Chapter 11

Innovation in Chemical Engineering Industries

In the face of rapid evolution in our society and the rise of new competitors at the global level, and the relative decline of industry in the developed countries over the past 10 years, there are great uncertainties and concerns about the future of our society. The reaction to this destructive slow evolution is very frequently used: "innovation is essential". As F. Barnu [BAR 10] emphasized, innovation appears to be the ultimate weapon for the West "to deploy" in the face of immense international competition.

From this perspective, innovation takes on an extraordinary dimension, but unfortunately it is also sometimes used as a catch-all response. Soon after the cry of "let us innovate" is uttered, everything remains to be done and nothing is achieved. There are approaches, however, that enable us to have a better understanding of innovation and to help us get our bearings, to act faster and ultimately give us more opportunities that lead to innovation.

Many of these methods are general in nature. Some of them have been adapted for the special features of manufacturing industries, services, or management of organizations. *There are some innovation methods specific to the chemical engineering industries and they are under constant evolution.* While making a connection between the market, technology and our discipline of reference, the chemical engineering, we can imagine that they will evolve considerably in the future.

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However, there is no “black or white” answer. The *pensée unique*[1] is poisonous to innovation. Innovation is a complex process and there is a large swath of possibilities. This is fortunate, because if there was a single response every time, then it would be very easy for our competitors to know our future implementations and the concept of innovation would become meaningless. Thus, *complexity is both the major difficulty of the innovation process, but also its major asset.*

Innovation cannot be confused with business strategy, but it must be integrated with it. It affects different levels of the company. So, within the company there are not people who must innovate and others who cannot, but on the contrary, it is a win-win process between the departments and leads to innovation.

Innovation has been with us for a very long time. Man has always innovated since the first tool or the discovery of fire, and western industry would not have reached its high level of development without innovations: innovation is synonymous with success.

The basic question about innovation is – what are we looking for? – at least to increase the survival capacity of the company (by retaining or growing its customers) and if possible, to increase its revenues. Ethical and environmental dimensions could be added, depending on the actors within each company. However, the evolution of the world, new needs, as well as what is represented by the third paradigm of chemical engineering [CHA 10, HIL 09], expands this concept of innovation by integrating the economic and social issues to the service of mankind, i.e. the integration of sustainable development issues: rational development of our industry, energy management, competition and international cooperation, health (notably emerging contaminants [RIC 11]), entrepreneurship, resource conservation, understanding society and its needs, preservation of industrial heritage, etc. This results in a growing demand for new processes: shorter implementation time (finding the solution faster), more flexible process units (reconfigurable, the product lifecycle becoming shorter and shorter), manufacturing of high quality products with a lower and safer ecological footprint, etc.

We must move towards a sustainable and competitive chemical engineering industry [CHA 07].

But before talking about innovation methods, let us recall what innovation is.

11.1. Definition of innovation

Innovation involves several levels of the companies and organizations. We thus have product, process, service, organization, or business model (for example, a

1 Here, a general meaning of this French expression, applied in several domains is implied. It highlights the fact of approach a particular problem, under a unique point of view.

recent innovation in the business model was the introduction in many countries of free newspapers and their mode of financing).

In the field of chemical engineering industries, it is clear that we are strongly concerned by the innovations of products and processes. However, other types of innovation may also have their places. The organization of the company can be improved or changed. For example, the introduction of *Open Innovation* (see section 11.4.4), is an organizational innovation that is contributing now to the creation of product and process innovations in some companies. Service innovation can also be an important leverage for some chemical engineering industries, for example by focusing on the functionality of certain products (e.g. physical or chemical properties) instead of talking about the products themselves.

It is interesting to note that sometimes the product sold may also be a process. This is the case in the field of equipment manufacturing; for example, a reactor of a wastewater treatment plant: this is a complex process sold as a product, which provides a service (to transform wastewater into clean water, which is meeting the requirements of regulations and which can thus be released into the natural environment). The concepts of product innovation and process innovation, and even service innovation, can thus sometimes cross over.

From the perspective of IP (Intellectual Property), the strategies to protect a process innovation can be very different if they involves a process innovation that can be kept secret within a company (and therefore closed to an outside view), or if they involve a process innovation sold as product, which will be found easily by contacting the competitors, and which may require patent protection.

It is also important to note that innovation is not invention. Innovation includes the concept of novelty (sometimes invention), which goes to the state of manufacturing (or of implementation for services and organizations), and which finally meets market success; innovation is therefore not just novelty.

Innovation is a complex process that finds its advantage and purpose in the significant improvement or commercial success that it brings to the company.

There are several alternatives to the definition of innovation. One of the most famous is that of the OECD (see Figure 11.1). It highlights the concept of significant improvement. OECD recently insists on the concept of success; for example commercial success, for products [OEC 05].

To complete the definition, we can define innovation according to the importance of its effects: incremental innovation, which sees small progressive and almost continuous effects, or breakthrough innovation (or *radical innovation*), which induces a dramatic change, and which can have significant effects on the company. They are often compared, because incremental innovation can strengthen the dominant position of a well established company in the market, and breakthrough innovation can allow a new company to emerge in the market, but can be difficult to manage for a company that already has a dominant position.

However, as breakthrough innovation is sought after (and sometimes difficult to obtain), these two types of innovation are complementary. And incremental innovations will often gradually improve breakthrough innovations (see Figure 11.2).

Innovation: the OECD Definition

There are essentially four types of innovation identified in the Oslo Manual for measuring innovation: product innovation; process innovation; marketing innovation and organizational innovation.

Product Innovation
This involves a good or service that is new or significantly improved. This includes significant improvements in technical specifications, components and materials, incorporated software, user friendliness or other functional characteristics. In the education sector, a product innovation can be a new or significantly improved curriculum, a new educational software, etc.

Process
Process innovation involves a new or significantly improved production or delivery method. This includes significant changes in techniques, equipment and/or software. In education, this can for example be a new or significantly improved pedagogy.

Marketing Innovation
Marketing innovation involves a new marketing method involving significant changes in product design or packaging, product placement, product promotion or pricing. In education, this can for example be a new way of pricing the education service or a new admission strategy.

Organizational Innovation
Organizational innovation involves introducing a new organizational method in the firm's business practices, workplace organisation or external relations. In education, this can for example be a new way organization of work between teachers, or organizational changes in the administrative area.

These innovations can be new to the firm/educational institution, new to the market/sector or new to the world.

