1

The Foundations of Complexity

1.1. Complexities and simplexities: paradigms and perspectives

Let us begin with a summary of the notions and definitions in existence as applied to the field for the "Control and Monitoring of Complex Systems". Such a thematic reference might seem absurd since, as we shall see, a complex system is neither controllable nor predictable. Nonetheless, the singular advantage for formalizing the vocabulary and concepts is that it enables everyone to make themselves better understood; even though terminological unanimity is not yet fully shared.

We therefore present the results of observations and work carried out for several years in the industrial field. If it is easy to put forward concepts of complexity, their implementation resists the known patterns, and the reaction of the practitioners often remains: "*Everything you say about Complexity is beautiful. But then what? How can I transpose this from theory into practice? And what should I do when my classical methods are not applicable?*".

So it is important to ask a few simple questions about the purpose of our work, the complexity involved and the return on investment that we expect, as well as the career opportunities in terms of the exploitation of acquired knowledge and its evolution. The ideas that follow are not mere mental constructions, but the fruit of extensive discussions with senior representatives of the manufacturing and agri-food industry, well-known scholars and consulting firms. We have successfully produced an engineering methodology of complexity – sometimes called "Converse Engineering" to refer to a "parallel" view of phenomena – as applicable to the field of industrial process improvement and, more generally, the management of innovation within organizations.

Because this book is both an essay on complexity and a treatise on innovation, the terms and concepts used do not yet possess the formalism and the level of abstraction that could otherwise shelter them from theoretical criticism. They do, however, reflect an authentic industrial way of thought without departing from the fundamental meanings expressed by theorists.

The ultimate goal of the book is to help empower a company to better understand its complex environments, solve its management problems and improve the quality and performance of its business system and innovative ideas. Given the growing complexity of the environment, it is no longer possible to continue to want to complicate our industrial systems, involuntarily transforming them into "white elephants"; there is an urgent need to change paradigm!

1.1.1. *Positioning the problem*

Among the new sciences studied lately, made possible thanks to the advent of high-performance computers – which have made it possible to model systems that do not have a simple analytical description – we distinguish:

– the infinitely small;

– the infinitely big;

– the complex.

Let us limit ourselves to the notions, properties and problems associated with said "Complexity". Whatever the field, the vision of the world has become one of complexity. This is necessary; given the fact that many people now have a vague perception of a notion that implicitly involves crowds, as such it is the subject of multiple research themes which now need to be clarified.

Our thinking is linked to the fact that we are constantly surrounded by complex systems, and as a result, we are sometimes immersed within this Complexity without knowing it. This fact is so natural that we simply assimilate it into our lives. It is regrettable that most people accept it and go about trying to solve problems without ever questioning whether complexity itself cannot be called into question. Thus, we *introduce the concept* of Complexity (which is in itself a new paradigm) without changing the approach and without seeking other ways to approach and deal with related problems. We often arrive at sophisticated solutions, which are admired by scientific purists, but which in practice nonetheless remain inapplicable; either because they are too complicated to implement, or not easily adapted, or too expensive in terms of the resolution, or the maintenance, etc.

To counteract the excess of this "*complexifying approach*", some authors have thought of introducing the notion of simplification, but can this provide answers to our problem? To clarify this term, and in light of common understanding and confusion, there is a need to compare the concept of "complicated" with that of "complex".

One of the scientific incentives of today is to understand how, from autonomous, independent and communicating elements, a structure is organized step by step, level by level to bring about new properties. Which ones? This led us to make some preliminary observations.

While we already have a methodology to improve the management of complex systems in the field, research and development and advisory activities are still needed to meet the various needs of industry. They demand first and foremost simple, economical and rapid solutions to their problems. As we create, improve and develop an innovative technology for the analysis, management and control of complex systems, our approach is designed to limit the ever-increasing complexity of classical analytical approaches. It is the "simplexification" of the system studied that must be proposed. However, if the notion of "simplification" is already well practiced, the notion of "simplexification" still deserves to be demystified and further refined.

In what follows, we will first take time to recall some basic concepts in order to avoid any difficulties brought about through communication and understanding; next, we will discuss analytical approaches; and, finally, we will become interested in their application and, in particular, the field of organization and management methods of distributed dynamic complex systems. On this basis, we are then able to propose some subjects of study which have yielded interesting results.

1.1.2. *Reminders, basics and neologisms*

1.1.2.1. *What is a system?*

Throughout this book, we readily use the term "system" as a very general concept. As a reminder, we will use the following generic definition (Mélèse, le Gallou, Lemoigne [LEM 06]): "*A system is a set of objects and/or entities, interconnected and organized according to a goal and immersed in an environment*".

In terms of an activity, a system manipulates very diverse flows of objects or information onto which it is supposed to add value. Thus, we can consider many such types of flow, such as:

– populations: humans, animals, plants;

– monetary: financial values;

– physical and energy: equipment, materials produce, transport;

– information: orders, events, data, knowledge;

– cultural and sociological: training, innovation, motivation, aesthetics, mysticism, ethics, etc.

It is here that we introduce systems engineering as *the art and the way of designing and realizing sets or complete, global artifacts* (hence the word "system"). This engineering activity includes a complete set of methods and tools, for example the principles of decomposition/recombination, emergence and aggregation, convergence and iteration, etc.

In general, a company is a system; a population of people is also a system, etc. In the presence of decentralized systems, we will refer to the more global notion of *ecosystem*: this means both a system formed by populations, as well as the interactions existing between these populations living within a specific biotope, their environment and the sociotope resulting from the human activities taking place there.

With regard to the specific content of this book, we will use the concept of "system" based on the C.W. Churchman's definition [CHU 79], in agreement with the notion of sustainability [MAS 15b]: "*A system is a set of objects and/or entities, interconnected, organized and managed according to a given goal and immersed in a sustainable environment*".

1.1.2.2. *Defining Complexity*

The following definitions and basic notions, although not identical between schools, remain fairly alike with one another and express the same overall values. For our part, we refer to those employed at the Santa Fe Institute (SFI) in New Mexico since they are widely used, for example by J. Horgan, Senior Writer at Scientific American, John Casti and Richard Bellman at the Rand Corporation, Stuart Kauffmann of the same Santa Fe Institute, Per Bak and John Holland, or even Harold Morowitz, as well as other authors.

In laymans terms, the term "complex" is defined by its characteristics: a complex system designates something that is difficult to describe, intriguing, non-intuitive, non-predictable and/or difficult to understand.

According to Jean-Michel Penalva (author of the Method Sagace used at the CEA), complexity rests on three joint characteristics:

1) *The emergence of phenomena that is not predictable or difficult to model.* The emergence is itself non-predictable because it is also joined by the notion of *sensitivity to initial conditions* (SIC), which expresses the fact that it is impossible to predict the course of things within a given horizon, even when it is close;

2) *The dynamics* of evolution over time;

3) *Uncertainty.* The uncertain nature of an event or fact is linked to the lack of knowledge and/or the prohibitive cost of obtaining and processing it.

The combination of these three characteristics induces the notion of *Risk* inherent to any intervention of a complex situation.

We see that it is immediately important to define "*what is a complex system*" in a more formal way. While many conceptual attempts and confusions have emerged, we can synthesize the work of industrialists and scientists, notably those of the Santa Fe Institute [FON 99] with the following definition:

"*A Complex System is an organization, or a system in the sense of Churchman [CHU 79]. That is to say, composed of a set of heterogeneous elements whose local interactions are diverse, non-linear and are independent of centralized control or synchronization*".

Thus, a programmable network whose nodes, like arcs, have active functions (or simple or elaborate programs) that form a complex system. Consequently, and according to Jean-Louis Lemoigne [LEM 06], it is "*the potential unpredictability (not a priori) of the behaviors of this system, associated with the recursivity affecting the functioning of its components, which elicit the emergence of phenomena that are intelligible, but not anticipated or predictable*".

1.1.2.2.1. A typology of complex systems

The study and understanding of complex systems falls into several types and forms of complexity. In practice, we distinguish the following four:

1) *Behavioral complexity* whose resulting interactions can lead to non-predictable behaviors, evolutions or *emergences of order*. These systems are often characterized by some principles and laws, often simple but *sensitive to initial conditions* (SIC). This is the case of cellular metabolism or vehicle traffic in a country's capital: it is easy to describe how each entity operates, but it nevertheless remains difficult to describe the global behavior and its dynamic evolution. This is said to be a "reductive understanding".

Such systems are generally subject to Chaos Theory [BER 88] which leads to "self-agitated" systems [MAN 89]. This theory involves "simple" systems, which correspond to two or three degrees of freedom, but whose behavior is unpredictable and infinitely complex because it goes beyond intuition. However, the Theory of Deterministic Chaos has also shown how certain systems, when placed in conditions called "far from equilibrium", can suddenly "jump" into new and more or less ordered phases. This is a property used in the self-organizing phenomena that is the basis of *self-adaptive* and *self-organizing systems*, which essentially affects the architecture or structure of the system rather than its state (the numerical value). Self-organized systems are always open systems, in interaction with an environment to which they can export their excess entropy.

2) The *computational* or *structural complexity* that arises when the number of elements to be taken into account, and their *properties*, becomes too high. The processing power available today does not directly solve these systems except: by modifying the optimum search technique; by searching for an efficient programming language in which to write the program; by regularly "reformulating" the problem; or by playing on the skill of the programmer. We integrate approaches from physics, biology, chemistry, economics and social sciences, etc. This is said to be a "compilative understanding", a situation increasingly being dealt with by Operations Research.

3) *Intrinsic complexity*, otherwise called *Ill-defined complexity* (or sometimes "*wicked problems*"). In this case, a general study of the problem is undertaken but the nature of the problem makes it difficult (if not impossible) to grasp the structure or concepts, or its modeling. A difficulty that is best illustrated by giving a few examples:

a) *What is life?* It is an intrinsically complex question.

b) In quantum mechanics, Pauli's exclusion principle should not be seen as a principle of energy distribution, but rather as a computer principle that allows structures and hierarchies to be constituted. It leads to the emergence of characteristic geochemical and biochemical structures, with very specific properties, etc. In this it makes it possible to make appear and "form" stable, structured entities, whose spontaneous emergence, or even evolution, are uncontrollable.

c) In a missile or nuclear power plant control system, the processing of results must be available in a fraction of a second to correct a trajectory (dynamic evolution) in real time in order to better control the object and avoid unpredictable or uncontrollable divergences.

It is thus important to prove whether or not a particular problem can be solved using an efficient algorithm. A classification of efficiencies was proposed by A. Cobham and J. Edwards in the 1960s; it was used at the IBM's European

Competence Center for Advanced Computing in the 1980s [MAS 91b], especially for problems regarding *decision-making*, that is, problems requiring a rapid response of the type *YES* or *NO*. These problems are encountered whenever the process of ranking, classification or selection is required.

We were thus accustomed to consider three classes of efficiency:

– the P-type algorithms computing in a polynomial time;

– conversely, non-deterministic polynomial time (*NP*) type algorithms or problems;

– finally, the algorithms of the exponential type which require $\boldsymbol{2^n}$, $\boldsymbol{n^n}$, $\boldsymbol{n^{\log n}}$ or $\boldsymbol{n!}$ steps to be resolved.

As per the example, in linear programming, a significant step was made by improving the processing of hollow matrices and introducing the Karmarkar algorithm [KAR 84] instead of the "simplex" method.

4) *Evolutionary complexity* is the form derived from the difficulty to reconstruct *a posteriori* the main influences of a resulting state or behavior. It is a common phenomenon within evolutionary theory to find that historical "accidents" and "catastrophes" have played a decisive role in the instinct (incitement), the extinction, or appearance of new species, unprecedented new political situations and so on. This is also involved in the plant "growing" mew mechanisms. S.J. Gould [GOU 02] classifies this complexity under the category of "historical understanding".

