6.7
My neighbors' screens distract me	13	25.1	32.1	27.5	0	0
The ringing and vibration of the devices bother me	38.4	40	12.2	7.3	0	0
The sound of keyboards bothers me	8.4	17.6	30.7	39.6	1.4	0
I don't like to see my colleagues using their digital equipment	11.3	17.8	30.6	35	4.3	0

Table 1.7. *Mixed relationships between NICTs and students*

1.9. Conclusion

> […] mainly the outcome of purely modern conditions (rapidity of communication creating a greater complexity and delicacy of the credit system) have rendered the problems of modern international politics profoundly and essentially different from the ancient. (Angell 1911)

Lamarck wrote in 1808:

> We know that every science must have its own philosophy and that it is only by following this path that one makes real progress. In vain, naturalists will consume their time describing new species, grasping all the nuances and small peculiarities of their variations to expand the immense list of listed species… If the philosophy of science is neglected, its progress will be unrealized, and the entire work will remain imperfect.

For more than a century, the estate has stabilized and maintains its technical legitimacy.

Process engineering is, it should be recalled, an Engineering Science associated with the study of the transformation of inert or living matter and energy, for application or finalized purposes. It is based on the acquisition of robust scientific knowledge to control these transformations by integrating all phenomena and processes (multi-scale and multi-physical) and their couplings (complexity as seen by engineers). The presence in the "scientific system" of centers of engineering excellence constitutes a specific potential for national and international attractiveness and influence, from which the economic world can benefit. This is how it is possible today, with an interdisciplinary vision, open to other disciplines and to society:

– to promote industrial innovation through the development of new processes or products, services, organizations, and business models in order to develop the competitiveness of companies;

– to support the transformation of all innovation stakeholders (companies, institutions, research, companies, citizens, etc.) towards responsible innovation (seeking a balance between economic development, reducing environmental impacts, and respecting societal and ethical values).

However, as will be discussed in this book, anyone who dares to question the procedures accepted by the majority of the scientific community risks being considered as deviant, non-compliant – but their work won't be. It will be considered uncontrollable until the day a happy idea passes into the economic field.

However, it is often by formulating different questions that new avenues of research are opened up for us. It is a fundamental balance between expert conformity and a sometimes-disturbing creativity that will be required.

Creativity and organization (real, often different from the one displayed) do not always go hand in hand. Organizing a human group means setting up a certain number of means, rules, procedures or values aimed at ensuring the effective cooperation of its members. It is in a way an attempt to channel individual actions, to reduce uncertainty and unpredictability in order to shape collectives for operational efficiency and desired performance. The research and training system has therefore been set up for deviants who have "succeeded" well in a period of strong growth. However, creativity and innovation promote deviance and upset the established order. It is therefore a very difficult art in the West, where the transformation of matter and energy drone on too much in a context where risk-taking and entrepreneurial spirit are lost:

> The myth of a happy convergence of technology, production and consumption masks all political and economic counter-purposes. How indeed could a system of techniques and objects conceivably progress harmoniously while the system of relations between the people who produced it continued to stagnate or regress? (Baudrillard 2005)

On this basis, in a world under various constraints, presented in the next chapter, there is therefore room for reflection on the public utility role of engineering sciences, and in particular process engineering:

> In mathematics we suppose, in physics we pose and establish; there are definitions, there are facts; we go from definitions to definitions in the abstract sciences, we walk from observations to observations in the real sciences; in the first, we strive evidence, in the last we strive for certainty. (Leclerc 2018)

And in process engineering?

> This imagination is absolutely amazing. But instead of using it to advance our knowledge, dogmatics restricts it and almost completely eliminates it: we learn the "truth" and then must either forget the rest, or completely dissociate it from the realm of truth and give over to poetry. This leads to a dry and boring science and unintelligent poetry. We can already see here that the dogmatic approach will not only influence the sciences. It will mould every activity of human life, emotions as well as thought. (Feyerabend 1999)

The daily dereliction [feeling of abandonment, loneliness] in which we operate tool systems that refer to each other, engages us in cycles of goal-oriented actions, the latter being stages in the functioning of tool systems, and nothing else. When it comes to choosing an action or performing it with reference to a value as oppose to a return of ustensity, the existence plunged into daily dereliction becomes helpless. (Puech 2016)