Figure 11.1. *Definition of innovation according to the OECD*

A more detailed description of the types of innovation was proposed by Henderson, Clark and Tushman [HEN 09]. For product design, they propose to take into account the different components constituting an "object" and the manner in which they are organized (connection between them), which they call the product architecture. For example, for a fan, the various components are the motor, the propeller, the foot, the debris guard, and so on. However, it should be noted that the combination of certain components can play on the architecture gathering them together.

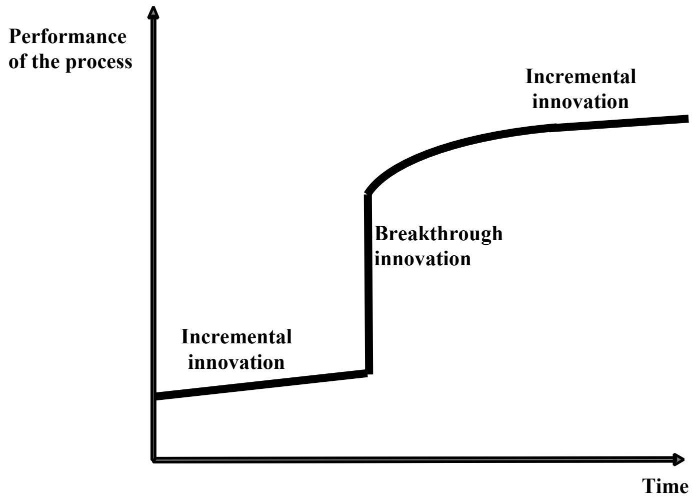


Figure 11.2. *Breakthrough innovation and incremental innovation*

We can thus define innovation according to two criteria: the evolution of one or more components and the evolution of architecture. We thus obtain four types of innovations that also include conventional types (incremental and radical):

– incremental innovation, small changes in the components and architecture;

– modular innovation, no (or small) change in the architecture but big changes in at least one of the components;

– architectural innovation, big change in the architecture, but not in the components;

– breakthrough innovation, big change in the architecture and components.

In the process industries, we can compare these types of classification with the process description by unit operations or processes. The process can thus be seen on different scales, the concept of component being associated with different devices:

– either on the one hand, various components constituting a unit operation (describing the architecture of the unit operation);

– or on the other hand, the unit operation representing a single component (describing the architecture of a workshop or a plant with several unit operations).

In this case, although the components cannot be associated equally, the architecture of process units can be studied from this point of view, for example to improve its flexibility.

Another type of innovation, often called disruptive innovation [CHR 97], affects the products (or processes, etc.), which do not provide real technical improvement (or even use inefficient technologies), but that finds by its characteristics (low cost, or very specific application domain, etc.) a niche market, and that finally meets success by progressively invading a large market. This is, for example, the case currently with the success of low cost cars in many countries.

Innovation is thus, in this case, more in the concept of use of the product than in the product (or the process) itself. For this reason, some refuse to talk about innovation here, even if there is a commercial success.

11.2. Field of innovation in the chemical engineering industry

The fields may differ depending on the type of innovation involved (product, process, process sold as product, service, organization, etc.). However, the broadest field of innovation is the one dealing with the product, starting from the evolution of the molecule and reaching the market, going through changes in processes (see Figure 11.3). We then realize the complexity of this process requiring staff capable of discussing among themselves and of understanding each other, from research and development department, the design office and so on, up to the marketing department. This requires a multiple, cross and multiscale approach, with more and more multi-disciplinary competencies as well as creativity. Here, each service should not allow its specialized competencies or be diluted in transversality.

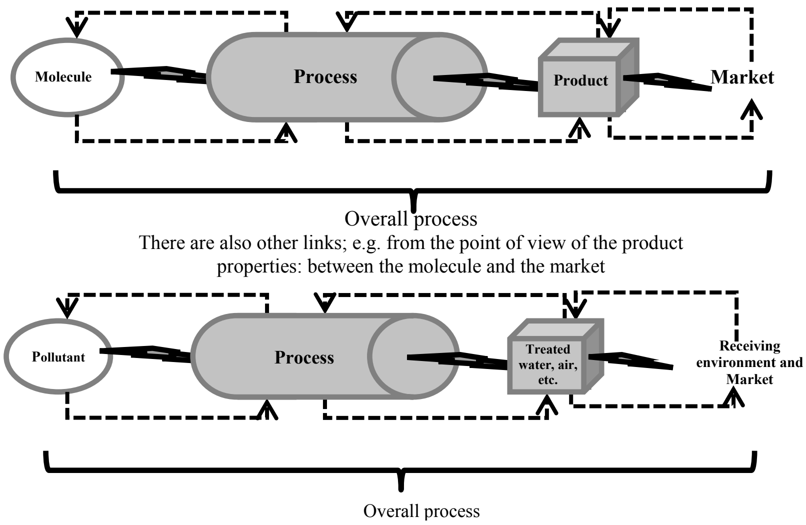


Figure 11.3. *Field of innovation, case of a chemical process from the molecule to market, and case of a pollutant treatment process*

On the contrary, the goal is that each specialist remains strong in their own field, but they must be able to communicate and understand people of other services. This refers to the *T-shape* [IAN 93]. The vertical line of the T symbolizes the specialist, and the horizontal line, their ability to understand and communicate in other domains.

Some companies have embarked on this very effective approach, but now it is still common to see that conflict arise in some other companies between marketing and R&D departments; one accusing the other of not understanding customers, the other accusing them of not understanding the technological constraints. These problems can diminish the innovation capacity. Thus, an ill-defined concept of customer–supplier between R&D and marketing services can be a source of conflict. A department of the company is not at the service of the other, but both have to work together toward the same goal.

The suppression of complexity may lead to conflict, but once better controlled, the complexity is also a great source of innovation.

This transversal vision (and mutual understanding) within the company is now essential to develop a sustainable and competitive industry.

This new innovation, integrating the constraints of the changing world, requires what we call *Creativity Under Constraints* (scientific, technological, economic and sustainable development constraints, etc.) to reach new results that are adapted to multiple requirements (see section 11.4.1).