Three remarks and comments:

1) According to the Nobel Prize Winner, Pierre-Gilles de Gennes, complexity is associated with a *high number of degrees of freedom*. Thus, a complex system ceases *to not be as complicated* as soon as it exhibits a coherent behavior involving the collective organization of a large number of degrees of freedom; when certain circumstances are met. An enormous assemblage of nature (10^{23} particles in only one-unit mole of substance), which are only subjected to "simple" forces of nature, can be organized and form a cooperative and complex system of activities.

2) As stated by Stuart Jay Kauffman [KAU 95], the world is *non-ergodic*. In an ergodic system, such as the gas contained in a small enclosure, the phase space can be explored on a reduced time scale, from estimated or approximate values and averages. In reality, such studies are impossible! Indeed, if we consider that the universe contains about 10^{80} elementary particles and that an interaction can be counted every femtosecond, 10^{193} interactions may have occurred and/or be studied since the Big Bang; at the same time, the number of possible proteins made from 200 amino acids is 20^{200} or 10^{260}, with nature having possibly tried all of these combinations.

This leads us to change our vision: when viewing the Universe as a calculator, it is no longer possible to study all cases of bacteria, cells, species, social and/or legal systems, etc. The Universe is thus *non-ergodic*, and we are certainly far from an optimal global equilibrium. The question is therefore open: to know how matter, energy and space, even our society, can organize themselves from conceivably simple laws to form a set of information flows and products far from equilibrium.

3) We are now familiar with the fact that decision makers need to be able to take uncertainty into account in their decision-making processes. In the context of public policies, for example, it is not possible to integrate uncertainty and to define a decision that is *a priori* reliable over time. In this problem, what is important is not what we do not know, but what cannot be known. Furthermore, the phenomena we manipulate can generate structures in which our actions have no inconsiderable effect, but *a priori* are not quantifiable. This necessitates new ways of thinking, as stated by Stuart Jay Kauffman [KAU 08].

1.1.2.3. *Let's define the term "Complicated"*

Around us, many people confuse the words "complex" and "complicated". Thus, it is first necessary to clarify the meaning of the latter term. Contrary to what is "complex", a *complicated* system is a system that is difficult to understand, model, apply, execute, etc. This may be due to the number or diversity of the component elements and associated processes. A *complicated* system is a system in which *there is no visible link between phenomena, manifestations and causes*. As structures or concepts cannot be understood, the difficulty lies in discovering and exploiting this structure (or the underlying deep properties). A simple enough concept, for which there is hence a need for abstract mathematical techniques or inductive reasoning; methods generally unfamiliar to those working on these issues. Note that we have not spoken here of interactions as we discussed above regarding complex systems.

The notion of understanding has thus shifted: there is a continuity between the "complicated" analytical process upstream, and the "intrinsic complexity" revealed or manifested downstream of this same process.

To complicate a system is to make it less simple, to make it more confused in terms of our mind, etc. The notion of complication can also be associated with that of simplicity. To be able to define a situation or object as "complicated" is to assert that they are intelligible from a "simple" model: therefore, these pose a practical problem. By contrast, a complex problem is irreducible.

Presently, in industry or economics, common approaches (following scientific accuracy rules) are based on "reductionism" and with the help of computers are devoted to the handling of systems. Only those which are complicated can be simplified, since both are quantitative. When we admire an elegant three line algorithm intended to solve a problem of optimization or scheduling between two or three devices on an assembly line, it will sometimes be seen as complicated. On the other hand, within a simple structure setting, as with the *evolution of inventories* (discussed in detail later on), we land upon the Mandelbrot formula of the type $f(x) = x^2 + c$ which leads to Julia sets, that are very beautiful, but also very complex.

Compared to a complex system, it is not so much the multiplicity of components, nor even the diversity or number of their interactions that necessarily characterize a complicated system. For example, in a complicated system, the entities are practically and exhaustively countable, but the effort devoted to the mathematical computer modeling of such a system, and the enumerative combinatronics needed to describe all its behaviors, is simply incommensurable. The approach for the study and analysis of a complicated system will essentially be based upon the *principles of decomposition*, which will not be the case in the presence of a complex system.

1.1.2.3.1. Complication is often a mockery of Complexity!

Complicated thought is in many instances simple; however, the simplicity is hidden behind an indistinct tangle of formal concepts and relationships whose architecture confuses the hypotheses, their consequences and the results. This may be a way of hiding some incompetence in the analysis of a complex system; nevertheless, this type of thinking is impracticable and often leads to inconsistencies in demonstrations. This is the case for instances of work, presentations, or reports, by scientists or engineers who inadequately dominate a subject as long as the model is simple and therefore vulnerable and allows, perhaps understandably, for them to continue asking embarrassing questions. What we tried to avoid doing here!

Thus, the complication of an approach, a model or a solution often simulates the complexity of reality. If just one part of this mental overload succeeds in capturing our attention, it will saturate the judgment, making it very difficult to advance. In short, it is not with “white elephants” that we solve industrial problems. Such approaches and models are not realistic and hardly ever induce respect or admiration.

It is now appropriate to define terms which are the opposite of “complex” and “complicated”. Indeed, we often associate the word “simple” with the word “complex” and, on the one hand, to some people’s way of thinking, it is therefore necessary to simplify complex situations. But is this possible? On the other hand, there are others who believe that the proposal of concepts related to simplification will allow progress, while avoiding the complication of situations and systems. Let us attempt to clarify these notions further.

1.1.2.4. *What is simple?*

The word “simple” first appeared in the 1100s and comes from the word “simplex”, which means “formed from a single element”. A simple system is therefore a “non-compound” set of elements. From a pragmatic point of view, it is a system made up of a reduced number of parts, that is natural and without artifice. In an abstract context, the adjective “simple” describes what is ordinary, what is alone and to which nothing is added, and hence what is explicit and by nature self-sufficient. By extension, *a “simple” system is a system without primer, without ornament, self-sufficient, uncomplicated, limited to what is strictly necessary. Therefore, it is comprised of a minimum number of unnecessary components* (see Definition by D. Saliba [SAL 03]).

Nowadays, the word “simple” characterizes an easy-to-use concept. It has provided some derivatives like the adverb “simply” which means: without detour, without disguise, modestly and without complication. More recently, the term “simplicity” appeared in the 17th Century to designate what is easy to understand or to perform.

1.1.2.4.1. Some characteristics linked to that which is simple

A *simple system* can be complex; this is the case, for example, with the Mandelbrot fractal evolution, as described by the *simple* equation $x = f(x^2, C)$, which forms a system with complex behaviors, possessing: a form of invariance, non-integer dimensions and fractal properties. On the other hand, the word *simple* does not mean “*simplism*”. In the latter concept, there is a flaw in the reasoning that neglects one or more essential elements necessary for the solution of a problem or the functioning of a system. The word “*simplistic*” is attached to “*simplism*”: for example, simplistic reasoning is considered as a rationale that only considers one aspect of something, simplifying beyond measure the system studied and thus remaining incomplete.

1.1.2.4.2. For application, pay attention to the relativity of simplicity!

Let us give a very good example. The study of the human genome concerns a set of chromosomes capable of generating very complete and complex living beings. Here is a question that scientists have asked: what would be the most “simple” and/or smallest genome imaginable that still results in a living organism? Here, the criterion chosen corresponds to the capacity of this organism to subsist and self-reproduce autonomously within a nutritious medium. Research on mycoplasma genomes has concluded that such organisms lead to the consideration of a genome group comprising between 500 and 1000 kilobase pairs. This leads to the definition of an information content close to 100 Kbytes – that is to say remarkably low – corresponding to a ribosome structure made of about 70 proteins. At the level of biochemical modeling, this makes it necessary to define a network comprised of approximately 300 programmable nodes. In theory, the processing and study of such a model is within the reach of a computer, however, as can be imagined, the concept of "simple system" and the question "what is Life?" remain very relative notions.

1.1.2.5. *Let us define "simplexity"*

In the design and development of current technologies, linguistic concepts have evolved and continue to do so. Thus, in the context of the Sciences of Complexity, the notion of "simplex", as mentioned above, has changed meaning:

– the mathematical term "simplex" first appeared in the 1950s to designate a set formed by the parts of a connected set;

– similarly, the term "simplex" appeared again in the 1970s, this time in computer science, to designate a system that allows the transmission of non-simultaneous signals;

– for the future of science and technology, *simplexity* designates a state, a character of what is *simplex*. For example, in the minds of car designers, the word simplexity refers to an action that reduces the notion of complexity. In this context, simplexification consists of making more accessible, technological sets that would otherwise be complex. In fact, the research centers for the car manufacturer Renault, originally, asked these questions:

- how to make a little *more aesthetic* the abundance of controls, instrumentations and adjustments that incorporate increasingly complex technologies?
- how to, at the same time, make the use of new technologies *simpler*?

This entails the *purifying* of the passenger compartment, and the *simplifying* of the interface between the technology and the customer. The technology is made visually more discreet, access to controls are adapted and simplified: for example, the driver can adapt and adjust the setting of the peddles and dashboard, etc. The term "interface" implies the challenges pertaining to interactions. Finally, we associate the combination of ergonomics, utility, efficacy and efficiency with the aim of providing more comfort, functionality and aesthetics to the customer.

The notion of *simplexity* is being deployed in some computer consulting firms, particularly in the United States. It concerns the automation of processes in terms of efficacy and efficiency:

– the increase in ROI (Return On Investment);

– a deeper and broader understanding of operations.

1.1.2.6. *What is meant by the word "clarity"?*

In addition to what has been said above, and in order to answer frequently asked questions, it is necessary to specify terms related to the way in which certain concepts are perceived and/or expressed. Indeed, in industry, we often hear that what is "simple" is "clear". But is it still true? The answer is no because the words *clear* and *clarity* seem to correspond more to the parameters of form:

– *Clear:* intuitively, the word "clear" is associated with being readable, well presented, etc. It is possible to present in a "clear" and complete way that which is intelligible. A *clear* system or behavior has explicit, clean and distinct aspects. From the explanatory point of view, it is therefore possible to apprehend and to represent a phenomenon in an obvious way, and to predict its various aspects (shape, state, configuration, etc.) without any difficulty.

– *Clarify:* this term consists of purifying and putting order into a system. This assumes that the system is subject to an order, that is, preferably stable. This also means making the system recognizable among others; thereby possessing a predetermined configuration and associated with an easily intelligible set of information in order to perform, either ranking or classification. Such systems – scalable – are predictable and have simple behaviors.

Here are some examples

If we speak of reasoning, the term "clear" must be opposed to the term "confused" since the complexity underlying these two concepts have very different aspects. Indeed, a confusing system, result, or complex reasoning, may manifest itself in a way that is not immediately clear to the mind. These manifestations correspond to unconscious and uncontrollable facts and are often assimilated to form new, unforeseen and/or expected situations.

On the other hand, a system that appears to be "clear" should not have any inadequate or unpredictable behaviors. For instance, the emergence of spontaneous orders, configurations or organizations (such as the constitution of a DNA-like body) does not correspond with a clear and obvious process. A clear system cannot be complicated as it cannot be modeled.

1.1.2.7. *Synthesizing and drawing consequences*

Everything discussed up until now leads us to consider a graph expressing the relations between the various concepts. The cross-links represent opposing relations (the impossibilities), while the vertical and horizontal relations represent the possible links between these concepts (possibilities). As with the Mandelbrot equation, a simple model can lead to complex behavior.