The scientist is always subjected to uncultivated scientific people who use him/her to establish their power, their ambitions, without even knowing how to evaluate the dangers of the actions they choose. (Vidal 2011)

Companies don't like to take too much at the [doctoral level]. The researcher is then too experienced, they already have many opinions on many things. They prefer more malleable young people, debauched at the master's level, who can ingest their corporate culture without asking too many questions, and who will grow with the company. (Professor Archibald, Research Chair in Human Retrovirology, Université du Québec à Montréal cited by (Heil 2010))

Science at its most interesting is provocative, surprising, counter-intuitive and difficult to plan – and those are very difficult values to institutionalize in an organization or bureaucracy of any size. I have seen my own grant proposals get chewed up and rejected with comments like "typically bold, but wildly ambitious", and wondered why it is wrong to be ambitious in one's research – but perhaps that is a conclusion fully consistent with science by committee. (Quake 2009)

The decision to embark on an innovative enterprise cannot be the result of a rational risk assessment, because the rational risk assessment will always lead to not undertaking and maintaining one's executive job or position as a project manager until better days for entrepreneurial openness. (Martinaud 2012)

It would be a great mistake to think of the content of chemical engineering science as permanently fixed. It is likely to alter greatly over the years, in response to the changing requirements of industry and to new scientific discoveries and ideas for their application. (Danckwerts 1966)

One of the weak points of the chart was that it kept no log of the calculations that were made: the work disappeared as it was

> completed. Impossible to verify the accuracy of a calculation unless it is repeated. (Hemenway 2008, translated from the French)
>
> A revolution in energy sources had to occur [...] along with the storage and measurement of a newly mobile energy – before humans and objects could be drawn into a fresh, objective dialogue, into a conflict-laden dialectic. (Baudrillard 2005)
>
> In competition for senior positions, an individual who wastes energy seriously questioning the limits and costs of development has no chance of achieving a "brilliant" career. (Cérézuelle 2011)
>
> The French reaction is to protect the acquired when it is already obsolete. (Brunet-Labbez 2013)

1.10. References

Alter, N. (1999). Organisation et innovation. In *Les organisations ; états des savoirs*, Cabin, P. (ed.). Sciences Humaines, Auxerre.

André, J.-C. (2019). *Industry 4.0: Paradoxes and Conflicts*. ISTE Ltd, London and John Wiley & Sons, New York.

Angell, N. (1911). *The Great Illusion*. G.P. Putnam's Sons, New York and London.

Ayache, G. (2018). L'humanité a atteint ses limites, mais elle ne le sait pas… encore [Online]. Available at: http://www.up-magazine.info/index.php/decryptages/analyses/5497-l-humanite-a-atteint-ses-limites-mais-elle-ne-le-sait-pas-encore.

Barles, S., Guillerme, A., Lestel, L. (2009). Pollution industrielle et réglementation des manufactures et ateliers en France au XIX^e siècle : les textes fondateurs. *Documents pour l'histoire des techniques*, 17, 174–218 [Online]. Available at: http://journals.openedition.org/.

Baudrillard, J. (2005). *The System of Objects*. Verso, London and New York.

Bauer, T., Erdogan, B. (2015). Creating culture change [Online]. Available at: http://www.peoi.org/Courses/Coursesen/orgbeh1/ch/ch15d.html.

Bensah, E.C., Ahiekpor, J.C., Boateng, C.D. (2011). Migrating from subject-based to competency-based training in Higher National Diploma Chemical Engineering: The case of Kumasi Polytechnic. *Education for Chemical Engineers*, 6, 71–82.

Berger, G. (ed.) (1962). Les exigences de la technique et l'éducation. In *L'homme moderne et son éducation*. PUF, Paris [Online]. Available at: http://institut-gaston-berger.insa-lyon.fr/sites/institut-gaston-berger.insa-lyon.fr/files/doctorat_mpescudie.pdf.

Berger, G. (ed.) (1964). L'idée d'avenir [Online]. In *Phénoménologie du temps et prospective*. PUF, Paris. Available at: http://institut-gaston-berger.insa-lyon.fr/sites/institut-gaston-berger.insa-lyon.fr/files/doctorat_mpescudie.pdf.