11.3. The need for innovation

Most companies and countries are now investing more into innovation. At the end of the decade, despite the economic crisis of 2008, the amounts of investments in public and private R&D hadn't stopped increasing [OEC 10]. To paraphrase A. Hatchuel, we are in an innovation-intensive capitalism. Several factors determine nowadays this race for innovation. Among others, we can cite:

– the constant renewal of products, as a result of more demanding consumers, who are better informed and who demand a product and personalized associated services;

– the adaptation of the industry to this demand has led to new organizations in order to enable a quick response at a lower cost. For example, the modularization of the manufacturing systems has enabled us to reduce the development lead times of new products, while components, subsystems, or finished products end up going everywhere in the world before reaching the final consumer [BER 06];

– the convergence of technologies, as opposed to a mono-disciplinary vision, has allowed us to multiply the possibilities of products and to expand their field of application. For example, collaborations between nanotechnology and biotechnology are opening up a range of applications which have so far not been imagined in fields as diverse as health, environment, or industry;

– the constraints of energy security, which now force us to look toward new sources and to overcome the technological obstacles of current solutions; e.g. in the automobile industry, with the evolution of new (electric, hybrid, fuel cell) motorizations and the continuous improvement of the heat engine in terms of consumption and CO_2 emissions;

– the sustainability and environmental constraints, as a consequence of climate change that directly affects the productivity of agricultural lands and the availability of food for a constantly growing population.

All these factors together, and many other factors, mean that pressure and constraints on the company are permanent. In an uncertain context, innovation will take on an even greater importance as a key factor in the survival and growth of companies. In view of the R&D investments, companies and governments seem to be aware of this constraint. But the advantage cannot be limited only in quantitative terms of investments. New approaches that can increase the effectiveness of the innovation process prove to be necessary, because despite the efforts and progress in terms of creation and development of new products, the success rate of the innovation process remains very low (14%, according to a study by Cormican and O'Sullivan [COR 04]).

On the other hand, the traditional vision of R&D as being the only source of innovation in the company seems to reach its limits. Le Masson *et al.* [LEM 06] have proposed the emergence of a new feature of innovative design (I) within the companies.

In fact, they define Research (R) as a controlled process of knowledge production, and Development (D) as a controlled process that activates the existing competencies and knowledge in order to specify a system. The function (I), allows for the co-evolution of competencies and products. In other words; (I) must activate (R) and (D), which makes it possible to organize new cross-domain possibilities (see Figure 11.4).

The work of *Le Masson et al*. [LEM 06] illustrates, according to an account of *Hounshell and Smith* [HOU 88], how in the innovation of nylon 6-6 by the DuPont company, a result of the function (R) had to wait for several years so that a stakeholder, function (I), identifies the potential value of the result of this research by an application in the textile industry: nylon stockings.

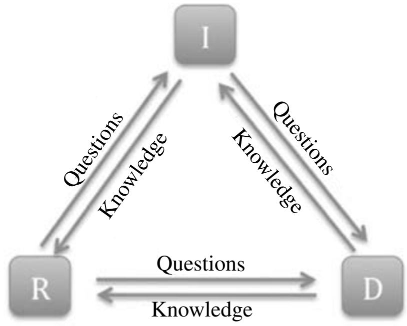


Figure 11.4. *Relations between R, I, and D (according to [LEM 06])*

Short history of nylon [ROB 83]

Nylon changed the history of the Dupont company forever and became the first entirely synthetic fiber, and also the first big success of this company. Used today for a wide variety of applications such as mechanical parts, guitar strings, parachutes, and all types of textile products. Here are some highlights of the history of its creation.

– 1927: Dupont decides to launch a research program without any clear commercial objectives, which was dedicated exclusively to artificial materials in the department of Elder Bolton (he became the head of the chemistry department in 1930). In fact, he had a true prospective and commercial vision of the researches he would undertake, his goal being to replace natural materials, especially for the automotive industry, which was growing strongly. He hired external academic consultants. At this time, this was a first.

– 1928: Wallace Carothers, until then an assistant at Harvard, is appointed to run the technical team. He started the research about obtaining polymers from basic constituent elements. For this, he developed a process that eliminated the need for hydrolysis of synthesized molecules, which deteriorates the technical performances of finished products.

– 1930: a member of the team (Julian Hill) obtaines a material for the first time, which is very solid after cooling.

– 1932: the research program is stopped, because the fibers obtained hitherto from aliphatic esters, presented more penalizing problems for a textile fiber: very low melting point and solubility or instability of organic solvents.

– 1934: Bolton refusing to give up, relaunches the program. Carothers decides to direct their researches more around polyamides. By relying on the results of the team which indicated that the most promising monomers were those of the C5–C10 order, Bolton decided to use benzene, a raw material that was available in large quantities for industrial processes. Thus, adipic acid and hexamethylenediamine, both derivatives of benzene, were selected as raw materials for polyamides (future nylon).

– 1935: the first filaments and fibers of nylon 6-6 are made. Their melting point reaches 263°C, an acceptable margin to withstand ironing temperatures.

– 1938: patent filing and release of the first commercial product using nylon: toothbrush bristle.

– 1940: marketing of the first womens stockings; in the first year, 64 million pairs of stockings were sold in the United States.

– 1941: during World War II, most of the production was dedicated to the manufacture of parachutes.

– 1945: second launch of nylon stockings; thousands of people are queuing up in front of the shops.

The creation of nylon was not only a technological and commercial revolution, but also a great scientific breakthrough, which required the development of new processes by Dupont.

Box 11.1. *The saga of nylon*

11.4. Methods for innovation in chemical engineering industry

Innovation methods adapted to the chemical engineering, or created especially for it, should take into account the technical and technico-socio-environmental-economic parameters, i.e. sustainable development which, in its global vision, also includes the problems of energy, health, etc.

The two most classical innovation strategies are: Market Pull and Technology Push. The first faces innovation and the business strategy through market analysis and its potentialities. The second strategy starts from the technological (and scientific) evolution in order to create new products to be supplied to the market. These two approaches can sometimes be very effective. They are opposed in their principles and applications. It can also result in an incapacitating opposition between certain departments of the company (see section 11.2). However, it is possible to overcome this opposition and combine these two methods, by not leaving the prevalence to one or the other, but by allowing for a real exchange between the departments: *the market analysis and research results taken together in a continual exchange, are together important sources of innovation*.

Other approaches can effectively lead to innovation. They are process approaches that we will develop further.

Nowadays, we teach these methods to engineering students, by integrating the concept of “Creativity Under Constraints”, in order to enable students to obtain this *T-shape* profile.

11.4.1. *Method of “Creativity Under Constraints”*

Why have we added the term constraints to the term creativity, which represents a certain kind of freedom? This is not about a terminology only affecting mechanics, or that evokes unwanted developments. The term is to be taken as a whole (scientific, technological, economic and sustainable development constraints, etc.).