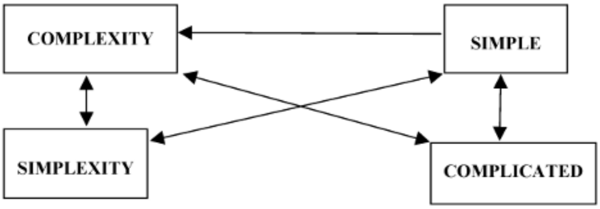

Figure 1.1. *Graphical summary of the concepts discussed*

This graph highlights some methodological shortcomings. Indeed, many people, while speaking of the *complex* and the *complicated*, conceive and develop very elaborate solutions to solve problems that are sometimes simple, without ever really dissociating the meaning of their terms. This reflects a commonly passive attitude and the acceptance of a situation without ever questioning it. Such a state of affairs is characteristic of a stereotypic culture or scientific approach.

We often speak of *simple* or *simplification*, but never *simplex* or *simplexification*. Here again, we can suppose an incompleteness in terms of the problem-solving processes: the appropriate technologies do not (yet) seem to exist, and a work of exploration and formalization is still necessary as it could lead to new problem-solving approaches, which are in fact more efficient and less costly.

In addition to what appears in Figure 1.1, several comments can now be made:

– The idea of *feedback*, introduced by Norbert Wiener in autonomous systems, breaks with the principle of linear causality brought about by introducing a local feedback loop. The cause affects the effect and vice versa. This mechanism of regulation allows for the autonomy of a system, and also its runaway reaction, when, in accordance with the signal of its feedback effect, it plays an amplifying role. Such stabilizing or inflationary feedbacks are common in technical systems (heating), economic, social or political phenomena (armed conflicts) or even psychological (applications of René Thom's theory of disasters). The notion of feedback is correlative to the behavioral approach and characterizes in part the complexity of a system.

– The *unexpected* is a "constructive" factor in complex systems and "destructive" in complicated systems. Complex thinking integrates uncertainty; it is able to conceive an organization to relate, to "contextualize", to globalize, and also to recognize the singular and the concrete. This is not a characteristic of "complicated" thought.

– *A complex system* presents a global unity and coherence that almost makes it irreducible and non-calculable. Already we have seen that something simple can have a complex behavior. Therefore, complex thought is not the opposite of simplifying thought; rather, it operates as an integration of simplicity and complexity. While the paradigm of simplicity requires *disjoining and reducing*, the paradigm of complexity enjoins to *connect the whole by distinguishing the parts of the whole.*

– When we move from a "simple – complicated" axis to the "complex – simplex" axis, we also change context: we pass from the experimental to the observable and non-reproducible, often from quantitative to more qualitative.

– In a whole system, it will often be observed that the "complicated" concerns the concepts and structure of a product or a service, whereas the "complex" relates to the process and the behaviors.

1.1.3. *What are the analytical steps in a complex system?*

1.1.3.1. *Attitudes towards a problem*

Let us place ourselves within a general context of the redesign or re-engineering of a process or processes (Business Process Reengineering), in other words, the improvement of a process. In view of what has just been discussed, two approaches are admissible and commonly used in response to a problem:

– the *corrective approach*: when the problem arises, it is diagnosed, the possible causes are identified and the action plan is defined. This plan is evaluated, validated and ensures its effectiveness after application;

– the *preventive approach*: here we act before the manifestation of the problem. We can distinguish with the *predictive approach* that which the problem consists of, and through the use of algorithms determine when and how a problem will appear and what importance it will have, before carrying out, for example, preventive maintenance.

At the same time, we often ignore (voluntarily or involuntarily) an approach known as "*Problem Avoidance*". This seeks to eliminate the problem either by addressing its causes (which is more conventional), or the structure of the system that generates it (which is, at present, less frequent), or finally its context or its environment: the problem no longer exists because its footprint has been eliminated. We therefore circumvent the difficulty, instead of attempting to solve it directly (as is normally the case with the Cartesian approaches). This will be referred to as the *Elimination Approach*.

It is precisely here that the notions of *simplification* and *simplexification* assume their importance; they make it possible to eliminate *a priori* certain difficulties and/or eliminate them by changing the structure and configuration of the system.

Some examples

Let us illustrate this synthetic approach with a few examples taken from everyday life. As we will see, it is frequently based on common sense. It does not always satisfy the mind in terms of "scientific beauty"; however, it is not the objective to satisfy a customer looking for a simple, fast, inexpensive and sufficiently effective solution to their problem?

– In *Sports*: faced with a rocky overhang, the mountaineer will save time and effort bypassing the obstacle and choosing a faster, cheaper and less risky route. It does not make Art for Art's sake, but rather avoids unnecessary difficulties with regard to efficacy, efficiency and security.

– In the *Sciences*: how many times have we heard Boileau's expression: "*What is conceived well can be expressed clearly, and the words to describe it come easily*"? Here, we will attempt to give a simple answer to a question to research and find a simple and elegant reason, or demonstration, to an (apparently) complicated problem. Here, the notion of apprehension and situational understanding aims to provide a simple solution to a problem (that is not to say trivial or simplistic).

– In *Industry*: it is common, for the sake of efficiency and responsiveness, to hear the following sentence: "*Thanks for providing a quick response to this problem!*". Here, a workshop manager will have sought out a "good" response, that is, a sub-optimized response (e.g. within 15% of the theoretical optimum), which nonetheless promotes the best method to improve an urgent situation, at a reduced cost. We therefore employ the Toyoda or Keizen Approaches, which are part of a permanent and continuous improvement of a process, with the aim to evolve a system without breaking either the dynamics or the strengths of that system which were probably acquired with some difficulty. It is important to note here that optimal and/or global solutions are not always sought, either because they are too difficult to model and solve (thus neither diffusible nor maintainable) and/or too costly in terms of time and mental acuity.

– *Defense Systems*: along the same lines, we can compare what happened to the French Nexter Company as it was reported in the press. The technologically sophisticated, French Leclerc tank, was designed to cover a wide range of military problems. This comprehensive approach resulted in a design and development which costs ten times higher than that of the American Abrams tank. In terms of the end product, it is a lean and agile weapon that is desirable in terms of its technical and functional features, nonetheless, from the macro perspective, these can be difficult to market commercially. Indeed, the utilization of any complex system can become expensive if it tries to integrate too many advanced features that result in a less operative and less reliable product. For instance, in many cases, it would be better if the product were tailor made to the specific mission, with the most appropriate features, complying with easy maintenance and logistical approaches.

– In *Administration*: the calling into question of information systems, procedures and forms (or screens) initially responds to a need for change, perhaps via suggestions, brought about from a diversity of problems. The critical analysis is based on the determination of the objectives on the basis of five simplifying questions: is the operation essential? What can we eliminate? Where should the operation be performed? By who? When can the operation be done? Often the misunderstanding will occur from the fact that the essential question is actually: is there a procedural objective or a resultant objective?

As can be easily seen, the “how to” follows on quite naturally, and again there are usually approaches to assist continuous improvement which gradually eliminate difficulties. The concept of *Business Process Reengineering* goes much further by integrating the process into its environment. In this way, all the approaches listed above can be taken into account.

In each of these examples we can identify the need and the notion of simplification (and simplexification), defined and expressed according to the context, and yet remain guided by objectives. However, there is always the concern to bring solutions or *methods* that are *useful, utilized and usable.*

1.1.3.2. *What approaches are being used for simplification?*

Simplification is the act of simplifying, that is to say, of making a system that is composed of few elements, increasingly simple, easy to understand and easy to use. Hence, the definition: *simplification is a process whereby the reduction or elimination of elements is not deemed necessary for the purpose of a product or service, loss of time, energy and material or resources*.

In terms of domains and applications, we will discuss the optimization of industrial methods, better implementations and lay-out, logistics (the reduction of transportation and handling), efficiency of operational procedures, stripped-down administrative forms, etc. A Simulation Institute [SAL 03] defined a set of nine rules (which shall not be described here), as well as a metric called “complication distance”. Based on the existing literature in this field, where “simple” is opposed to “complicated”, the following characteristics can be identified.

1.1.3.2.1. What steps can be used to analyze a complicated system?

Usually analytical or Cartesian approaches are employed, given the fact that the system is supposed to be decomposable. For this reason, we first carry out an identification and analysis of the constituent elements of the system or the problem to be solved, without worrying about the synthesis which will only be integrated towards the end of the process. The effort is concentrated on the essential entities being analyzed and on the corresponding functions being performed; we thus describe and model each problem encountered, as well as the approaches used to solve it "bit by bit". Only at the end, at the time of integration and/or general synthesis of this process, will we obtain the overall picture of the system under study, and a hierarchy of its functional subsets.

In this approach, we construct a diagnosis, through the accumulation of separate elements as acquired by analysis, carrying successively or in parallel, distinct aspects of the object under study but that have no link to one another. Only the second time round are we concerned with the recombination of that which we have taken so much care to dissect. This is the way in which a patient, when taken to a hospital in order to diagnose a disease with suspected symptoms related to a serious condition, is successively treated and manipulated by many specialized professionals who study his/her organs independently, etc. Ultimately, it will be either the "general" practitioner (GP in medicine), or the broad-based scientist, or the knowledge-based expert, who, at the end of the process, integrates the results and makes the final diagnosis.

This is, nonetheless, a problem. Whenever the system is divided into parts, we risk losing the notion of the whole, the overall objective of the whole, the sum of all the parts and their role within the whole. That being said, let us not forget that a complex system is more than a simple sum of parts: these are not isolated functions whose interactions are predominant locally, and which result in specific internal structures (assemblies of parts), neither deductible nor reducible. Sometimes, more generally, the same part can be a part of different "wholes", and furthermore, the "whole" part can also be broken down and decomposed into different parts.

There are many methods used to *study and simplify a system*:

1) The method of D. Saliba [SAL 03];

2) For organizational analysis in the 1990s, decomposition approaches were used to decompose a system, starting from the fact that there was structural invariance. The concept of The Fractal Factory (by Prof. Warnecke, [WAR 92]), developed at the Fraunhofer Institute, is a system-based approach that has yielded good results, where the part of a whole can itself be a "whole of parts", and which thus involves the replication of a structure at different levels of organization;

3) Value analysis, for research, identification and selection of important and significant elements of a system;

4) The Kaizen approach which favors not the search for results but the gradual improvement of the processes that lead to it. Therefore, the structures and the configuration of a system are changed, the working methods, the internal communication system, the culture and, consequently, the humans, are evolved.

For information systems, which are repeatedly “redesigned” in industry and/or in organizations, the approach generally employed involves simplification.

1.1.3.2.2. What are the advantages and limitations of simplification?

Simplification has been around for a long time. After all, what is more natural than to simplify things? It is natural to desire the most obvious solution, to schematize, to separate the elements of a set, to keep only that which is essential for the core understanding, explanation and representation.

Even more rationally, for reasons of quality and efficiency and also for performance or efficiency, simplification is an approach that has become increasingly necessary, as we approach increasingly complex and complicated worlds. In truth, they always existed, but we suffered them passively; whereas today, we want to know them more and more, master them, control them and direct them. Only by simplifying procedures will we be allowed to better study and integrate these worlds into our lives. That being said, it is also necessary to define the portion of the universe studied, or the level of integration being considered, if the isolation or the existence of a field of autonomy can be envisaged (this is a function of relativity or the intensity of linkages).

Nevertheless, as can be observed in the phenomena of society, in all fields in which many forms of intelligence are exercised, the simplistic approach is sterilizing, because it arbitrarily constrains what in reality is constantly changing, because it separates what is bound by nature, because it keeps itself from the chaotic, the contradictory and the random. All the principles inscribed in the nature of things (Olivier Schmitt’s presentation at the 2004 conference at the Ecole des Mines de Paris) [ARM 04].

1.1.3.2.3. How can we position ourselves in relation to simplification?

In designing, analyzing or redesigning a process, it is common to see specialists rushing over computing resources, to model the system under study, describe it and specify it in a comprehensive, consistent, global and complete way, in order to develop solutions which are sometimes too complicated.