Berube, D.M., Cummings, C.L., Frith, J.H., Binder, A.R., Oldendick, R. (2011). Comparing nanoparticle risk perceptions to other known EHS risks. *Journal of Nanoparticle Research*, 13, 3089–3099.

Bhaskar, V., Gupta, S.K., Ray, A.K. (2000). Applications of multi-objective optimization in chemical engineering. *Reviews in Chemical Engineering* [Online]. Available at: https://www.researchgate.net/profile/Ajay_Ray/publication/228552913_Applications_of_multiobjective_optimization_in_chemical_engineering/pdf.

Bigelow, J. (1829). *Elements of Technology*. Hilliard, Gray & Co, Boston.

Birck, F., Rollet, L. (2015). La Faculté des sciences de Nancy dans le processus de constitution d'universités régionales (1854–1918). In *L'Université à Nancy et en Lorraine : histoire, mémoire et perspectives*, El Gammal, J., Germain, E., Lormant, F. (eds). Éditions universitaires de Lorraine, Nancy, 82–112.

Bird, R.B., Stewart, W.E., Lightfoot, E.N. (1960). *Transport Phenomena*. John Wiley & Sons, New York.

Böhme, G., Van Den Daele, W., Hohlfeld, R., Krohn, W., Schäfer, W. (1983). *Finalization in Science – The Social Orientation of Scientific Progress*. Springer, Dordrecht.

Boston Consulting Group (2015). Industry 4.0: The future of productivity and growth in manufacturing industry [Online]. Available at: https://www.bcgperspectives.com/Images/Industry_40_Future_of_Productivity_April_2015_tcm80-185183.pdf.

Bousquet, J. (2008). Chimie industrielle et génie des procédés. *L'actualité chimique*, 320–321.

Breton, C. (2008). Procédé Solvay à l'ammoniac. *Techniques de l'Ingénieur*, 1, J6195.

Brunet-Labbez, J. (2013). *Innover avec la génération Y*. Studyrama, Paris.

Burhop, C., Lübbers, T. (2010). Incentives and innovation? R&D management in Germany's chemical and electrical engineering industries around 1900. *Explorations in Economic History*, 47, 100–111.

Burri, R.V., Bellucci, S. (2008). Public perception of nanotechnology. *Journal of Nanoparticle Research*, 10, 387–391.

Bush, V. (1945). *The Endless Frontier*. United States Government Printing Office, Washington.

Cameron, R. (1982). The Industrial Revolution: A misnomer. *The History Teacher*, 15, 377–384 [Online]. Available at: http://www.jstor.org/stable/493817.

Cérézuelle, D. (2011). *La technique et la chair : essai de philosophie de la technique*. Parangon, Lyon.

Chaptal, J.-A. (2009). Pollution industrielle et réglementation des manufactures et ateliers en France au XIXe siècle : les textes fondateurs. *Documents pour l'histoire des techniques*, 17, 174–218 [Online]. Available at: http://journals.openedition.org/dht/363.

Charpentier, J.C. (2002). The triplet “molecular processes – product – process” engineering: The future of chemical engineering?. *Chemical Engineering Science*, 57, 4667–4690.

Charpentier, J.C. (2016). What kind of modern “green” chemical engineering is required for the design of the “factory of future”?. *Procedia Engineering*, 138, 445–458.

Charpentier, J.C, McKenna, T.K. (2004). Managing complex systems: Some trends for the future of chemical and process engineering. *Chemical Engineering Science*, 59, 1617–1640.

Chen, C. (1996). The early history of chemical engineering: A reassessment. *British Journal for the History of Science*, 29, 171–94.

Churchill, S.W. (2007). Role of universalities in chemical engineering. *Industrial & Engineering Chemistry Research*, 46, 7851–7869.

Citton, Y. (2014). *Pour une écologie de l’attention*. Le Seuil, Paris.

Cobb, M.D., Macoubrie, J. (2004). Public perceptions about nanotechnology: Risks, benefits and trust. *Journal of Nanoparticle Research*, 6, 395–405.

Comité de valorisation de l’enseignement (2015). L’utilisation des appareils mobiles en classe [Online]. Available at: http://www.bsp.ulaval.ca/docs/RapportGTUAMC.pdf.