Creativity sessions often occur in two steps.

The first step, also called *divergence*, seeks to promote the emergence of new ideas, and for this, it is important not to cause any deadlocks by the criticisms that would make difficult the process of idea creation, such as: what you say is not realistic; it is not economically feasible; or we do not have the resources, etc.

This process is easy for some and difficult for others. Besides, this is not very surprising because, generally, people are not trained to do this. The selection and training process in Western economies is mainly based on convergent intelligence, which enables students to produce solutions (and to focus on them very quickly) from things that have been learnt; this is mostly favorable to reproduce the existing, but not for promoting the emergence of new solutions, then of innovation.

This first phase of free creation is thus fundamental. There are many methods such as Brain Storming, to facilitate the process. A good summary of the methods is presented in the *Techniques de l’ingénieur* [VID 98].

The second step of the creativity process, also known as *convergence*, allows for the criticism and selection of the ideas proposed in step 1. They are closely remained through different criteria such as scientific, technical, and sustainable development criteria, etc. Some of these analyses can be very fast, and others will require additional studies or tests prior to validation.

By applying these techniques in companies or during the training of students, over the last few years, it seems that these two stages are often not sufficient to create new and concrete ideas. On the one hand, the blocking process in step 1 is not always overcome, but on the other hand, paradoxically, it seems difficult for some scientists and technicians to produce realistic ideas. We thus reach a dichotomy: on one side, ideas, and on the other, constraints, with no common ground leading to new and concrete ideas.

This is why we have set up a third step, the phase of *Creativity Under Constraints*, which corresponds to a production of ideas by taking into account, the scientific, technological, and social constraints, etc. The number of ideas provided in this step is less than those produced in step 1, but the proportion of concrete and achievable ideas is much greater.

Steps 1 and 2 are still necessary, as they gradually lead to the ability to generate ideas and to criticize them.

We can notice that during step 3, *the identification and study of constraints will often become a source of new ideas*.

This step of *Creativity Under Constraints* can be facilitated by also using other methods, for example by combining the market pull and technology push strategies (see beginning of section 11.4). In this regard, it would be better to generalize this second term into *Science and Technology Push*. More conceptual scientific dimensions can be added to this case as a basis of reflection; for example, constructal innovative approaches [TON 04].

Another method can be derived from the RAR approach (Result-Activity-Resources) which represents the process operation, such as a workshop, a company, or even problem resolution. It is generally used to identify the activities, and then the necessary resources to achieve a goal: the result. This corresponds to the market pull approach.

This RAR method can also be transformed and integrated in different ways at the third step, for example:

– with our (financial, technical, etc.) resources and taking into account the market, what product can we make by changing few of our activities?

– or, by changing some of our resources (e.g. raw materials, new competencies) and part of our activities, what product can we make?

– etc.

RAR is often used as a simple tool for business strategy. Sometimes, it is integrated into the customer–supplier approach, but all the constraints can also be added to it (see Figure 11.5).

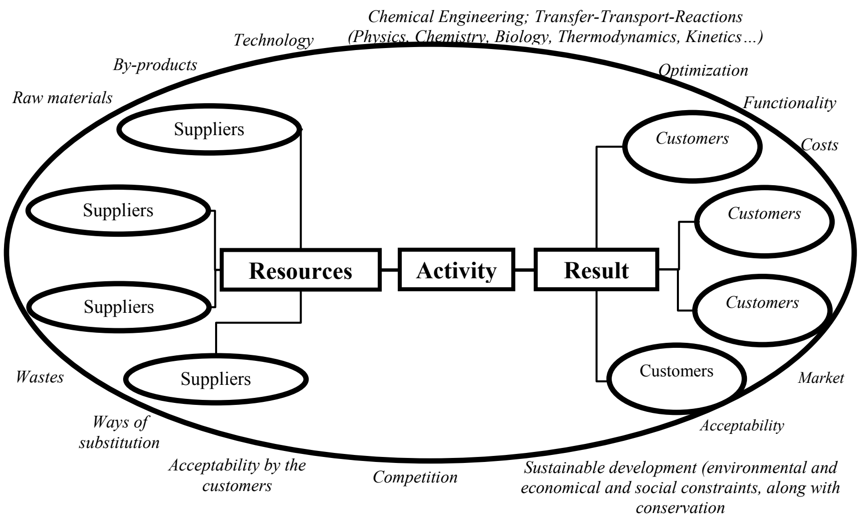


Figure 11.5. *Example of generalized RAR to present different socio-technico-economic-scientific constraints*

11.4.2. *Approach by the TRIZ method*

In contrast to the above constructivist methods, for which the ability to generate ideas depends on the inherent creative competencies of the participants, the TRIZ method proposes a positivist approach, where the technological problems are reformulated, and analyzed from different angles or principles [CAV 99]. This is a method of creativity, whose Russian acronym means theory of inventive problem solving. It was developed by the Russian inventor and scientist Genrikh Altshuller (1926–1998).

Altshuller found, after analyzing hundreds of thousands of patents, that there is an algorithm for solving an engineering problem. He also proposed a set of generic creative principles. The TRIZ method is implemented at the beginning of a design process [BOL 07]. It is used:

– in a prospective manner, to explore new concepts on future products;

– to resolve recurring technological problems or deadlock situations on the existing products and;

– to anticipate the ways of product development [ALT 99].

In order to have a general overview, we will cite the five key notions on which the TRIZ method is based:

– *contradictions:* TRIZ prohibits any direct transition from the initial problem to the solution, as well as compromises. Thus, any problems that have to be solved with TRIZ should be stated under the form of a contradiction, which the search for solutions will have to face. A contradiction must be aimed at improving one parameter, without degrading others;

– *resources:* these are substances, energies, pieces of information, etc. necessary for a technical system;

– *ideal final result*: consists of describing what we wish to obtain in the ideal case. It is a fantasy of the mind, an unattainable dream destined to open the pathway for problem solving;

– *laws of evolution:* G. Altshuller formulated eight laws of evolution of technical systems. Their knowledge would help to solve invention problems, and even to anticipate their appearance. Any technical system goes indeed through four ages: 1) evolution toward a successful combination of its parts, 2) development toward the ideal via the priority perfection from the least-effective part, 3) acquisition of dynamic properties (combination or fragmentation of parts) and 4) transition toward a self-controlled system (automation);

– *psychological inertia:* preconceived notions, tried and tested use of solutions, expertise, professional jargon, etc. are obstacles to creativity. They lead to self-limiting.

