PART 1

Dealing with Complexity

1

Engineering Complexity within Present-Day Industrial Systems

1.1. Introduction

This chapter describes some new basic concepts and mechanisms applicable to industrial systems and organizations. The resulting properties are necessary to analyze them and provide them, from their design stage, with the adaptability and reactivity required by the new challenges encountered in today's economic world.

1.1.1. *Reference definitions*

In this chapter, we will refer to "system", in Churchman's sense [CHU 92], as *any set of elements coordinated to achieve an objective.* By "industry" we mean all economic activities that produce material goods or services through the transformation or implementation of added value on basic components or raw materials. Thus, a software development center, a production system, a manufacturing workshop, a travel agency, etc. are industrial systems. The study and analysis of a complex industrial system is based on its modeling.

Historically, we have first retained the **quantitative** aspect of the systems studied, then more recently, the **qualitative** aspect, for example through knowledge-based systems (KBS). The notion of complexity that we have just become aware of has been processed by the techniques of artificial intelligence, but the approach has remained based on the fact that we can mathematically formulate a problem using parameters, variables and algorithms. This "Galileo principle" assumes that the system is predictable and that there is no ambiguity; the state of a system at a given time is assumed to be able to determine its state at any subsequent time. It is therefore purely a matter of determinism. More precisely, we will call **determinism** the theory according to which causal laws govern all things in the universe.

Any event can then be considered as the effect of previous events and as the cause of subsequent events; the successive natural states then follow one another as if by necessity. Laplace [LAP 25], a strong supporter of Newtonian mechanics, formulated the theory of universal determinism, and this theory has been considered a "religious hypothesis" for a very long time. Thus, by knowing at a moment's notice the position and speed of each particle in the sky, it is then possible to know the future of the **universe**. This assertion is theoretical because one cannot make predictions from a present state due to instabilities that amplify errors or minute variations in a system.

This deterministic approach always remained in force when physics underwent its second revolution with the publication of Albert Einstein's theory on the "Theory of Special Relativity" in 1905. The "space-time" structure was then introduced, and it has shown that any event, in order to be described, must be related to a four-dimensional spatial-temporal continuum. The notion of space-time is then the only one that can be described as absolute. However, the intellectual approach remained the same.

These efforts in the search for truth have always favored the current followed by theorists, and more and more phenomena have been described, explained and interpreted. Advances have made it possible to achieve immense scientific progress and better control our environment. By applying such principles in specific areas of industrial engineering, such as planning or scheduling, we could say: "if we know the position, condition and manufacturing process of each product in a production system, it is then possible to precisely determine the situation and condition of that system in the future, as well as how it will evolve". This obviously requires in-depth and rudimentary knowledge of technical data such as nomenclatures and ranges, a technical description and history of products and processes, etc.

However, considering multi-product and multi-process systems involving hundreds of operations and references, we cannot calculate or predict a specific event at a future time. The same is true for the dynamic behavior of this system: this is simply due to the application of the principles of uncertainty as defined by Heisenberg and to nonlinear amplification phenomena relating to the system under study. In addition, our scientific theories are more and more elaborate, and mathematical formulas and demonstrations are more and more complicated, in order to be able to identify the increasingly imperceptible, growing and hidden difficulties in phenomena.

On another level, the change in industrial needs nowadays imposes more stringent requirements to take into account technical (dismantling, reuse of components), social (customization of products), ecological and economic (pollution, energy savings) constraints. These constraints are grouped under the name NMPP (New Manufacturing Production Paradigm) and their consideration in future industrial management systems raises adaptation problems in terms of approaches, techniques and methods. The transformation of a discipline is attributed to the development of a new technique or the use of a new technique that has been ignored until now. In fact, it is never a question of developing a new technique: it is the nature of the results obtained that prevails and enables us, compared to other approaches, to implement or reveal new properties.

In the following, we will focus more specifically, after defining it, on the behavioral complexity of a system and explore the notion of deterministic chaos. Its nature is fractal and we will see how to exploit its properties in complex industrial systems.