Conso-Globe (2018). Production mondiale de bicarbonate de soude [Online]. Available at: https://www.planetoscope.com/hygiene-beaute/1433-production-mondiale-de-bicarbonate-de-soude.html.

Costa, R., Moggridge, G.D., Saraiva, P.M. (2006). Chemical product engineering: An emerging paradigm within chemical enginering. *Amercian Institute of Chemical Engineers*, 52, 1976–1986.

Da Lage, A., Amat, J.-P., Frérot, A.-M., Guichard-Anguis, S., Julien-Laferrière, B., Wicherek, S.P. (2008). *L’après développement durable : espace, nature, culture et qualité.* Ellipses, Paris.

Danckwerts, P.V. (1966). Science in chemical engineering. *Chemical Engineering journal*, CE155–CE159.

Davies, G.E.A. (1904). *Handbook of Chemical Engineering*. Davis Brothers, Manchester.

Davis, M.E. (2009). The rise and realization of molecular chemical engineering. *AIChE Journal*, 55, 1636–1640.

Delaplace, G., Loubière, K., Ducept, F., Jantet, R. (2014). *L’analyse dimensionnelle : un outil pour conduire des changements d’échelle raisonnés ; méthode et exemples résolus*. Hermes-Lavoisier, Paris.

Deloitte (2014). The decade ahead: Preparing for an unpredictable future in the global chemical industry [Online]. Available at: http://www2.deloitte.com/be/en/pages/manufacturing/articles/the-decade-ahead-unpredictable-future-global-chemical-industry.html.

DGGB – Département de génie chimique et de génie biotechnologique (2017). Historique de la profession. Université de Sherbrooke [Online]. Available at: https://www.usherbrooke.ca/gchimiquebiotech/futurs-etudiants/au-baccalaureat/futurs-etudiants-bacc-gch/la-profession/historique/.

Divall, C., Donnelly, J.F., Johnston, S.F. (2008). Professional identity and organization in a technical occupation: The emergence of chemical engineering in Britain. *Contemporary British History*, 13, 56–81.

Drechsler, W. (2009). The rise and demise of the New Public Management: Lessons and opportunities for South East Europe. *Central European Public Administration Review*, 7(3) [Online]. Available at: http://cepar.fu.uni-lj.si/index.php/CEPAR/article/view/131/128.

Dudukovic, M.P. (2010). Reaction engineering: Status and future challenges. *Chemical Engineering Science*, 65, 3–11.

Dudukovic, M.P., Mills, P.L. (2015). Scale-up and multiphase reaction engineering. *Current Opinion in Chemical Engineering*, 9, 49–58.

Etzkowtiz, H. (2002). *MIT and the Rise of Entrepreneurial Science*. Routledge, New York.

Etzkowitz, H. (2008). *The Triple Helix: University-Industry-Government Innovation in Action*. Routeledge, New York.

EUA Publications (2015). Trends 2015: Learning and teaching in European Universities [Online]. Available at: http://eua.be/.

European Parliamentary Research Service (2015). Higher education in the EU: Approaches, issues and trends [Online]. Available at: http://www.europarl.europa.eu/EPRS/EPRS-IDA-554169-Higher-education-in-the-EU-FINAL.pdf.

Faibis, L. (2014). Grandes écoles et déficit d'entrepreneuriat [Online]. Available at: http://www.xerfi.com/Newsletter/xerfiactiv/Live/Xerfi_Paroles-d-experts_Laurent-Faibis.html.

Fauvel, P. (2007). Les ingénieurs de demain : des forts en maths ouverts sur le monde. *L'Usine nouvelle* [Online]. Available at: http://www.emploi-pro.fr/article/les-ingenieurs-de-demain-des-forts-en-maths-ouverts-sur-le-monde-138.html.

Favre, E., Marchal-Heusler, L., Kind, M. (2002). Chemical product engineering: Research and educational challenges. *Transactions of the Institution of Chemical Engineers – Part A*, 80, 65–74.

Felouzis, G. (2001). *La condition étudiante. Sociologie des étudiants et de l'université*. PUF, Paris.

Feyerabend, P. (1999). *Une connaissance sans fondements*. Dianoïa and PUF, Paris.