At this point, it is advisable to point out again that we forgot an essential step, that of the preliminary simplification of processes. IT (Information Technology) resources are basically a set of tools capable of modeling an information system, which help to design a previously specified solution and the automation, through programming, of a process. However, simplification must always precede the automation phase: automation or computerization remains the last step in designing and/or improving a process. The gains made during simplification operations are at least as great as those which can be expected from automation. In addition, it is not possible to properly automate a process from a description, model, or bulk specification of a complicated system or process. We thus always recommend as an indispensable prerequisite, the dissemination of the methods, techniques and tools of a “Simplification Technology”. To illustrate this, let us mention some examples of applications that are part of the past, but which have helped us to progress in our discipline:

– *Example 1 – The steel industry* in the South of France. A large company, before setting up a sophisticated management system, aimed to simplify the processes involved by implementing the concept of “Lean Manufacturing”. In the case of the production of stainless steel, delivered in different forms to their customers, it sought to reduce the number of references thereby obtaining better delivery times. This, combined with scrap reduction, increased revenue (emphasis had therefore been placed on the notion of the “Value Added Chain”).

Depending on the type of industry, it should be remembered that by reducing inventories and work-in-progress, we decrease the financing costs for fixed assets, which are sometimes much higher than those resulting from machine downtime. On the one hand, a reduction in the cycle between control and delivery is achieved with no need for technical computer processes. This involves the gradual reduction of stock targets and the addressing of bottlenecks on a case-by-case basis. On the other hand, there is continuous operation at the beginning of the chain, whereas at the end of the chain, the final outcome will be an overcapacity of production that is able to meet peaks in demand.

– *Example 2 – Global logistics.* Today, logistical concern spans the company and the various trades that compete to bring the customer the best service. The Internet and computer tools make people hope for new possibilities, but the practices are still very far from the vision of the consultants. Indeed, the Internet allows for a denser and faster exchange of information with an infinitesimally lower transaction cost. The IT approach allows Supply Chain players to better communicate via Databases, which are often grouped in Enterprise Resource Planning (ERP). However, this mechanistic approach, supported in the background by powerful and heavy computing, works well insofar as it is in a stable state, and which can nevertheless be severely disrupted by transitional regimes, which is the innate circumstance of ever changing environments!

As much as they are tools, Organization and Cooperation seem to be the adhesive necessary for global SCM (Supply Chain Management) logistics. The fundamental tendency of integrating the functions of the company and logistics in a thorough way implies the ability to think well on the flexibility of the organizations, as well as the motivations of the personnel.

– *Example 3 – Poorly managed computerization.* In general, only a project manager is able to have a global vision and mastery of the system (often, specialists are only certified for part of the system). If the project manager is outside of the company, then there is a loss of information about the company, a loss of independence, insofar as the *a priori* compartmentalization and the psychological or social principles are not necessarily integrated from the start of analysis. Any operation of simplification must be carried out, independent to notions of cost, in order to make the system less opaque and to involve the people working with the IT tool. This should lead to better architecture and better organization. Thus, the computerization of a process has considerable structuring and formalization forces, and also limitations. Application designers are often the only ones to understand the functioning of a system must participate in the simplification of the processes, not only to automate them at the lowest cost, but also to make them easier for personnel to take on board and for those who are not necessarily always very motivated. This results in easier maintenance and further development.

– *Example 4 – The "Post Manufacturing Paradigm".* As a common practice among producers of customized products, the OKP (One-of-Kind Production Systems) approach was introduced and followed by the concept of "Mass Customization", which alongside the Internet today allows information to circulate globally (and worldwide), faster and cheaper than material or product flows. A "delayed differentiation" of the products is generally carried out and consists of generating (albeit minimal) stocks of semi-finished products, which are assembled only during the final preparation of the order, at a point as close as possible to the customer. The industry of the PC (with manufacturers like Dell) is an example of this type of organization: each device is customized during the last assembly phase, that is, assembled with specific components and software, as ordered by the customer, before delivery. In order to simplify configuration or reconfiguration, everything is designed from the development of the product or service. This avoids manufacturing and storing models that do not match demand; the logistics, costs and traceability of the product are improved. We thus approach the standardization concepts of the products and the notions of monitoring configurations, which is only made possible at the price of the simplification of the processes and the products. Here again, organization, human factors and simplification prevail over computerization.

1.1.3.3. *What characteristics are specific to simplification approaches?*

This section discusses some elements of the approach used for the treatment of complex systems and also highlights important hierarchical notions for this same approach. From this we can deduce some workflows.

1.1.3.3.1. Understanding complex systems

Recall that a complex system is composed of elements (sometimes numerous) whose interactions are often nonlinear. As with any population, such a system often seems organized, in a more or less hierarchical way, within space and time, with intercommunicating, functional levels. The interactions between the entities of the system allow for the emergence of global properties that cannot be predicted at a lower level. To better understand and try a glimpse of such properties, complex systems are analyzed with mathematical models and simulation. Let us investigate two such techniques.

In a mathematical model, the system is usually represented by equations, differential or not, and which are solved in simulation by using a computer program that describes the process; in this case, the computer scrolls the program step by step and observes the evolution of the system over time.

But models may not be mathematical: they may also be cognitive, qualitative, etc. Similarly, there is a tendency to use the term "simulation" whenever a computer is used to study the solution. Therefore, in the case of computational complexity, theorists come to simulate the equations of a mathematical model by asking it to seek an approximate solution of the theoretical solution corresponding to these equations.

In fact, in every computer simulation, the primary objective is phenomenological; we do not attach ourselves to the realism of the system of equations and/or its behavioral representation, but rather focus on the notion of understanding. Whereas in the mathematical approach, the exact and/or optimal solution is sought. The important thing in economics and in industry – we will remind you many times – is to get a "good" answer or solution in a short time. With the odd exception, risk-taking for instance is integrated into the decision-making process: reactivity and accuracy take precedence over precision. It is therefore important to characterize and differentiate the particular objectives of the two approaches:

a) Mathematical modeling does wonders in terms of abstraction. It obliges the mathematician to make an effort in the field of "reductive comprehension" as he tries to describe qualitatively (e.g. with semantic graphs) and quantitatively (mathematically), a system based on a reduced number of principles, equations of bases, theories, etc. In short, with the knowledge we possess, we proceed to a simplified, sometimes incomplete representation of the system.

b) Simulation does not necessarily simplify. On the contrary, we try to integrate into the simulation program as many details as we can (even if we generate more noise than relevant information!). We describe and/or reproduce the behavior of a system in a given context, with or without equations.

Therefore, the "modeler" seeks to abstract and simplify the system, even if it means sacrificing realism, and cannot do this better than with the mathematical tools available; this approach is typically scientific. While the "simulator" tries to model the system with realism, even if it means losing its simplicity; this is the approach of the engineer. The engineer can thus reproduce a very complicated behavior without having understood it, having only solved a problem related to computational complexity! Nothing is perfect. Each technique is not at the service of the other and they are in fact complementary.

1.1.3.3.2. Let us introduce notions of hierarchy, reductionism and holism

In a system, each problem, each question, calls upon a specific model. It is therefore important to clearly define the objective of the study, to simplify the mental process to focus only on what is related to the problem, to the question being studied and to focus only on what is essential. Two alternatives are thus possible:

1) The "Top-down" approach. Depending on the system of complexity, the "top-down" approach consists of asking questions at the macroscopic level, modeling it formally at a global level, then, in increasing detail as the level of Globality decreases, finally decomposing it in a hierarchical way into sub-systems, as per the fractal approach. The analytical methods commonly used are based on reductionist and deductive approaches.

2) The "Bottom-up" approach of a system (called "inverse modeling") is used to create a global knowledge of the system under study, by exploring and analyzing the consequences of existing interactions at the local level, between entities within the system (the emergence of a global order). In this holistic conception of a system, emergence is only the expression of our ignorance: we do not know how to link several organizational levels independently of the constituents of the system. Nonetheless, this approach has the advantage of being part of a philosophical theory called "vitalism". Unfortunately, the deep knowledge that we can get for each individual element is not sufficient to understand all the global properties associated with a more elaborated organism, leading to a greater assembly.

As mentioned above, the notion of *hierarchy* is always present in a complex system, even if only at the *phenomenological* level and also found in the analytical process. For example:

– In neurology, we are interested in how the brain works and how it combines knowledge in memory. In a network of artificial neurons, we are interested in the interactions between two layers of neurons (learning). In a detailed biological model of the brain, attention is paid to potential differences between ion channels, etc.

– In physics, when studying the pressure variation of a gas or its properties, it can be stated, for example, that in the top-down approach (macro level) we are interested in diffusion equations, whereas in the bottom-up approach (micro level), we try to represent the activities of atoms and the localized interactions between atoms, etc. within a model.

– In biology, the study of immune defenses at the macro level focuses on their evolution and their effects on human activity. At the micro level, we are interested in 3D modeling, seeing active sites or interactions between genes, or even intercellular, disabling hormone or antigen secretion and so on.

– Similarly, exhaustive knowledge of molecules or cells is not sufficient to identify and understand all the properties and behaviors of a living organism.

– Why not consider the Internet as a macro organism allowing millions of human brains and computers to interconnect? Therefore, the resultant activity of the Internet (a kind of global and planetary brain) allows for the emergence of orders, behaviors and/or global properties not visible through the behavior of individuals. It is a new type of collective intelligence, that is extra corporeal, perhaps even the beginning of a new societal nature, as demonstrated by the social network trend.

1.1.3.3.3. Which approaches to adopt?

The question is therefore to understand and know how a programmable structure can be organized, step by step, level by level, to bring out new emerging properties. Hereafter, specific aspects of the new paradigms will be analyzed in detail later on in this book. There are new theories and new technologies, different to conventional tendencies, which make it possible to exploit and control the functioning of complex systems. For example:

– *chaos* theory (which includes the so-called *catastrophe theory*) allows for the description of appropriate behaviors and to highlight the influence of the ICS and the notions of bifurcation;

– the theory of *fractals* is a new geometry that best describes the real structures of complex systems; their dimensions are not integer and have scale invariance properties;

– the analysis of dissipative structures and *quantum theory* make it possible to explain “irregularities” in complex systems;

– the *theory of evolution* (with the exception of the Darwinian approach, which although important, nonetheless, only provides partial answers), through the notions of prey-predator models, stigmergy, cooperation and collaboration (i.e. ants, bees, etc.), demonstrates how solutions always converge and come, not from the individual, but from the collective;

– *programmable automata networks* make it possible to determine the conditions of convergence and the lengths of the cycles, as a function of the number of elements, their interactions and their connectivity, etc.;

– finally, on the economic level, everything can be considered as an interconnected *market*. In today’s open and communicating world, markets are everywhere: inter-company markets, consumer markets, resource allocation in distributed production systems, labor markets, financial and monetary markets, consumer markets, inter/intra cellular exchanges, social networks, etc. All these markets are based on sharing, negotiation, cooperation, collaboration, competition, game theory, etc. The first act is to organize the game of “coopetition” and “comperation” (a combination of cooperation and competition). This is how the concepts of *coopetition* and *comperation* were born (see J. Reaidy’s thesis [REA 03a]). Around these concepts were introduced notions of auction, local negotiation and decision-making protocols, etc. Thus, with the “*agents*” *technology*, it is possible to define the appropriate levels of coordination to be implemented in distributed and cooperative systems to find the best match between products, resources, customers and logistics; and better manage complex systems.

It is now possible, with the condition of behaving differently and relying on good transpositions, to help companies and political decision makers in the study and resolution of their complex systems.

1.1.3.3.4. What developments are observed in the analytical process?

We can conclude from the above, independent of analysis and problem-solving techniques and without changing paradigm, that there is always an attempt to structure our methods. This structuring takes place according to our perception of a possible hierarchy within the notion of complexity:

– the complexity observed depends first of all on the question that we ask and what we seek to know;

– different specific models will be implemented according to each response. But above all, for the same answer and following the same tactics, we can attack the problem in different ways, either by attempting to decompose it (a conventional approach, which is often impossible) or by proceeding with an analysis by several sequential steps. According to J. Casti [CAS 94], *the more we need models to solve a problem, the more complex it is*;

– some think that we can "approach" a problem in a comprehensive and global way with a general and full model. How long does it take to develop such a "white elephant"? Is it economically good and technically reasonable? And how about when the problem is entangled or not decomposable?