1.1.2. *What are the problems to be solved?*

The ultimate objective – the purpose – of a complex system is the gain, which means that it tries to achieve, collectively, an overall objective. We therefore continue here on the topic of intentions, but not on firm and rational commitments, rather "safe" strategies to achieve an overall optimum. Indeed, in a programmable network, comprising many interacting elements and complex behavior, we are confronted with strange attractors; we cannot predict in advance the attractor on which we are, at which precise point in the cycle we are and at which precise horizon we will have converged. Methodological elements need to be defined to identify which sets of objectives can be achieved.

We can be inspired by the approaches used in the game of checkers for example. In this case and according to a context, each partner, when playing, chooses a tactic and explores the moves as much as possible; he or she tries to anticipate the opponent's reactions, evaluates them and decides on the least bad or best possible movement. By doing so, the player optimizes an economic function over a given time horizon. On the contrary, to accelerate the process and according to past experiences, he or she will be led to carry out reflex actions that are the result of winning repetitive strategies and that will have been the subject of successive learning. In this simple example, relating to a specific game, we see an interesting approach emerging:

– it is a system in which agents are intelligent (i.e. with behavior capable of emulating, in part, that of the human brain), autonomous, capable of communicating or exchanging information with partners or agents, with whom they are in a competitive or cooperative situation (hence the notion of conflicting objectives!);

– it is a situation and a mode of operation that we encounter, to a greater or lesser extent, in any distributed system and whatever the field considered. For example, we can cite decision-making problems in industry, the evolution of the immune system in a cell, the phenomena of metabolic adaptation in a living being, the flexibility of the behavior of a population of individuals in the context of the human and social sciences, etc.;

– understanding how global objectives and behaviors can emerge is a key factor in guiding the evolution of complex systems at the structural, organizational and operational levels, in order to move step by step towards a predefined goal.

Many other examples exist in chemistry, economics, metabolism, the immune system, etc. However, communication techniques between agents based on game theory make it possible to define very elaborate strategies whose **evolutions and results are impossible to guess**. Indeed, several elements specific to a complex system come into play:

– there are many interactions in a given neighborhood;

– each element modifies not only its own state, but also that of its close neighbors, according to rules with a low visibility horizon;

– the objectives are local but it is common for them to overlap with those of the neighborhood and to be in conflict with others;

– each element tries to improve a number of its own properties and reduce the least valuable or effective ones in relation to a given criterion.

From these examples, it can easily be deduced that the strategies and tactics commonly used in production or industrial engineering are not applicable here. Indeed, the systems we currently have are not decomposable and are nonlinear. Moreover, because of all the existing diffuse feedback, it is impossible to start from a global objective (linked to quality or performance) and apply it to the subsystems and finally to the agents, i.e. the elementary components of the system.

For this, and in order to deduce how to proceed in practice, we can refer to Sontag's work in Mathematical Control Theory [SON 98]. This work describes how to make local adjustments to system parameters to achieve certain objectives.

However, a different approach in Control Theory, based on Horowitz's work [ALB 02], consists of designing feedback loops and links such that they allow the system to evolve within predefined tolerance bands.

Finally, the strategies developed by IBM as part of the Deep Blue project in the 1990s to improve decision-making processes (with the famous application to chess games) are remarkable in the sense that they combine the concepts we have just mentioned with learning techniques.

1.1.3. *What is the "engineering" approach developed here?*

This chapter is intended to present a modern and global view of the design and management of complex systems. In terms of engineering, the problem can be approached in two different ways:

– either we start from the production system as it is, and we adapt the production management system to manage it as well as possible. New management methods are therefore defined, a different IDSS (Interactive Decision Support System) is designed and the decision-making process of the decision-maker is modified, etc., in order to try to control the effects of this complexity and to keep control over the production system. We remain confined to method engineering (what we could call **Manufacturing Management System Engineering**);

– or the production system itself is modified, i.e. its structure, organization and possibly its architecture. We then move into a radically different field: that of **Process Design or Manufacturing Process Engineering**.

For each case studied, we will examine the actions to be taken to design and develop these complex systems and will also discuss the approaches to be implemented to make them simple (and not simple, as in situations of non-complexity).

1.2. Basic properties of complex industrial systems

In the field of the study of complex systems, and from a functional point of view, the understanding of Nature and living organisms is fundamental insofar as it implements several layered visions:

– molecular vision, which corresponds to the microscopic level and includes the functions and actions covered by the agents;

– cell vision, which corresponds to the mesoscopic level and essentially involves interactions;

– the macroscopic vision, which involves an aggregation, sometimes an interweaving, that is more or less structured, of the previous elements.