Freund, H., Sundmacher, K. (2008). Towards a methodology for the systematic analysis and design of efficient chemical processes – Part 1. From unit operations to elementary process functions. *Chemical Engineering and Processing*, 47, 2051–2060.

Foray, D. (1992). Choix de la technique, rendements croissants et processus historiques. In *La technoscience – les fractures du discours*, Pradès, J. (ed.). L'Harmattan, Paris, 57–92.

Forest, J., Faucheux, M. (2013). Rationalité la mise en œuvre d'une pédagogie de l'aventure creative : vers. *Université de Sherbrooke*, 505–512 [Online]. Available at: https://hal.archives-ouvertes. fr/halshs-00842171/document.

Freshwater, D.C. (1989). The development of chemical engineering as shown by its texts. In *One Hundred Years of Chemical Engineering – From Lewis M. Norton (M.I.T. 1888) to Present*, Peppas, N.A. (ed.). Kluwer Academic Publishers, Dordrecht, 15–25.

Fressoz, J.-B. (2012). *L'Apocalypse joyeuse – une histoire du risque technologique*. Le Seuil, Paris.

Friedman, Y. (2018). *L'ordre compliqué et autres fragments*. Éditions de l'Éclat, Paris.

Furter, W.F. (1980). *History of Chemical Engineering*. American Chemical Society, Washington.

Furter, W.F. (1982). *A Century of Chemical Engineering*. Plenum Press, New York.

Galbraith, J.K. (1967). *The New Industrial State*. Hamish Hamilton, London.

Germinet, R. (1997). *L'apprentissage de l'incertain*. Odile Jacob, Paris.

Gingras, Y., Keating, P., Limoges, C. (2001). Du savant au chercheur entrepreneur. *Sciences humaines*, 31 (special edition), 32.

Giroudière, F. (2008). *Élaboration des schémas de procédés – de l'idée à l'unité industrielle*. Techniques de l'Ingénieur, Paris

Gorz, A. (2011). *Critique of Economic Reason*. Verso, London and New York.

Gosh, P.S. (2015). How chemical engineering will drive the 21st century [Online]. Available at: http://web.mit.edu/psgleadership/pdf/1_required_reading/How%20Chemical%20Engineering%20will%20Drive%20the21st%20Century%20Woburn.pdf.

Grangier, G. (1986). Pour une épistémologie du travail scientifique. In *La philosophie des sciences aujourd'hui*, Hamburger, J. (ed.). Gauthiers-Villars, Paris.

Grelon, A. (1988). Les écoles d'ingénieurs et la recherche industrielle. *Culture Technique*, 18, 232–239.

Grossetti, M. (2004). L'académisation des savoirs techniques. La lente progression des sciences d'ingénieurs dans les universités et la recherche académique. Report, Sciences, innovation technologiques et sociétés, Tours [Online]. Available at: https://halshs.archives-ouvertes.fr/file/index/docid/476803/filename/Grossetti-Tours-textes.pdf.

Grossetti, M., Detrez, C. (2000). Science d'ingénieurs et sciences pour l'ingénieur : l'exemple du génie chimique. *Sciences de la Société*, 49, 63–85.

Grossmann, I.E. (2003). Challenges in the new millennium: Product discovery and design, enterprise and supply chain optimization, global life cycle assessment. *Proceedings of the 8th International Symposium on Process Systems Engineering*, 28–47.

Guillet, L. (1908). *L'industrie de la soude*. Éditions Gauthier-Villar, Paris [Online]. Available at: http://iris.univ-lille1.fr/bitstream/handle/1908/3390/42163-165.pdf.

Hachtable (2012). Sciences Po, ENA : ces fabriques d'élites déconnectées [Online]. Available at: http://h16free.com/2012/11/29/19067-sciences-po-ena-ces-fabriques-delites-deconnectees.

Hegedus, L.L. (2005). Chemical engineering research of the future: An industrial perspective. *AIChE Journal*, 51, 1870–1871.

Heil, C. (2010). De la science à la technoscience, du chercheur au technologue. PhD thesis, Université d'Évry [Online]. Available at: https://www.biblio.univ-evry.fr/theses/2010/2010 EVRY0016.pdf.

Hemenway, P. (2008). *The Secret Code*. Evergreen, Cologne.