Currently, the TRIZ method is increasingly used by companies as large as Motorola, Dow Chemical, Unilever, Siemens and Intel [JAN 06]. A significant number of companies are still skeptical because they see in TRIZ the quest for an equation for innovation, which removes its unique character. Others see it as one more approach, just like the Six Sigma or Lean Manufacturing, which helps to improve the performance and productivity of companies.

It should be noted that TRIZ is designed for the manufacturing industry. It takes care of different functions that are found, for example in mechanics, but it includes only just a few of the many processes of chemical engineering.

TRIZ, in its initial configuration is therefore not very suitable for chemical engineering industries, but its adaptation could be very useful. Its application therefore remains limited compared to other fields of engineering [COR 09]. However, we can cite the works of Hipple [HIP 05] on TRIZ applied to the analysis of process failures, or those of Le Lann [LEL 07], which explores the application potentialities in the field of processes, or still the works of Cortes Robles [COR 09], where the authors propose an innovation accelerator applied to chemical engineering. This accelerator consists of two parts: the first is focused on incremental innovations and based on knowledge management (case-based reasoning), and the second is focused on radical innovations and based on a TRIZ algorithm.

11.4.3. *Management of the innovation process*

11.4.3.1. *Technology: a complex system*

Hammel & Prahalad [PRA 90] defined the core competencies (or technological competencies) of a company, as not only being the differentiating factor enabling the company to be competitive, but also as the most important component of the technological capital that must be managed to innovate.

Thus, controlling the evolution of the key-competencies of a company cannot be reduced to launching a research program or changing the equipment of a process unit. To remain at the forefront of technology, a patent, a machine, or a particular process is not enough; we must also be able to rely on the competencies of men and on managerial practices.

Later, Leonard Bauton [LEO 95] defined the nature of these core competencies as being constituted by four principle dimensions:

– physical systems;

– the skills and knowledge;

– the management systems encouraging knowledge creation;

– the values of the organization that guide and channel knowledge creation.

Any innovation process must take these dimensions into account. This idea is also reinforced by the concept of technological system [CAS 87], which expresses its competencies as being constituted by a core, which corresponds to the scientific and technical know-how, surrounded by a set of related competencies, such as financial, economic, managerial, or logistical competencies.

In all cases, the innovation process must be studied from a systemic point of view, as several levels of the company intervene in its implementation. This explains its interdisciplinary and multiscale nature. Indeed, the success of the process is ensured by the coordinated interaction of a set of stakeholders and tasks. These stakeholders must work in a synchronized way and their associated tasks are performed simultaneously and/or sequentially, with decision making at every levels. Boly and Morel [BOL 06, BOL 08, CAM 09] have defined four main levels: the *strategic* level, the *project management* level, the *product development* level and the level *of the individuals (cognitive process and learning)* (see Figure 11.6).

Every project fits in this innovation system, which will be more or less complex depending on the line of business and on the type of innovation to be marketed. However, taking into account the different levels will help to better control the innovative process, with the aim of reducing uncertainties.

– *Strategic level*: definition of the strategy.

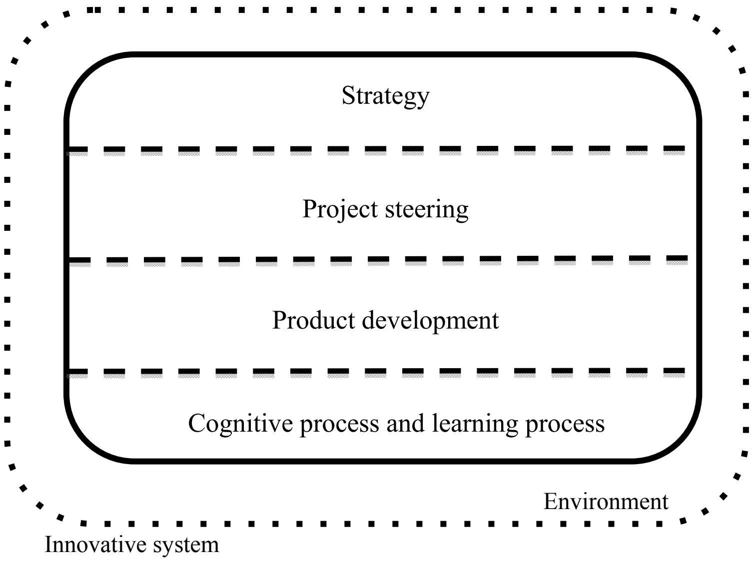


Figure 11.6. *Intervention levels of innovation engineering*

This strategy is defined by taking into account the context in which the company evolves, but it should aim at defining the main lines that will determine the future and nature of the project, as well as the resources and effort that will be allocated to it. Thus, any new definition of an innovative project should be assessed with respect to this level.

The characteristics of a new project which will be defined at the strategic level are: the temporal space in which it can take place, the allocated budget, the technological and commercial risks involved, and the impact (customer and field).

Two main lines of projects can be differentiated: the current projects and the major projects. The current projects: they correspond more to a defensive development; thus the company will favor improvement projects (incremental innovation), short term projects, and projects with limited budgets. Major projects: correspond to a conquest development, in which preference breakthrough innovations will be favored, in the medium or long run, and which have larger budgets.

– *Project management level*: from an idea to a new technology.

This level concerns the ability and effectiveness with which the company system is able to market new products or new technological solutions.

It primarily affects the development of competencies, technical resources, and project management making it possible to follow the evolution of an innovation project and if necessary, to take the necessary decisions to make corrections [COO 05, KLI 86]; for example, the integration in the last few years of technologies enabling us to develop the products faster and to reduce the development cost. We can cite, among others, PLM (*Product lifecycle management*) systems, simulation and modeling tools (molecular simulation, process simulation) or platforms-products.

It also concerns the innovative ways to make the whole process more effective: for example, the valorization of intermediate products and use of external resources, as it is the case in open innovation, which has been today at the center of the innovation strategy of companies like P&G [CHE 03], or else the growing trend to integrate the user at the center of the design process, not only in a validation role, but also as a co-creator of the new innovation (user centered innovation).

– *Product development level*: an integrated vision.

Here, the word product is taken in the broadest sense: it concerns all that is affected by innovation. Thus, it can also be a process or an organization.

This level concerns a global vision of the product based on its constituent components (e.g. material), its architecture, its functional properties of use, or the acceptability criteria of the customer. This subject will be developed in section 11.4.3.2.