These findings lead us once again to emphasize the fact that the two concepts are opposed. Is exhaustivity linked to reductionism? Is globality or holism specific to the notion of emergence? In fact, as has been seen in practice, these concepts are complementary; they cannot be cast in the same mold, but nonetheless can still coexist in synergy. Many more and less sophisticated examples can be observed in nature: these can help us better understand how to manage complex systems [CAS 94, WEB 09].

1.1.3.4. *Simplexification*

This section discusses some elements of the approach used for the treatment of complex systems. It also points out that notions of hierarchy are important in this process, and thereby deduces some workflows.

1.1.3.4.1. Preamble to the notion of innovation

In the history of science, whether in the fields of engineering, life sciences, economics and social sciences, etc., products and services have always progressed step by step, moving from the simple to the complicated and complex. Similarly, their evolution has sometimes been fast (the phenomena of disruptive events) and sometimes progressive (in a new product, for example, it is common to take 80 to 90% of already existing components and sub-assemblies). The same applies to the study of such systems. How does this happen? In general, some difficulties arise and will guide the processes:

– In a complex system, we begin by studying a salient fact, a clear phenomenon, in order to understand it. Then we add "complexity" little by little, taking into account new added effects and elements. Thus, we are gradually integrating and combining more and more phenomena and entities as we do in the *systemic or system approach*. This is due to our limited ability to grasp complex and complicated things or phenomena at once.

– This requires a lot of time to acquire real expertise (as opposed to "false" or "computerizable" expertise). In spite of this, in a given critical production process, such as the retirement of an expert in a company, the lack of an "experienced old timer" will be considered as a difficulty: in many cases, he is replaced by many "young people" or by new low-skilled specialists. And despite any formalization, description or modeling, the prior shaping of know-how, and/or computational algorithms, does not facilitate a skill or experience transfer. A disruptive event has been introduced and the simplest solution is to act differently, to leave or simplify the usual process. Hence the interest of constantly questioning given processes, reconsidering them rather than improving or enhancing them (it is the aim of the Business Process Reengineering approach).

To solve mathematical models or equations, the same phenomenon happens. Moreover, the algorithms and model-solving approaches have evolved. An increasingly more precise algorithm can be used; solutions can be computed faster and faster, thanks to the development of computer science (evolution of numerical and analytical approaches). However, if we want to deal with increasingly difficult problems, we must be able to solve them in acceptable time delays. The simplification and reduction in computational algorithms saves time. This simplification is necessary in terms of performance, although it is necessary to be careful not to lose too much precision. *Simplification should make it possible to curb and/or compensate for the effects of the approximation* of where we would like to be if we want to continue working in a passive way. Therefore, experimentation, methods and experimental calculations require continuous work to improve choices of the right parameters, good iterative methods, good routines for minimizing errors, etc. But how far can we go?

1.1.3.4.2. The process of simplexification

It is an unusual approach in relation to the subjects discussed above, which consists of "decomplexifying" a system. There is no precise theory or methodology in the scientific sense, but we can now lay down some basic rules and principles, fruits of experimentation, which will be used throughout this book. The first question that the practitioner asks is: *to what points should I give my attention?*

There are many methods in current practice that we will not list here and which have proved their worth. But in so-called complex situations, it was nevertheless necessary to show flair and intuition (the real expertise!) in order to apply them in a specific way that shows the limitations of certain academic approaches. For the record, a complex system is characterized by a set of autonomous and communicating elements, with dynamic and nonlinear interactions; finally, the evolution of their process is subject to a strong "sensitivity to initial conditions". From this it is easy to anticipate, in standard cases, the difficulties encountered when resolving a matrix of differential equations, but at the same time allows us to guess how to proceed since one of the basic elements is interaction.

Some methodological elements

Based on our experience of the theory of programmable networks, we can easily determine that complexity is a function of:

– the number of elements, which affects the quantitative number and the attractor cycle lengths (see below);

– the sophistication of the function/activity carried out by each element or agent (granularity of the network node);

– K-connectivity of the graph (i.e. the number of relations, or links, within the neighborhood of the agent involved: four for the Conway automata or eight for those of Moore);

– the presence and nature of feedback loops, about the notion of dynamicity, etc.

These parameters lead to unexpected remarkable properties; that is to say the system converges to a specific singular state called an "attractor", "organization" or "configuration" whose form is very varied: a stationary state, or a rhythm (periodic movement), or a bounded oscillating movement and without any period (chaos), or a "strange attractor". The methods to be implemented are clear and we must act, whenever possible, at the level of the organization or the architecture of a process. Even if this is only a part of the possible actions (given here for information only), it is necessary to:

– proceed to the *decoupling*. In this case, we try to identify and reduce the interdependencies and relations between the elements of a system. Technically speaking, "group technology" (which is an industrial technique designed to analyze and group different parts or components by similarity of their physical, functional characteristics, etc.) may be used;

– perform *structural breakdowns* to reduce the number of elements involved in a system. For these destructuring approaches (note: not destructive of global properties), we will call on the theory of graphs by making maximum or minimum cuts. Multivariate Data Analysis can also be used to regroup strongly related subsets;

– to develop the notions of *autonomy* and therefore the independence of the elements between them. This is where the notions of functionality and learning intervene at the level of each element.

On these points, we can refer to the various works of Dr. Pierre Massotte in semiconductor manufacturing lines: the deterministic chaos that existed was suppressed and stable configurations appeared spontaneously, with some modifications at the level of the structural feedback loops. The entire line operated without a supervised control tool, with minimal effort, and global performance (Work in Process or WIP, Turn Around Time or TAT) was reduced by about 10%.

In this context, we can also refer to the work of J. Costanza ("The Quantum Leap" [COS 96]). However, several problems arise from this approach:

– Which functional mode should be preferred? For example, do we have to make orders (actions on product/information flows)? Or should we make dynamic reconfigurations (actions on physical structures, logical and functional architectures)? This work remains to be deepened despite the advances made in the thesis of Y. Liu.

– In terms of modes of operation, should the effort be focused on the intrinsic functionality of each element (closed system approach of the complicated type)? Should we consider only functionalities linked to an open system (notions of auction, "bids", market place, etc.)? Which ones? (see the thesis of J. Reaidy [REA 03a]).

– From the moment the complex system is considered as a programmable network, an issue relating to the measurement of performance arises. We know how to define the convergence of the complex system but we do not know how to determine the basin of attraction! Similarly, it is unclear whether the global performance that will emerge is optimal. This last point is, however, minor since we do not always seek the global optimum (see note above).

– What level of simplexification should be considered without modifying the properties of the system? (see the example described above on the minimum life model).

1.1.3.4.3. What are the alternatives to simplexification?

Finally, in the case where it is not possible to simplexify a system, we can proceed by using a few simple techniques:

– Let us assume that we are confronted with a madman. Faced with a chaotic, therefore unpredictable behavior, any attempt at logical and rational action will fail. It is by injecting incoherence into our remarks that we can destabilize it and/or counteract his own action and thus change his behavior. Therefore, as is the case for the nonlinear dynamical systems (NLDS), we act on the inputs and on the stimuli, to counteract the spontaneous evolution of the complex system. This leads us to say that we must oppose order with order, disorder with disorder and chaos with chaos.

– Transdisciplinary approaches may also be used, especially if we are at the cutting edge of a technology or particular approach. This approach is called "*Inspiring Modeling*" and practiced in advanced research centers. Knowing that nature has had billions of years to model, evolve, adapt and perfect itself, it is necessary to transpose the steps that have engendered their success onto other fields of study. For example, in the engineering sciences, it is essential to copy what is done in the life sciences (e.g. bio-inspired or biomimetic approaches), economics, humanities and social sciences, architecture, etc. It is a transverse approach specific to the "Intersciences Centre" which was advocated at the Alès School of Mines in France.

– When a chaotic behavior is observed, it is easier to continue evolving in this context so as to achieve new stable singular states, rather than bring a system back into zones of non-turbulence. In terms of energy consumed, the balance sheet is far more unfavorable (see Pierre Massotte on the behavior of IBM production lines).

– Problem avoidance: this consists of removing the sub-system involved in a problem, by circumventing the problem and changing the context. In short, we are looking for alternative ways to either change the nature of the problem with other goals or differently focused subjects of interest: when "customized mass production" or "production on demand" cannot be achieved under sufficient conditions (through flexibility, reactivity, etc.), the notions of "*dynamic pricing*" will be considered rather than attempting to solve problems of organization or scheduling, etc.

– In complex systems, these are very often sensitive to initial conditions (SIC). On the one hand, this feature is interesting because it can quickly destabilize the system. On the other hand, this implies an interest in the mastery of techniques related to the detection of weak noise.

The "upstream" problem as presented here offers important advantages. It is universal and the problems encountered in the industrial field are also reflected in other fields of application: public "policy-making" problems, management of dynamic systems, social phenomena, etc.

Many efforts are still needed to formalize a methodology and its associated tools. Indeed, in this book, we focus on mass-personalized production systems; however, we still have to keep in mind that we are presently working on a future step: the mass-personified production systems [MAS 13].

1.1.4. *Organization and management principles in complex systems*

This section was developed following a meeting with officials and economists from the Montpellier Region (UM1 and UM2 Universities, Regional Collectivities, Elected politicians, the Army, Simplification Institute, etc.). This meeting, held in 2006, was initiated by the Institute of Simplification with the help of the French Languedoc Roussillon Region, and made it possible to specify some of the notions discussed above. In the face of complex systems, the challenge is how to control and master them. How should they be organized? At the level of their administration, is it necessary to decentralize, and how? In large administrations, how is it best to delegate responsibilities and powers to territorial and/or regional authorities? What level of autonomy should be advocated, etc.?

Taking into account the various comments made, the existing approaches and the discussions on this subject, it is first necessary to specify and clarify certain terms and concepts, and place them accordingly in several workflows (dealt with in more detail further on).

1.1.4.1. *Definitions specific to organized and self-organized systems*

To begin, let us briefly define basic terms that define an organization and an organized system:

1) Definition of the *Organization* [MOR 77]. *"Organization is the property of a system capable of both maintaining and maintaining itself, connecting and connecting itself, producing and producing itself"*.

2) Definition of an *Organized System*. The following definition is strongly impregnated with the concept of "automatic" flow: *"A system is said to be organized (also called 'organized behavior') if each element of the system acts in a defined way according to external orders issued by a supervisor. The result is a coordinated and global behavior within the framework of a common action intended to produce a good or a service"* [MAS 08]. In this context, we do not specify the best good or service: indeed, in a complex system, the objective is to get an acceptable solution, as best as we can, as fast as we can.

Note that in any study of a process, "*everything starts with organization, and everything ends with organization*". Between these two stable states, one or more cycles of evolution, accompanied or not by disorder, may succeed the other. The problem must therefore be considered in a global and integrated manner.

Self-organization, on the other hand, comes from the theory of complex systems. It refers to the *spontaneous appearance of a structure* through the interaction of its constituent elements. Self-organization is a fairly recent concept. It was initially studied and applied in the fields of biology, physics and chemistry. It is active in the domains of systems, artificial life, business, natural systems, etc., but is still under research within the field of information sciences and/or engineering [LES 95, CAM 98, FOI 98, BES 95, MER 98, GUT 99].

Several definitions have been proposed to better clarify and understand the notion of self-organization. We can cite some of them by adapting them to a context in order to show how it may be interpreted.