Hers, H.-G. (1998). *Science, non-science et fausses sciences – réflexions sur les chemins de la connaissance*. L'Harmattan, Paris.

Hill, C., Lawton, W. (2018). Universities, the digital divide and global inequality. *Journal of Higher Education Policy and Management*, 40, 598–610.

Hoffmann, A. (2000). Institutional evolution and change: Environmentalism and the US chemical industry. *Academy of Management Journal*, 42, 351–371 [Online]. Available at: https://deepblue.lib.umich.edu/bitstream/handle/2027.42/136182/1349_Hoffman. pdf.

Jarrige, F. (2012). Jean-Baptiste Fressoz, l'apocalypse joyeuse. Une histoire du risque technologique. *Revue d'histoire du XIX^e^ siècle*, 45, 187–189 [Online]. Available at: http://journals.openedition.org/rh19/4354.

Kahane, J.-P. (ed.) (1994). Mathématiques et formation. *La Pensée*, 88–102 [Online]. Available at: http://www-irem.ujf-grenoble.fr/revues/revue_x/fic/40/40x1.pdf.

Karpik, L. (2010). *Valuing the Unique: The Economics of Singularities.* Princeton University Press, Princeton.

Kaufmann, J.-C. (2001). *Ego – pour une sociologie de l'individu*. Éditions Nathan, Paris.

Lamarck, J.-B. (1808/1999). *Philosophie zoologique*. Le Livre de Poche, Paris.

Lardellier, P. (2006). *Le pouce et la souris : enquête sur la culture numérique des ados*. Fayard, Paris.

Lauth, C. (1879). Lettre au ministre de l'Agriculture et du Commerce ; fragment. In *L'industrie chimique en question*. A&J Picard, Paris.

Le Goff, P. (1965). *La mise en équation d'un problème de génie chimique*. Techniques de l'Ingénieur, Paris.

Le Moigne, J.-L. (1993). Sur les fondements épistémologiques de la science de la cognition. In *Systémique et cognition*, Andreewsky, E. (ed.). Dunod, Paris.

Le Moigne, J.-L. (2002). Sur l'épistémologie des sciences de conception, sciences d'ingenium : concevoir des artefacts évoluant. In *Proceedings of The Sciences of Design: The Scientific Challenge for the 21st Century, In Honour of Herbert Simon*. Centre des Humanités, Lyon.

Le Moigne, J.-L. (2013). Sur l'intelligence de la complexité, en entrelaçant épistémologie et pragmatisme. In *Intelligence de la complexité – épistémologie et pragmatisme*, Le Moigne, J.-L., Morin, E. (eds). Hermann, Paris, 13–27.

Leclerc, G.L., comte de Buffon (2018). In *Petit recueil de pensées scientifiques*, Masson, N., Caudal, Y. (eds.). Éditions du Chêne and Hachette, Vanves.

Lenglet, F. (2014). *La fin de la mondialisation*. Pluriel, Paris.

Li, J., Kwauk, M. (2003). Exploring complex systems in chemical engineering – The multi-scale methodology. *Chemical Engineering Science*, 58, 521–535.

Li, J., Kwauk, M. (2004). Complex systems and multi-scale methodology. *Chemical Engineering Science*, 59, 1611–1612.

Licoppe, C. (2009). *L'évolution des cultures numériques – de la mutation du lien social à l'organisation du travail*. FYP, Paris.

Maldonaldo, C.E., Gomez-Cruz, N.A. (2012). The complexification of engineering. *Complexity*, 17, 8–15.

Malinowski, B. (2004). Les dynamiques de l'évolution culturelle [Online]. Available at: http://classiques.uqac.ca/classiques/malinowsli/dynamiques_evolution/dynamiques_evolution.html.

Malisoff, W.M. (1941). Chemistry: Emergence without mystification. *Philosophy of Science*, 8, 39–52.

Martinaud, B. (2012). *Startup : anti-bible à l'usage des fous et des futurs entrepreneurs*. Pearson, Orléans.

Mashelkar, R.A. (1995). Seamless chemical engineering science: The emerging paradigm. *Chemical Engineering Science*, 50, 1–22.