This level includes all the stages from the potentially innovative idea, by passing through the intermediate stages (e.g. test, model, prototype, or associated tools), up to the finished product.

– *Level of the individuals* (cognitive process and learning).

It reconsiders points seen previously, especially in sections 11.4.1 and 11.4.2, with the need of thinking differently, to analyze paradoxes and contradictions, to develop imagination and the creativity then associated with cognitive reframing, to take into account the parameters under different aspects of science and technology but also non-technical parameters, and in some situations, to use systematic methodologies of types: TRIZ, knowledge reuse, usage analysis, and prospective.

11.4.3.2. *Product development: a new integrated vision*

The concept of innovation, beyond the design of a new product or its associated process, is fundamentally linked to its success in a given market. This success is now more than ever, determined by a set of economic, environmental, and social constraints in constant evolution. As J. Villermaux [VIL 93] had anticipated, this complexity implies that a vision exclusively focused on the technical performances of the product or on the optimization of the process yield, is not relevant anymore.

Indeed, in process chemistry and engineering, the term product development was traditionally associated with synthesis, experimentation, and calibration at the industrial level of a product [HIL 09]. Most of the efforts are allocated to these stages. However, in other fields of engineering, the term product development is used in a broader sense that also includes the properties of use, perception of the user, or the study of the associated supply chain [ULR 08].

In the last few years, we have witnessed the rise of a new global and integrated vision of the design of chemical products in the scientific community [CHA 00, CHA 02, EDW 04, GAN 05].

This dynamic will help us, in the forthcoming years, to better represent its complexity and therefore to get closer and closer to the reality of the innovation process.

This phenomenon was facilitated by several factors, including:

– the emergence of conceptual frameworks or metamodels, which allow logical bridges between different design fields. As an example, we can cite, the [SUH 01], in which product design goes back and forth between four related spaces: the space of consumer attributes, the space of the product functional requirements, the space of physico-chemical and biological properties of the material, and the space of the process variables;

– the level of the sophistication attained by tools such as the *Computer Aided Process Engineering* – CAPE tools, thanks by the development of process computation, simulation, and optimization capacities at different scales (from the molecule, by going through the industrial process, up to the associated supply chain). This makes it easier to establish and formalize the existing links between the different design levels and spaces and to seek an optimization of all of its components [GAN 05];

– advances in decision engineering by the integration of the decision maker, the point of view forms an integral part of this global vision. There are thus nowadays decision support techniques, in particular multicriteria analysis, and multiobjective optimization [AZZ 01, FON 04, MAS 03]. They enable the formalization of for example: user perceptions, the uncertainty of the measurement or to simultaneously handle the criteria belonging to different dimensions, such as ecology, product performances, or the efficiency of the associated process. Some of these techniques enable us to link the sought after product properties to the process operating conditions [CAM 11].

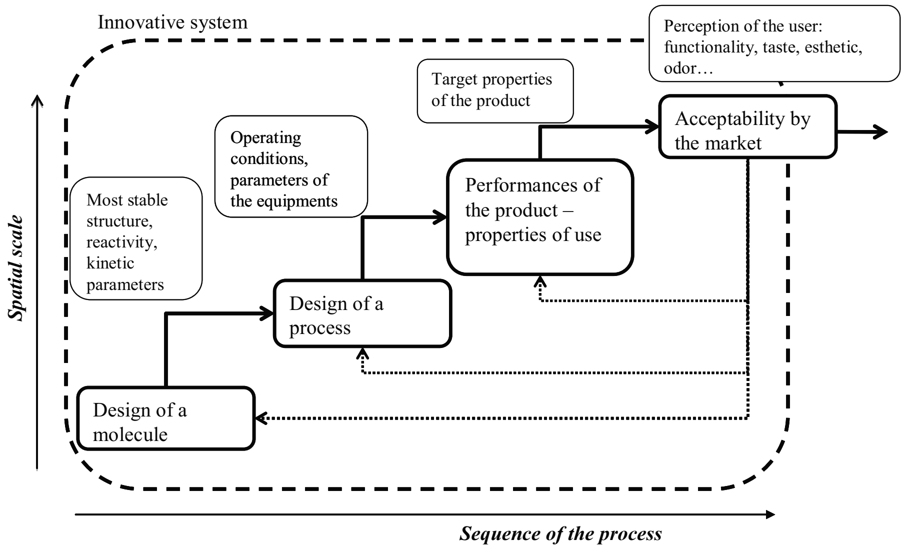


Figure 11.7. *Overview of the innovation process*

In Figure 11.7, we propose an overview of the whole process, of the spaces, variables, and associated interdependent criteria.

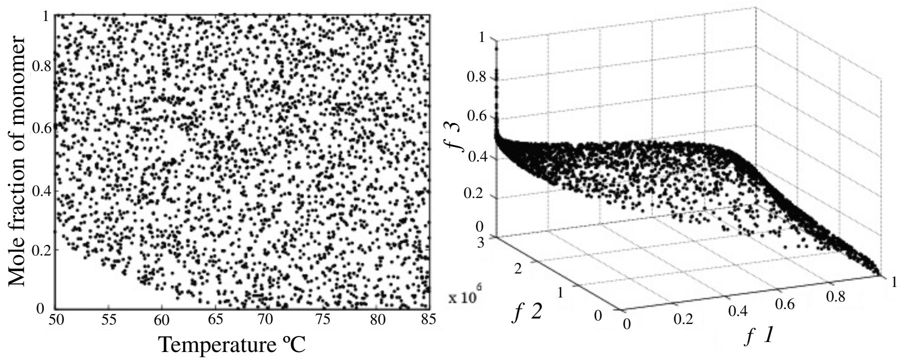
Example of application for the optimal product–process design by using the multicriteria analysis.

In the polymer industry, engineers always seek to obtain, with the highest productivity and the lowest cost, macromolecules with characteristics adapted for specific usage properties for a targeted market. The optimization of manufacturing processes thus takes on a multicriteria nature that will have to result in the best possible compromise.

This example concerns the optimization of batch polymerization in styrene and α-methylstyrene emulsion; for more details please refer to [JOL 08, CAM 11]. The multicriteria optimization procedure chosen is based on the use of an evolutionary algorithm and on the concept of domination in the Pareto sense[2]. Thus, potential solutions, optimal in the Pareto sense, have been generated from a simulator of the process (including, in particular, material balances and stoichiometry).