1) Definition of the self-organization of E. Bonabeau [BON 97]:

> *"A process in which structures emerge at the collective level (the appearance of a structure on the N+1 scale, based on a dynamics defined at the N scale), and from a multitude of interactions between individuals and entities, without having been coded explicitly at the individual level".*

2) K. Krippendorff proposes a more concrete definition:

> *"Self-organization is a process in which the organization (constraint, redundancy) of a system grows spontaneously, for example, an increase not being controlled by the environment, by what surrounds it, or by an external system"* [KRI 97]. This definition is too general and has caused us some problems within the industry.

3) P. Marcenac and S. Calderoni [MAR 97] try to be less aggregate:

> *"Self-organization defines the property of a system that is organized or reorganized over time to form semantically remarkable structures".* This definition requires further detail.

4) As part of a logistics seminar, the following definition of self-organization was proposed by P. Massotte and accepted [IMS 94]:

> *"It characterizes a system that is not coordinated from outside. The elements are endowed with autonomy and carry out tasks together, in interaction and mutual understanding; the sum, or combination, of individual tasks generates an order, or the emergence of a global good, function or service".*

Thus, the self-organization of a system consists of the transformation of the topology (i.e. the structuring connections of the network), into its parts, as a result of the operation by this same network within the framework of structural coupling with the environment.

5) Another definition was recently introduced for the framework of studies on information systems:

> *"Self-organization in a complex system is a characteristic of interconnected programmable networks. It makes it possible to mobilize resources intrinsically and to organize them in terms of*

> *functionality and communication in order to achieve a global objective without direct external action"* [PAB 02a].

In terms of application: in a multi-agent system, the organizational rules are internal to the system, those which appear to be informally closed. Such multi-agent systems belong to the class of autonomous systems (systems specified by internal self-organizing mechanisms) and which are not heteronomous (defined by external control mechanisms) [VAR 93].

In this brief overview of the different definitions, we introduce in fact fundamental notions related to self-organization: organization, interaction, autonomy, emergence and appearance of structure. Self-organization is always associated with properties which we will begin to address in the next section, and which will be dealt with in greater detail later on in this book, when and as needed.

1.1.4.2. *What conditions and properties are linked to the notion of organization?*

In general, an *organization* can be defined as a *structure*. This makes it necessary to specify what a structure or coordination can provide, or more exactly what a structured system can provide and how. Note that an organization is not always static or physical. Indeed:

– It is possible to think in terms of functionality. That is to say, to consider an organization as a set of processes arranged in such a way so as to realize a given number of "things". It is difficult to determine the relationship between a structure (linked to the usual notion of organization) and the notion of functionality (knowing that an organ fulfills a function). This fact becomes particularly evident when we consider the biological organization of a body or even a social and economic organization. Here, however, it remains *static*.

– In any organization, the notion of structure is necessary but not sufficient. It is imperative to also have associated functions at the level of entities and reactions, and at the level of relations between entities (interactions). It is the nature and combination of these functions and interactions that will allow for the *emergence* of a global functionality of the system. This global function is in fact a "spatio-temporal order" that appears at a higher level of assembly.

Therefore, we must also look at organization as the essential underlying process of transformation and not just as a structure: indeed, here we become *dynamic*. An organization will simultaneously be a structure and a process, that is to say, subject to a temporal evolution of its elements whose causes are equally important. Any change of organization or order in a nonlinear dynamic system (NLDS) is, as such, an internal property of the system; it is a self-organization. This is important insofar as we wish to speak of an organized, self-organized, self-repairable, autonomous system and so on.

Self-organization generally corresponds to a reorganization that is decided autonomously by the agents within the system, and becomes a means to overcome the possible disturbances caused by the environment. The self-organization of a system has occurred if the system has changed its structure [MAR 96].

1.1.5. *Action and decision processes in self-organized systems*

The following terms are often used in *Organizational Theory* (see the work of H. Mintzberg [MIN 82]). We will adapt them to the theory of self-organized systems in order to broaden their meaning and principles.

Indeed, the main difficulty does not consist of applying well-known organization principles to fairly stable structure and analyzing them overtime [BAK 96], but to see how we can control and monitor them under self-critical conditions. Based on Thom's theory and recent works [DAU 03] in complex systems subject to disruptive events, we were able to publish a book including some advanced concepts on that subject [MAS 08].

In some regard, the world around us, everything, can be construed as a system. This is "normal" if we consider that a system is made up of several agents, elements, constituents or entities (an entity here is anything anywhere, which can do anything, anytime, no matter how). To be a little more precise in Churchman's sense: "a system is a network of entities, interacting more or less strongly, coordinated (functionally or not) with a view to achieving a mission and achieving an objective. We can thus speak of production systems, computer systems, telecommunication networks, cellular biology, populations of individuals, administrative services, etc. For example, as we write this book, our hands, brains and computers constitute a system. More technically, it is a programmable network whose entities are interacting and coordinated. When we speak of *Interaction*, we mean that there is:

– an exchange of information or messages;

– an exchange of orders or shares.

There is an underlying notion of *communications protocols*.

When we speak of *Coordination*, it is inferred that there is either an arrangement or a combination of actions intended for a well-ordered and coherent purpose. Inevitably, this involves information processing and decision-making. The *decision* is the result of a calculation, an optimization, etc. (the domain of "Computer Sciences"), and an auction, a promotion or a negotiation, etc. (e.g. in Games Theory – field of "Business Science") brought about through *decision and negotiation* *protocols*. In any system, therefore, there are three types of protocols to be taken into account.

It is most important to extend these concepts to non-rational complex systems where decision-making is not only based on quantitative data but also on qualitative and psychic data. For example, an attempt towards holistic systems was successfully applied to the field of "tourism business strategy". The issue investigated was: "how to ensure the resilience of a complex system whenever disruptive events may occur?" [MAS 15a]. Another debate can be articulated on the usefulness of cognitive robotics. This point will not be developed in this book as it still requires specific validations.

1.1.6. *Notions of centralization and decentralization*

The purpose of this section is to address the issue of decentralization. On many occasions we have found that business leaders tend to associate this notion with (and sometimes even state it as the solution for) the problem of complexity. First, in terms of definition, the following situation will be considered: a structure is centralized when all decision-making powers are located at a single point within the organization – they are therefore located within the same entity. A structure is decentralized when power is distributed among several entities.

1.1.6.1. *What are the characteristics of centralization?*

In Organizational Theory, centralization is considered to be the most powerful mechanism for coordinating decisions in a system. The decision is drawn up within the framework of a single entity and is implemented under direct supervision. On the other hand, if it makes it possible to satisfy the taste for power, and if it is simple to implement, it presents many problems when:

– An entity cannot collect and process all the information necessary for decision-making. This may be due to problems of direct links, the erosion or distortion of information, the interpretation of the context, the cognitive capacity of the decision maker, information overload, etc. Emerging here are problems regarding accuracy, consistency and relevance of information.

– An entity cannot process all the information in a sophisticated and comprehensive manner. Often there are too many variables and constraints. However, a decision maker shows cognitive limitations in terms of reasoning and contextual apprehension. In addition, the evolution of the system depends on the importance of interactions and feedback loops. It is thus limited to the level of the intellectual and computational capacities of the decision-making system. We are therefore dealing with two types of complexities:

- *intrinsic complexity* (when *it is too complicated*);

- *computational complexity* (when *it is a problem of combinatorial explosion*).

– The transmission of directives and orders to the lower levels of the organization is not integral. It may be that it is subject to modification, if not error, interpretation, etc.

– The entities that hold the information do not make any decisions and systematically refer them to the entities that have power, which in turn do not know the setting, the environment or the context – elements which are indispensable to the decision-making process. There is therefore a problem of quality and reliability in the decision-making process.

– The transmission, or rather the feedback of the information in the network, takes time. This transmission has a cost and poses storage and pre-processing problems. This situation penalizes the responsiveness of the decision-making system.

– Finally, excessive centralization is contrary to the notion of independence and the autonomy of entities. However, creative and entrepreneurial people need room to maneuver, take up initiative and so on. Centralization is thus acts as a brake on the motivation and emulation of entities, that is to say, on their learning capabilities, whatever the mode of learning: either by trial and error or otherwise (for instance, deep learning or social networking); and whatever the control system (supervised or not).

At the same time, the distribution of powers within an organization also raises problems of architecture and the integration of physical, logical and functional characteristics. For example, which of the two models below is the most centralized:

– a centralized database whose users and decision makers are dispersed in the network?

– a distributed database whose manager has all the decision-making power?

Therefore, by extension, we cannot only consider the notion of power or coordination. Decentralization is sometimes confused with “distribution” or “allocation”, and it is common to observe some confusion between the notion of (delegated) decision-making power with that of the fragmentation, physical, logical or functional delocalization of resources.

1.1.6.2. *Why decentralize and how?*

Although centralization is the most powerful mechanism for coordinating decisions within an organization, some benefits of decentralization need to be taken into account. Let us put forward several arguments:

– one center, or one brain, cannot “understand” all decisions;

– a decentralized organization should be better able to respond (more) rapidly to local conditions;

– decentralization is a means of involvement and motivation.

Decentralization is in fact a continuum: there is no diagram describing in a discriminatory way, the different forms of decentralization. We will therefore limit our definition by the extremes, specifying only that:

– the dispersion of formal power down the hierarchy – also called delegation to hierarchical officials – constitutes a “vertical decentralization”;

– the dispersal of decision-making power to elements outside the structure – for example, informal power entrusted to functional managers – constitutes a horizontal decentralization. It therefore constitutes as a transition for the control of decision-making processes to people outside the hierarchy;

– decentralization can result in the physical dispersion of services or means of production. In this case, there is a pure and simple transfer, or even abandonment, of decision-making power. This dilution of power will not, however, be addressed in the rest of the book.

Whether it is horizontal or vertical decentralization, the dispersion of power can take several forms. Decentralization can be:

– selective and decisions can be made at different points of the organization depending on the areas (finances, personnel, etc.) and degrees of autonomy of each entity;

– global when power is dispersed and distributed (functionally) consistently and in the same manner within the structure;

– a simple distribution of functions in an IDSS (Interactive Decision Support System) whose partial results will be aggregated, integrated and validated before being diffused into the network.

1.1.6.3. *The power of decision-making and the problem of complexity*

Without going into the details of all the categories of the IDSS in a centralized and decentralized mode, we can already ascertain that “nothing is perfect” and that it is not possible to have the advantages of both models at the same time, since this requirement itself is a complex phenomenon. Consider therefore the following points:

– In a *centralized organization*, supervision is carried out *directly* by a single entity. This entity cannot grasp all aspects of the problem. We are therefore dealing with a problem of intrinsic complexity.

– In the case of *decentralization*, direct supervision is replaced by *regulations*. However, the use of rules to reduce or disperse the power of the hierarchical or functional superior never has the effect of giving power to the subordinates. Indeed, the use of rules reduces the power of subordinates and brings us back, in terms of complexity, to the previous problem, which remains open.

– To avoid activities becoming routine, we can reduce the influence of the rules and be satisfied with *a control associated with coordination*. This makes it possible, through the standardization of certain procedures, to homogenize the working context (e.g. methods and processes of production or technologies) to give more autonomy to employees in their work. Here, we penetrate to the heart of virtual organizations where the stakes are to ensure *consistency* between decisions made in a distributed way and to avoid the problems of interactions. Any of which could lead to behavioral complexity (e.g. deterministic chaos).

– Finally, in the case of *open decentralization*, autonomy is complete and we proceed here by mutual adjustment. We are in the presence of *heterarchical* systems, more precisely of self-organized systems where forms of competition and cooperation are involved. The complexity encountered is that of programmable automata or autonomous spatial robots that cannot be controlled directly by man. From now on, it is known that, under certain conditions, the system will converge towards an attractor; however, what is not known, is whether the obtained shape will be globally optimal.