Massard-Guilbaud, G. (2004). Histoire : les industriels de la chimie et la pollution au XIX^{e} siècle [Online]. Available at: http://www.industrie.com/chimie/histoire-les-industriels-de-la-chimie-et-la-pollution-au-xixe-siecle,35731.

MEC – Ministry of Education and Culture of Finland (2015). Towards a future proof system for higher education and research in Finland [Online]. Available at: http://www.minedu.fi/export/sites/default/OPM/Julkaisut/2015/liitteet/okm11.pdf.

Millet, J.-C. (2008). Chlore (Cl2). *Techniques de l'Ingénieur*, J6215 v2.

MIT-ChemE (2018). History [Online]. Available at: https://cheme.mit.edu/about/history/.

Musil, R. (1930/2011). *L'homme sans qualités*. Livre de Poche, Paris.

National Academies (2005). Educating the engineer of 2020: Adapting engineering education to the new century [Online]. Available at: http://nap.edu/11338.

National Research Council of the USA (1971). Technological forecasting and its application to engineering materials. NMAB-279 [Online]. Available at: http://www.dtic.mil/dtic/tr/fulltext/u2/726221.pdf.

Neerdael, D. (2014). *Une puce dans la tête*. FYP, Paris.

NSF (2015). National Science board: Revisiting the STEM workforce [Online]. Available at: http://www.nsf.gov/pubs/2015/nsb201510/nsb201510.pdf.

OECD (2015). Education indicators in focus [Online]. Available at: http://www.oecd.org/edu/skills-beyond-school/EDIF%2031%20(2015)--ENG--Final.pdf.

OIC – Observatoire des industries chimiques (2016). Les métiers des industries chimiques [Online]. Available at: https://presse.apec.fr/.

Perkins, J. (2002). Education in process systems engineering: Past, present and future. *Computers & Chemical Engineering*, 26, 283–293.

Perrin, R., Scharff, J.-P. (1993). *Chimie industrielle*. Masson, Paris.

Pigasse, M. (2014). *Éloge de l'anormalité*. Plon, Paris.

Pillai, R.G., Bezbaruah, A.N. (2017). Perceptions and attitude effects on nanotechnology acceptance: An exploratory framework. *Journal of Nanoparticle Research*, 19.

Puech, M. (2016). *Homo-sapiens technologicus*. Le Pommier, Paris.

Quake, S. (2009). Guest column: Letting scientists off the leash. *Opinionator – The New York Times*, February issue.

Richer, M. (2018). Les X et les Y : générations perdues pour le travail ? [Online]. Available at: http://www.metiseurope.eu/les-x-et-les-y-generations-perdues-pour-le-travail-thinsp_fr_70_art_30738.html.

Roby, C. (2014). Place et fonction des SHS dans les Écoles d'ingénieurs en France : état des lieux, enjeux et perspectives épistémiques. PhD thesis, Université de Rennes, Rennes.

Rosenberg, N. (1998). *Chemical Engineering as a General Purpose Technology*. MIT Press, Boston.

Salzer, R., Taylor, P., Majcen, N.H., De Angelis, F., Wilmet, S., Varella, E., Kozaris, I. (2015). The professional status of european chemists and chemical engineers. *Chemistry European Journal*, 21, 9921–9935.

Science/Business (2015). Views of 2030: Transport, manufacturing, education and health [Online]. Available at: http://sciencebusiness.net/.

Séon, T. (2018). *Les lois d'échelle – la physique du petit et du grand*. Odile Jacob, Paris.

Serres, M. (2017). *Homo-informatix*. Le Pommier, Paris.

Sörnik, J., Kleibrink, A. (2015). Mapping innovation priorities and specialization pattern in Europe [Online]. Available at: https://ec.europa.eu/jrc/sites/default/files/JRC95227_Mapping%20Smart%20Specialisation%20Priorities.pdf.

Standford (2015). Standford entrepreneurship network [Online]. Available at: http://www.sen.standford.eu.

Steelman, J.R. (1949). Science and public policy: A program for the nation. The President's Scientific Research Board, Washington.

Stengers, I. (1989). L'affinité ambiguë : le rêve newtonien de la chimie au XVIII^e siècle. In *Éléments d'histoire des sciences*, Serres, M. (ed.). Bordas, Paris.