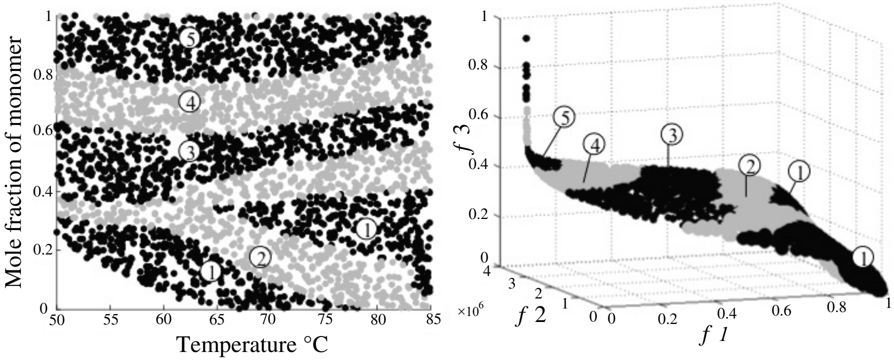
2 In a multicriteria problem, for which we seek to simultaneously optimize several contradictory objectives, this consists of finding all the points of the research space, so that there is no other better point on all the criteria simultaneously.

Subsequently, a decision support system, using a method of multicriteria analysis, has been developed to determine the optimum operating conditions taking into account the preferences of a decision maker with a view to obtain the target product.



a) b)

Figure 11.8. *a) Pareto zone and b) Pareto front*



a) b)

Figure 11.9. *Classification of the best solutions by quintiles from 1 to 5 of the Pareto zone (a) and of the Pareto front (b)*

The left-hand side of Figure 11.8 shows the Pareto zone of optimum points, a space of variables of the operating conditions of the process (temperature and mole fraction of the monomer). However, it covers almost the entire studied area. The right-hand side of Figure 11.8 shows the Pareto front a space of criteria of the use value of the product, which makes it possible to visualize the phenomenon by presenting a surface in a 3D space. We note that it is absolutely impossible to simultaneously maximize the objective functions *f1* (monomer conversion) and *f3* (reaction yield), all the while minimizing *f2* (the difference between the target molar mass and the actual molar mass).

However, if the first phase of multicriteria optimization gives a very broad result, using a decision support system will help to give recommendations.

This approach makes it possible to take into account the experimental observations and the know-how of the product and production experts in order to determine, but also to assess the interactions between the variables. A classification of operating conditions, with the help of an overall assessment index, makes it possible to identify the most interesting parts of the Pareto zone (see Figure 11.9). In addition, obtaining a reliable classification subsequently helps to better integrate the consumer preferences, and also to determine the optimum operating conditions and new design spaces.

The study and application of multi-criteria analysis methods are useful nowadays, since decision-making in design is becoming more and more integrated with the dynamics and constraints of the entire organization. Thus, among others, the application of a decision support method takes into account:

– the various levels of analysis, to which a design object pass through before its industrialization (strategic, tactical and operational levels). The actions or resulting measures are developed through a long and complex process mobilizing many actors. In design, there is not one decision or one decision maker, but a series of strategies and compromises between different viewpoints, or between groups that do not share the same solution;

– often, given the complexity of the process, the taken decision does not respond to optimality, in the mathematical sense of the term, but rather to a satisfactory solution [GRA 96], which takes into account the maximum information (criteria) that brings the problem closer to reality;

– the aggregation stage is part of every multicriteria decision-making process where the assessment is performed according to several criteria and several experts, especially in subjective evaluation [GRA 96].

11.4.4. *The company organized to innovate*

11.4.4.1. *Open innovation*

On 7th July 2003, the Businessweek journal, entitled its front page "The P&G revolution" explained the breakthrough approach of the CEO, Mr. Langley, which allowed P&G to significantly reduce its R&D expenditures, while retaining its innovation dynamics in terms of the introduction of new products in the market. In fact, this company is the largest producer of consumption products in the world, is more than 170 years old, and is recognized in the world for its technological capacity based on a powerful internal R&D. This company decided to incorporate more technology coming from outside.

The objective was not only to integrate the innovative capacity of its thousands of commercial and institutional partners, but also to enhance its own technological capacities toward the outside, such as selling royalties to other lines of business.

The strategy was setup through their C+D (Connect and Develop) program [HOU 10]. Thus, with the help of their Website, for example:

– inventors can visualize the current needs of P&G and propose their inventions;

– subcontractors may propose a specific cooperation to develop a new product;

– other companies can browse the list of technologies that P&G is offering for purchase.

The aim of this approach is to help P&G to get easily in touch with sub-contractors or global inventors, who have technologies that can meet the requirements of P&G. In addition, due to the sale of patents and licenses to companies that do not compete with it, P&G collects additional funding; with a bit of creativity, there can be very many applications of their patents in other core competencies.

In order to better understand the concept of open innovation, let us look at how the innovation process was traditionally applied. In fact, this process is often represented in the form of a funnel (see Figure 11.10), in which a set of ideas and concepts are filtered in a systematic way until they obtain the product or service best adapted to the market. Usually, this process is carried out by the individual investment of a company, and by using its internal resources and keeping them within the company. This traditional vision can be called closed innovation.

In contrast to this traditional vision, H. Chesbrough [CHE 03] has proposed the idea of an open and distributed innovation process. In fact, he has identified several factors, which currently make the closed model no more effective (effectiveness in terms of the effort necessary to create a new product).

Among other factors, we can mention:

– the mobility of the most competent people;

– the worlwide distribution of knowledge (before it was concentrated locally);

– the information and communication technologies that facilitate the collaboration with the suppliers and partners, but also with the users.