– During our industrial practice, we developed techniques based on new concepts in Computer-Assisted Production Management (CAPM), expressed in terms of task allocation, in well-identified business sectors. These techniques employ the notions of auctions, Game Theory and hybrid approaches that we have called “coopetition” and “comperation” (see the European PABADIS project). As already touched on, this is a question of replacing a global MES (Manufacturing Execution System) with distributed MES adapted to their local environment. The difficulty of implementation is not technical, but social, insofar as the notions of the role and responsibility of decision makers have been upset.

– The most decentralized form we come across in terms of organization is *Peer-to-Peer* (P2P). This computer concept represents a system for exchanging resources and data between connected machines. Some of its most emblematic illustrations are the Napster exchange model of the late 1990s, the free telephony model over IP Skype since 2003, etc.

In fact, a *Decentralized System* forms a structure where each piece of information is made available to the community, where each user (or "peer") shares and manages resources as he or she wishes: definition of file permissions, structures for access to information, etc. No central server is provided to manage data, information or load. Computer processing is distributed equally between machines/users. This idea is a result of the democratization of information technology, the reduction of the costs of computer systems and the new methods of work. It has reshaped the ability to communicate on a peer-to-peer or equal-to-equal basis, particularly in the business world. But where is the notion of power or coordination now? It is broken, like all the constituents and all the "views" of the system!

The Peer-to-Peer, or egalitarian approach, modifies the relationships that allows for storage and the direct access to information, without the need of going through an intermediary. It also makes it possible to constitute and align a community of interests at the speed of the networks, to constitute network content, which again, modifies the relationships of human and/or experts in relation to the company.

A first problem of the Peer-to-Peer approach is that each peer is an administrator of its own machine and this implies, in terms of system architecture, the need to provide a server that establishes and supervises the communication between the machines of these users. Thus, decentralization is not entirely total and the exchanges to some extent remain under control. A second problem concerns the security policies (access) which must be effective despite the constantly fluctuating topology of the network. Finally, given that the storage of information is distributed – there is the risk of redundancy, and also the benefit of security in the event of a physical problem – the global level of performance may vary. Depending on the occupancy rates of each peer, it is difficult to guarantee a given level of service quality.

1.1.6.4. *Hierarchies and heterarchies in complex systems*

As a corollary to the concepts of Centralization and Decentralization, we must begin to address the problems related to organizational structures.

In the case of *hierarchical structures* – that is, based on master–slave type relations – we obtain advantages at the level of the decision-making model, the main ones being:

– readability: this type of model is easy to understand;

– standardization: this type of model conforms to the classical way of solving problems;

– efficiency: this type of model gives fast answers, due to the master–slave coupling between units;

– ability to perform a global optimization (conventional approach).

By contrast, this type of structural model has difficulties in changing its structure when, for example, faced with disturbances it has to adapt.

On the other hand, *heterarchical structures* form entities that assume, in collegiality, the coordination of a collective action. In this sense, it is truly opposed to the term “hierarchy”. In this type of structure, there is no upper level control unit coordinating all the units. Usually, the entities are provided with the following capabilities:

– same priorities to access resources;

– ability to be linked and provide mutual accessibility for all agents;

– autonomous mode of operation at the level of the agent;

– full compliance with the rules and protocols used in the global system.

Consequently, the resulting advantages are multiple, such as:

– a reduced complexity in their global management, as well as good sustainability when faced with any type of faults and/or malfunctions;

– easy maintenance and modification of the network structures;

– easy knowledge acquisition about the characteristics of each and every entity.

However, difficulties lie in the prediction of global performance, security and overall system consistency.

We can now carry several notions as already discussed in this chapter: that of “structure” with that of the “delegation/distribution” of decision-making power, for example. In reality, all the cases of figures are possible and are not just a function of the notion of “complexity”. Thus, in this case, we can draw the following table:

Structure	CENTRALIZED Model	DECENTRALIZED Model
HIERARCHY	…	…
HETERARCHY	…	…

When the master–slave relationship, which is based on authoritative “orders” (such as directives, instructions or centralized standing rules, etc.), is not used, we can employ a less constraining mode based on the client–server approach. Now, with the rising power of social networks [MAS 13], we are implementing more open management systems (i.e. near to P2P) based on *competition and cooperation.* These are the two basic interactive communication principles between units or agents. It is precisely in other cases of “peer-to-peer” relationships that the process of assigning a task or an order becomes different. In the remainder of this book, the form of the decision-making protocol that we will use will be as follows:

– first, an *auction* or proposal for providing a service is issued;

– following on this, the auction is followed by a *negotiation*;

– based on this information, the best balanced *decision* is developed and shared with the neighborhood.

The resulting *order*, *a set of commands*, is rather a production program or an order planning in the broad sense: it is a planning related to different proposed action plans, that is to say, a succession of well-identified tasks of spatial, physical, temporal and logical character, and so on. Nevertheless, the application of these two principles of negotiation varies according to the context. For example, in the case of “client–supplier” contracts, the aim is to maximize a gain or to optimize an economic function locally. This approach may be hybrid (see Reaidy’s thesis [REA 03a]). The “markets” approach is interesting because, as has been previously stated, “*everything is a market*”. Without anybody becoming aware of it, each one of us, by assuring his own interests (in a local way), best serves those of the whole society – in a global way. This view towards an open and global context, that which we have collectively made emerge and which now permeates throughout our societies, will remain our working hypothesis.

Moreover, this mechanism is not very demanding in terms of information. If each economic agent knows only their own preferences (e.g. the amount of money they are willing to pay for the acquisition of goods or services), or their own costs (e.g. the price below which they would refuse to sell or produce goods or services), they can make decisions in their own interests or towards their “local” affinity. The famous “Invisible Hand of the Market” of Adam Smith is often ascribed the ability of coordinating markets and selfishness to ensure the public good: it is the direct implementation of self-organization principles. This is the ultimate step of a complex management system. More and more, management systems based on free mechanisms will have to set up and include appropriate safeguards to ensure the sustainability of the whole system.

It is for these reasons that markets are accompanied by numerous safeguards. These include anti-trust legislation, labor laws, product and service standards, financial audits, the National Courts of Auditors and so on. These centralizing constraints are supposed to guarantee the transition from individual efficiency to the effectiveness of society.

In any self-organized system, this coordination, the condition of convergence towards a given attractor, is problematic because it is necessary to organize and arrange our actions. As we cannot say to which global optimum (i.e. basin of attraction) and which cycle (i.e. the length of the course within this basin of attraction, or the time required to reach the optimal point) the convergence is related, then we cannot properly manage and control a complex system. These are issues that need to be resolved.

We will not develop these issues further in this chapter, but will do so in another chapter. Let us conclude that the above analysis will have an influence on the nature of the interactions (quantity and type of interactions, positive or negative feedback loops between entities, etc.), and therefore on the complexity of the system being studied.

1.2. What is the prerequisite for the handling of a complex system?

In what follows, we recall some properties pertaining to certain approaches and make reference to the theory of Deterministic Chaos (which will be introduced in the next chapter – in which we shall give bibliographic references to obtain greater in-depth knowledge).

In view of the problems mentioned above, the approach we are going to touch on now uses a *bypass strategy*, designed to respond to complexity with complexity. This can be expressed at the level of the inputs but also in the sense of the modification of control parameters and operating conditions. Finally, it can affect the structure of the network via simplexification. It will always be that, by virtue of analogy with what is being done in other fields like automation, we will be able to bring about a technological answer to complexity.

In automation, in the case of a dynamically situated system, deterministic chaos can occur, affecting one of the system parameters, even one with stable inputs and stimuli. On the other hand, it may also be present in the input signal and thus disrupt the behavior of a system that was previously stable. This chaos (which we will describe in detail later on) reflects that a form of system complexity can now exist both at the level of the system and at the level of the inputs. So what will happen? Although this case study will be discussed later on, for now we can say that in a different sector, such as CAPM, disturbances in the controls of a management system will counteract and compensate for any "pumping" phenomena and "over-reaction" that exists in a system.

This way of thinking allows us to envisage an original strategy for an industrial system that encompasses the Global and that is able to define the favorable operating conditions with which to better "manipulate" complex systems. We thus set the principles for a conversion of approach in terms adapted to the treatment of complexity; let us temporarily call this *Converse Engineering*. We are faced more and more with *networks of networked companies* and industrial systems that are subject to great flexibility (in terms of both product and volume), and also to a great internal and external reactivity. Starting from an example, let us assume that the evolution of an e-company needs to reduce its technological costs by 50%: this implies mastering the system concerned, which therefore must be *simplexified*.

To facilitate an understanding of the issue, we will only handle the process concerning the information system. Before embarking on the implementation of new information technologies, networks and telecommunications that rely on known techniques, we will consider a new paradigm for redesigning the whole. The *re-engineering* of the system (BPR or Business Process Reengineering) will proceed, as per the example, in six key steps:

1) *Simplification*. This is essentially about "dismantling the Tower of Babel", that is, reducing the number of products and components by unifying and making the communication network more coherent, etc. This leads to a destructuring/restructuring of the system with a focus on the *design of the product or service*, tool or system itself. This is essentially what Steve Jobs did, when he returned to Apple in August 1997 after his exile (since 1985). He reduced the company's heteroclite catalog of more than 600 products to just 20 fundamental ones.

2) *Effectiveness*. This involves setting up the notions of the virtual network via a holographic approach of the company, where "everything is in one and one is in everything". It goes beyond the principle of the factory and enters into self-organized approaches with permanent reconfigurations of processes and products. What are the critical functions and parameters that contribute to this?

3) *Simulation*. Given what has been previously been developed, an attempt is made here to modify or adapt the structure of the network, its dynamics and its SIC in order to better converge towards an attractor, that is to say, to better monitor and control a complex system. We are moving, not towards efficacy, but towards efficiency. The *design of the process* is thus used to improve performances and control.

4) *Grids*. In industry, the current problem is not the modeling of knowledge, but its collection at the right place and at the right time in order to store it, then to find it quickly and to deploy it more easily throughout the whole company. Access and dissemination of information will be based, for example, on "grid computing" which is a virtual data processing infrastructure including heterogeneous and distributed resources interconnected through very specific architectures and technologies.

5) *Notions of utility*. This is the “Return to Basics” or basic needs. This decision management approach is required as the influence of social networks increases over time. As we know, this is based on “utility theory”. In short, this can be defined as: “*A theory used in economics that holds the belief that a product, item or service’s utility is a measure of the satisfaction that the consumer will derive from the consumption of that specific good or service, as per their needs*”. In other words, we must concentrate our efforts only on what is necessary, eliminate all that is redundant, useless or needless or that which does not belong to the core business. This avoids “reinventing the wheel”, and promotes the use of what already exists elsewhere and which has proved its value. Thus, plunging us into the well-known “make or buy” logical reasoning, or into the well-understood disintegration–integration mechanism (disorder–order) with the well-known phenomena of decentralization/delocalization, or even internal development versus external acquisition strategy.

6) *Expertise*. This is the real “Big Kahuna”, in other words the capitalization of knowledge and know-how, traceability and the implementation of the means specific to cooperative work and collective intelligence. Everything is based – centered – on the Web: any person, any process, wherever it is, is connected at all times to common databases, with a cost of access to information that is derisory (another derivation of the classic injunction common to the world of innovation: “Anywhere, Anytime, from Any device”).

In this context, we have obtained a different way of organizing business, the emergence of new business models that will “decomplexify” the behavior of some key companies, in order to make them more consistent, enabling the evolution of the presently poor *dynamic* towards a better one.

1.3. Applications: industrial complex systems

The purpose of this section is to introduce examples that will be discussed in detail later on. Here, we are interested in the problem raised by two real-life case studies, based on the realizations of this chapter, and which we envisage some avenues for further study.