Taddeï, F. (2010). Inventer une nouvelle maïeutique pour apprendre à apprendre. *Cahiers pédagogiques*, 478 [Online]. Available at: http://www.cahiers-pedagogiques.com/Inventer-une-nouvelle-maieutique-pour-apprendre-a-apprendre.

Thom, R. (1986). La méthode expérimentale : un mythe des épistémologues (et des savants ?). In *La philosophie des sciences aujourd'hui*, Hamburger, J. (ed.). Gauthiers-Villars, Paris.

Tough, P. (2013). *How Children Succeed: Grit, Curiosity and the Hidden Power of Character*. Mariner, New York.

Tubella, I. (2015). Nouvelles technologies et éducation [Online]. Available at: http://www.college-etudesmondiales.org/fr/content/nouvelles-technologies-education.

UIC – Union des industries chimiques (2018). Image de la chimie [Online]. Available at: http://www.uic.fr/content/download/419965/4680092/file/OSER%20LA%20CHIMIE_Image%20de%20la%20chimie.pdf.

UNIDO (2018). Structural change for inclusive and sustainable industrial development [Online]. Available at: https://www.unido.org/sites/default/files/files/2018-04/Structural_Change_for_ISID.pdf.

Usher, A.P. (1920). *An Introduction to the Industrial History of England*. Houghton Mifflin, Boston.

Usine Nouvelle (2019). Les écoles réservées aux candidats "bac + 2" trustent les premières places [Online]. Available at: https://www.usinenouvelle.com/comparatif-des-ecoles-d-ingenieurs-2019-bac-2.

Van Antwerpen, F.J. (1980). The origins of chemical engineering. In *History of Chemical Engineering*, Furster, W.F. (ed.). American Chemical Society, Washington.

Van den Wende, M. (2015). International academic mobility: Towards a concentration of the minds in Europe. *Center for studies in higher education (Berkeley – USA)*. Available at [Online]: http://www.cshe.berkeley.edu/sites/default/files/shared/publications/docs/ROPS.CSHE_.3.15.Wende_.AcademicMobility.2.10.2015.pdf.

Veltz, P. (2007). *Faut-il sauver les grandes écoles ? De la culture de la sélection à la culture de l'innovation*. Presses de Sciences Po, Paris.

Vidal, B. (2011). *Le conflit science-société*. Technedit, Paris.

Villermaux, J. (1995). Future challenges in chemical engineering research. *Transactions of the Institution of Chemical Engineers*, 73 (part A), 105–109.

Vinck, D. (1999). *Pratiques de l'interdisciplinarité*. Presses universitaires de Grenoble, Grenoble.

Voncken, R.M., Broekhuis, A.A., Heeres, H.J., Jonker, G.H. (2004). The many facets of product technology. *Chemical Engineering Research and Design*, 82, 1411–1424.

Vryzas, K., Tsitouridou, M. (2011). Technologie, culture et éducation. *Synergies Sud-Est européen*, 3, 15–34.

Wagner, T. (2012). *Creating Innovators: The Making of Young People Who Will Change the World*. Scribner, New York.

Walker, W.H., Lewis, W.K., McAdams, W.H. (1923). *Principles of Chemical Engineering*. McGraw-Hill Book Co., New York.

Wei, J. (2004a). Design and integration of multi-scale structures. *Chemical Engineering Science*, 59, 1641–1651.

Wei, J. (2004b). The integration of process and product design. In *Proceedings of the 6th International Conference on Foundations of Computer-Aided Process Design*. FOCAPD, 7–18.

Wesselingh, J.A. (2001). Structuring of products and education of product engineers. *Powder Technology*, 119, 2–8.

Wikipedia (2018). Procédé Solvay [Online]. Available at: https://fr.wikipedia.org/wiki/Procédé_Solvay.

Wintermantel, K. (1999a). Process and product engineering – Achievements, present and future challenges. *Chemical Engineering Science*, 54, 1601–1620.

Wintermantel, K. (1999b). Process and product engineering – achievements, present and future challenges. *Transactions of the Institution of Chemical Engineers*, 77 (part A), 175–188.

Wolf, M. (2009). Consentement, autonomie, complexité [Online]. Available at: http://www.ethique.sorbonne-paris-cite.fr/.