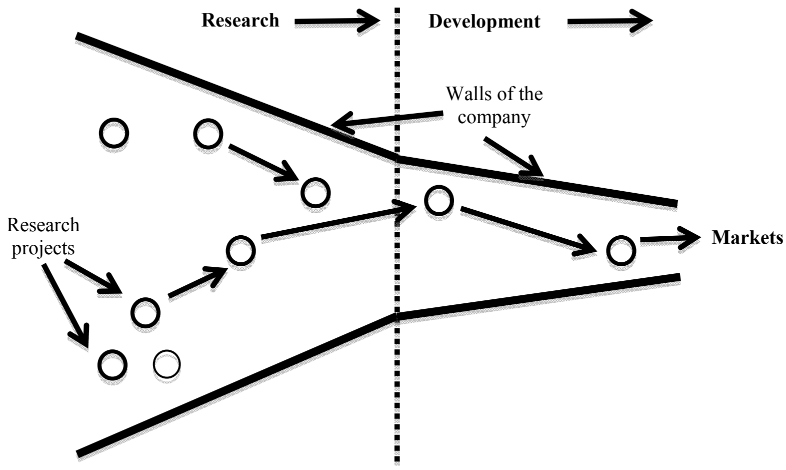


Figure 11.10. *Traditional view of the innovation process [CHE 03]*

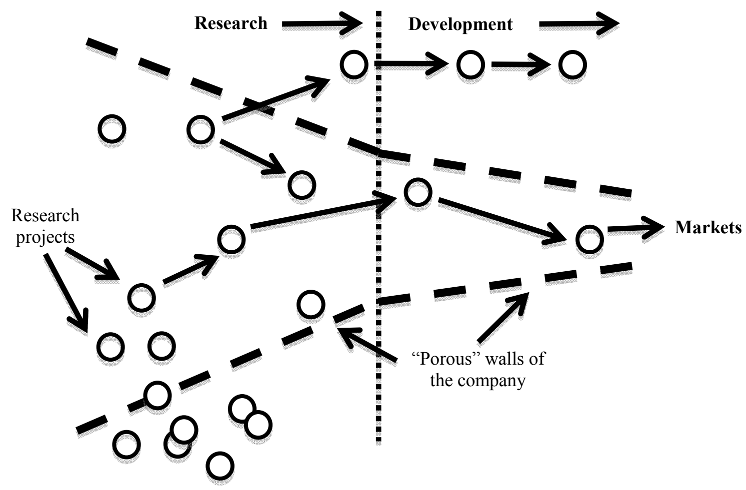


Figure 11.11. *Representation of open innovation*

This view naturally leads us to look toward the outside and to cross the walls of the company to engage external sources in the innovation process (see Figure 11.11). Thus, Open innovation is often described as the combination of ideas and internal and external resources, in order to improve the development potential of new technologies.

In this vein, the external sources, processes, and infrastructure required to apply this approach take a fundamental role:

– sources: partners, spin-offs, universities, and users (communities or individuals);

– processes: all forms of intellectual property management, (in-out) licensing, patents, partnership agreements, and so on;

– the infrastructure: communication technologies, Internet in all its forms as well as its actors, virtual reality, simulation, etc.

In this vein, the control of intellectual property becomes a decisive factor in the success of the implementation of such an approach. Currently, many companies deploy initiatives to promote the implementation of open innovation. We can mention for example Apple, BMW, and Renault and Solvay in France. We are experiencing a growing dynamics around this subject, and the forthcoming years will tell us if *open innovation* has kept its promises in the entire process industry.

11.4.5. *Technical choices*

In the previous pages, even if it was not directly presented, the technical dimension was always underlying. There can be no innovation in the process industries without the involvement of a strong scientific and technical knowledge in chemical engineering, and/or chemistry, and/or biology, etc.

The new constraints of the modern world, lead us to the development of systems, which are often very sophisticated, to control the processes from the point of view of sustainable development and preservation of health. We are referring to the constraints, but we do not want to present it negatively. It is also a source of creativity and a necessary development path for our society. Our industry now sees its development through green chemical engineering and green chemistry [ANA 98]. And process intensification becomes an essential lever for process transformation. This is where most of the major innovations are found currently. However, innovation should not be limited to a very restricted area; a breakthrough innovation will overturn economic data even more if it is unpredictable.

As for intensification, it can be relocated according to the presentation of conventional definitions: process improvements will generally be from the domain of incremental innovations and even modular innovations, while the development of microprocesses is a technological leap and represents a radical innovation.

Such a document on innovation in the chemical engineering industries should reconsider a description of these technical development options. However, within the scope of this book, we can suggest readers refer to the chapters concerning these domains. However, we can now summarize the four options of development proposed by Charpentier [CHA 11]:

– total multiscale control of the process for increasing the selectivity and productivity: customized nano and microprocessing of materials with controlled structure;

– process intensification: design of new technologies and new equipment based on scientific principles, on new operating modes or on new methods and production scales;

– manufacturing of usage properties: formulation and manufacture of the product with special attention paid to complex fluids and solid technology (the green products/processes couple);

– application of modeling methods and computer simulation of chemical engineering to real situations: from the molecular level up to the production site, including the control and safety of the sustainable process.

11.5. Conclusion

Throughout this chapter, we have gone through the fundamental points for a better understanding of innovation in chemical engineering. Most of the subjects could, by themselves, be the subject of a chapter, and innovation in chemical engineering industries could be the subject of an entire book. Some points have been tackled and others could not be dealt with in the space of a chapter, such as the concept of risk-taking and its assessment by FMECA (failure mode, effects, and criticality analysis) methods, or the concept of scoreboard and criterion for the management and organization of the innovation process in the company.

Another issue that has only been discussed here tangentially is the concept of technology transfer, seen not only from the point of view of intellectual property, but also from our ability to transmit new competencies, especially from the research sector toward the industrial sector.

However, we hope to have clearly presented the different key fields of the innovation approach. It is neither only by chance nor only by inventiveness, even if creativity is essential. There exist approaches, methods, and techniques. However, there is always a risk of not being successful and there is no ready-made answer.

Technical and scientific skills are essential. A good organization of the company is also necessary, and we know that a poor organization and a bad work environment, can kill innovation. We need to go toward a sustainable and competitive process industry, and this forward movement is very complex, combining performance and fulfillment of societal needs, while taking into account its constraints. The concept of company actor, who, although a specialist, also to exchanges their ideas with other actors with very different profiles makes sense here. We find this T-shape concept interesting and necessary. And perhaps, we can paraphrase this old slogan, by saying, *innovation is everyone's business*.

Even if there would be enough information to fill an entire book, the formal study of the innovation process for the chemical engineering industries is still as its early age. *Thus, our job is not only just to exchange information on this subject, but also to continue building this new approach together for example, by creating more connections between management and technical disciplines, and also between the different technical disciplines that make up chemical engineering, by creating better tools to better synthesize the information from different researchers and industrialists, to allow everyone to create their own strategy, and by developing new teaching methods. Similar to the innovation cycle in companies, the development process of our discipline, innovation for chemical engineering industries, must follow a process of continuous improvement, such as the famous PDCA (Plan, Do, Check, Act)*.

This challenge of innovation could also take us, beyond the present operation, to raise some other questions on the future of our society and on the connections between companies, research, and universities: *What are the links between research, transfer, and industry? What type of research for tomorrow*?

Many questions remain open.

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