1.3.1. *Distributed workshop management system*

Let us focus our attention on the “control” of a production system. At the MES level, this system includes many workshops dispersed geographically. The interactions are strong and there are undesirable “caterpillar” effects at the global level in terms of outstandings and stock-outs.

Each workshop taken independently is a complex system. In general, the latter is not decomposable, but it is often characterized by Cartesianism with the view that a complex system *can be decomposed* into a series of elementary problems of limited importance and limited difficulty. It is a methodological process inspired by a simplifying process (itself derived from René Descartes' Discourse of the Method) and hence a problem.

The principle of non-decomposition eliminates many techniques and methods that we know well. Moreover, and by experience, a complex system is only a set of simple elements in interaction, with amplifying feedback loops [THO 95]. Each entity is governed by simple operating rules. But the study of such a system cannot be approached in a "simple" way, because complexity is a function of:

– the number and size of constituent entities;

– the autonomy and its potential for evolution, where each entity considered alone is insufficient to fulfill the common objective;

– interdependence: the function and behavior of each entity depends on those of its neighbors with which it interacts.

Any reduction in the number of entities, functionality or interdependence (and their collection as a whole) strongly alters the emerging global properties of the system: a whole cannot be reduced to its parts. This is what underpins the characteristic of *non-decomposability*.

Similarly, the emergent order cannot be predicted accurately because, even if we know how to position the critical point corresponding to a bifurcation, it is not known if the behavior of a system will eventually converge towards a given basin of attraction (we cannot know this because of the SIC and the effects of feedback amplifiers).

Moreover, the characteristics of a holonic system are not to be sought in each of its parts (e.g. each organ of our body is not a reduced representation of our *global* behavior, but nonetheless, contributes to it through the phenomena of cooperation, competition, coopetition and/or comperation with some other organs, etc.; we will explore and go into further detail of these terms in a later chapter). If we modify the relations, the liaisons between organs, that is to say the structure and protocols of communication and negotiation, we thus obtain completely different behavior and configuration states.

It is therefore towards global approaches such as *systemic analysis* that we will inevitably have to orient ourselves. This analysis shows that it is not possible to decide on an isolated point without simultaneously taking into account the fact that the decision, even when it appears as secondary, reacts to the previous one and so on. Let us recognize that this approach and the application of these principles are more difficult than those relating to the sequential scheme in which a problem is decomposed into simple parts with direct cause-and-effect relationships. In the latter case, there is a linear chain of successive cause-and-effect relationships, an effect which in turn causes a new effect and so on. However, in a highly connected network (e.g. decision tree feedback loops or interlocking cause-and-effect loops), we find that we are far from such a simplified reality: a cause can cause effects on several distinct elements; vice versa, over time and through other entities and in a non-synchronized manner, feedback will induce different and unexpected causes and effects. Therefore, the combinatorics that can result is almost infinite.

It can be seen that depending on the influence (even small, positive or negative feedbacks as a function of their number), it is possible to obtain resultant phenomena and/or non-predictable states of convergence. Thus, if we wish to avoid falling into a simplistic pattern of thought based on linear causal relations, it is no longer possible to consider a process as a chronological and irreversible process made up of small, successive, sequential steps. We will now discuss an evolutionary approach. In contrast with the systemic global approach, it is necessary to pass several times through the same steps, to traverse the same entities, to return to their initial states/configurations and to follow their progressive modifications over time. Configurations, in perpetual evolution, are only "furtive" (not to be confused with "provisional"), and often only stabilize, when the process is interrupted during the interpretation of results and decision-making process. We are thus in the presence of an *iterative type analytical process*.

1.3.2. *Analysis and diagnosis of a complex system*

The aim here is to detect anomalies existing in a complex system and to correct them. Such a system can be a production management system dedicated to the assembly of current consumption products, an organization made up of a population of individuals so as to provide a service, etc.

The first step is to determine the desired objectives since the apprehension and comprehension of the system depend on it. This approach makes it possible to correctly select the relevant elements and properties (not the functions!), thereby identifying the determining factors before developing modes of action by which to analyze their effects step by step.

1.3.2.1. *The context and structure of the system*

We first place the studied system in perspective with regard to its environment, but not by placing the entities to the fore (in relation to their natural and functional content). Before focusing on details, we are interested in the *global view of the* *system*, the study of the mission, its objectives and the framework within which it operates.

For a system formed of interacting subsystems, it is this interdependence that ensures a certain consistency that will condition the emergence of forms. It is thus the relations between the elements that give a system unity and which therefore must be dealt with directly, rather than the constituent elements themselves.

Indeed, in a complex system, the detailed analysis of an element does not present itself in the same way when viewed in isolation and when viewed as a whole. The knowledge involved at the level of an isolated element is not the same as that which corresponds to the element taken in the global context. To return to the problem of the patient in hospital, after being taken on by many specialized services, we can imagine that serious anomalies are detected on each of their organs; in this case, each service, considered in isolation, will deploy an elaborate therapy, when in fact, it is only a minor global pathology. There should be compensation effects and interactions between the bodies that require an effort of synthesis and foresight to determine what will emerge from this data set, so as to know with what to lead with.

1.3.2.2. *The dynamics of a system is more important than its invariants!*

More formally, a complex system is a programmable, nonlinear SIC network. It continues to evolve more or less deeply (this is related to the cycle of the attractor or to its course within the basin of attraction). Even at the end of the cycle, when a stable state or configuration is reached, it will evolve while maintaining some permanence, within certain limits (e.g. predator–prey system). In the study of such a complex system, the essential point comes from the difficulty in controlling its tendency to evolve: does it diverge or converge? Is such a tendency increasing, up until what point? The important thing is to apprehend a system in time so as to predict its future, rather than dwell on a situation of a given moment, the search for illusory understanding.

1.3.3. *Some recommendations and comments to conclude*

Here is an easy-to-follow action plan that makes it possible to understand a complex system:

– first, we need to be interested in its *dynamic behavior*. What matters are the assumptions, evolution mechanisms and action plans that will guide its future, rather than its narrative, the history of its situations and the knowledge we already have of it, and which will nourish its memory and also conditioned its present situation;

– pay more attention to the *imbalances* that the system expresses towards the elements of disorder that agitate it. Because a given, but unknown, order always arises from a disorder. As in nature, it is always from disorder that a "catastrophe" (e.g. a fold or a mutation, a disruptive break) from which an order is thus made to emerge and is progressively constructed as per a well-known closed loop principle (Figure 1.2).

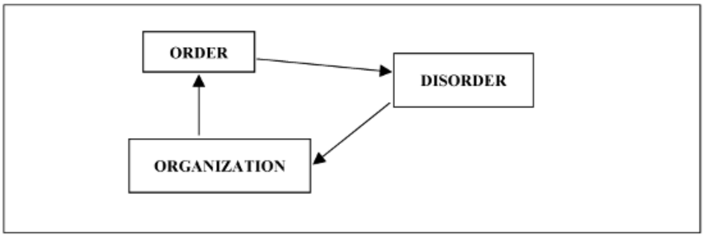

Figure 1.2. *The loop of imbalances which feeds the complex system of evolution*

These remarks are challenging: we must appeal more to our *imagination* than our experience. In order to do so, there are three pre-existing conditions required for this to succeed:

– in order to be imaginative and immersed in a "creative" situation, it is necessary to have needs, desires, a "*hunger to become*", to evolve, progress or grow;

– to exploit these imaginations or ideas, and make them productive, it is essential to have multidisciplinary skills;

– finally, to take action and take initiatives, it is useful to have a culture! That is to say, have references, experiences, curiosity and a goal.

Finally, our plan of action would not be complete without a new clause: it is by constantly changing and evolving that a system can adapt and succeed in maintaining and sustaining itself. However, in order to ensure such flexibility, it is necessary to know how to situate and evolve:

– it is the limitation of stability that determines the reactivity of the system;

– in zones of weak chaos, that is to say close to the phases of imbalance, new forms can emerge, that is to say "period doubling", breakings and branchings. The presence of such catastrophes is an opportunity to switch from one basin of attraction to another, from one state to another, from one kind of evolution to another.

Between simple, simplex, complicated and complex are laid the foundations of a new engineering approach aptly called the "Complexity Sciences". The following chapters will develop each of these new aspects and expand upon them making use of examples from industrial practice.

1.4. Time to conclude

1.4.1. *Summary*

This chapter was devoted to the definition and description of concepts and notions related to complexity. In this work, we can deduce a philosophical and methodological approach because we see that there is no opposition between change and stability, between innovation and tradition, but rather complementarities between so-called complex and complicated systems. A complex system generates new forms, original behaviors, which must be integrated into all engineering projects. The implementation of a new approach consists of making use of the technologies and methodologies linked to each of the properties of the system and its constituents. We are now bound to effect continual "comings-and-goings" between the whole and its parts.

When the Cartesian approaches and Laplacian principles were implemented and developed, thus permeating several centuries of scientific (i.e. rational and analytical) approach, unfortunately only a portion of the principles were adopted. This is because the perception of the world at that time was limited to this world. Yet the influence would have been quite different, and our culture would even more so, if the scientists who succeeded each other had integrated what Pascal had already said so well, and which has always been observed in the Eastern tradition: "*Since everything then is cause and effect, dependent and supporting, mediate and immediate, and all is held together by a natural though imperceptible chain, which binds together things most distant and most different, I hold it equally impossible to know the parts without knowing the whole, and to know the whole without a particular knowledge of each part*".

There is thus a certain complementarity between all the existing approaches, each of which provides a particular perspective depending on the situation encountered. Therefore, the Cartesian approach (i.e. based on an analytical approach) and the Holistic and the Systemic (i.e. global) approach are complementary, and can be used in synergy when Complexity and Complication are manifested.

1.4.2. *Lessons and perspectives*

Through this introductory chapter, we wanted to clarify a few terms and concepts, some of which are taken into account by the European Program on "Modeling Complexity". Some points, however, merit to be illustrated by a more industrial and societal context. Nonetheless, we have already been able to observe, through what exists around us and as highlighted in this chapter, the approaches and steps that deal with the design, as well as the conduct and control of dynamic systems, which can be either complex and/or complicated.

On the methodological level, it is therefore possible to propose a complementary approach that is two-fold:

1) To deal first and simultaneously with the *simplexification* and *simplification* (which is, again, quite unusual) of complex and complicated systems. These approaches, although radically opposed to conventional approaches because they are complementary to them, are situated upstream of current practice and yet position themselves in the current already known to "*Problem Avoidance*". These approaches are very important as generators of gain and effort.

Given the interest in the approach, its necessity and complementarity with the current situation, there is merit for the development of a scientific approach in this direction. This is why a specialized institute; the *Institut de la Simplification* was recently set up in the Languedoc-Roussillon region in France. According to this Institute, it is necessary to consolidate an approach already founded on common sense, with a little more formalism and rationality: the approach will gain credibility and will thus deploy a methodology that we hope will not be questioned beyond measure by pessimists.

As it stands, this approach is already promising in that it responds perfectly to the needs of industries and organizations of this coming century, with the ability to improve their quality and performance. Moreover, in the case of SMEs and SMIs, simple, effective and efficient procedures are required to develop sustainable economic development.

2) Hence, we have introduced a consistent way by which to improve the control and monitoring of complex systems, via specific techniques, aiming to better handle the various *mechanisms of complexity*. Indeed, if complexity is a new concern, or at least a new theory, whose properties are newly understood and cannot be avoided nor planned, then this new paradigm must be processed with tools and methodologies relevant to a new approach and a new way of thinking, in terms of risk management. This point was mentioned above, and as we have seen, some handling steps still need to be improved as there are many problems still open. For example, even if we can demonstrate that a system is complex, we still do not know

how to determine its mode of convergence, and we are even less able to control it, or the system in real time, to a fine degree of precision.

Each of the appropriate steps will of course have to be undertaken, whenever the first attempt has revealed its limitations or when it becomes obligatory to change the paradigm so as to conform with the new context.