Similarly, recent discoveries [STE 88, AME 98] on the complexity of cellular societies show that cell differentiation or specialization arises from small asymmetries in the cascade of messages sent and received by initially identical cells or agents. It is amplified by intercellular activities and leads to different configurations or assignments; some functions are activated and developed at the agent level, and others are locked, inhibited and repressed.

1.2.1. *Structure and organization of system functions*

In an industrial system as a whole, it is logical to consider a cellular organization similar to that found in living systems. Thus, a production system is composed of a set of agents, or cells, each with its own behavior. In this organization, although operations are defined *a priori* at the global level, each agent is good at autonomy; each agent carries out his or her own tasks and has his or her own operating modes in a predefined evolution space (field of eligible solutions, still called "prototypes"). Each agent is a complex system that can be subjected, under given conditions, to deterministic chaos or unpredictable behavior. In such systems, the difficulty results from the implementation of agents and interactions between several agents whose functions are different but complementary. In terms of a model and always referring to cellular approaches, the system's activity is based on the exchange of messages from an agent. Messages are associated with an address (to allow for their dissemination and controlled distribution) and intercepted by other agents and then interpreted and executed.

It should be noted, which is not yet a generality in our industrial systems and is not taken into account in the models used, that the functions in question here are capable of controlled modifications: for example, **multiple assignments** of equipment or agents to the same task, moving an activity from one agent to another (**migration**), task **differentiation** or specialization, **adapting** an agent to changing contexts, task **inhibition** or agent removal. Moreover, the order in which these activities or inactivities are programmed reflects an organization's maturity level. In terms of functionalities and organization, we find the characteristics encountered in increasingly sophisticated and complex societies: indeed, the difficulty increases when it comes to managing, depending on the context, problems of assignment and differentiation (variety of form), migration, adaptation (modification of function) and, finally, "suicide".

1.2.1.1. *Importance of interactions in social behavior*

By always comparing itself to supposed models of living systems, the current industrial approach is based on the molecular approach that attempts to explain the behavior of a system by the direct action of a function. Models are then developed to study the propagation of effects, their synchronization, etc., so the effort focuses on the diversity of functional responses in a system. However, it is not the functions performed by the various elements or agents and their scheduling that generate, produce or determine a good or service, but the **interactions** existing between these agents. Indeed, social control of an activity (or inactivity) condemns the agents involved in a system to interdependence and coexistence. This implies the implementation of an alternative using specialized agents (distributed functions) performing complementary production and control functions, following stacked structures (nested cell architecture) corresponding, themselves, to hierarchical sequences of operations (functional organization specific to a given level), with control and regulation steps. Their behavior in such a communicating system is dictated by the situation and condition of neighboring agents.

1.2.1.2. *Interconnections*

As we have just discussed, it is necessary here to highlight the fractal nature of the organization or its effects. In such groups, there is a stacking structure with multiple levels (operation, equipment, cell, workshop, factory, etc. in the sense of computer-integrated manufacturing). This fractal structure is equipped with self-similarity or invariance of scale. The same basic mechanisms can be used at these different levels, and the operating point (system configuration) is only a variety (an attractor) of the system, itself based on a small number of initial conditions or simplifying assumptions. The problem here is how such a property is reflected at the upper structural level.

From the above remarks, a number of favorable conditions are nevertheless met for the presence of chaos (diversity factor), studied on the basis of modeling on simple basic cells and associated properties, to exist on more elaborate assemblies. This also leads us to talk about the **increasing complexity** of systems, the subject of the following section, which will allow us to deduce new approaches to control and management.

1.3. The complexity of systems

It is necessary to understand how increasingly sophisticated systems can be made available as they evolve and how they are structured and organized. These facts can be pinpointed down to several reasons.

1.3.1. *The basic principles of complexification*

In conventional autonomous systems, the dynamics of evolution are regulated by the eight archetypal changes, grouped here two by two:

– **at the interaction level**: the relationship between the network elements will be able to be expressed in a more or less strong way and will identify either aggregations of elements or unbundling. Hence, the notion of structure that will appear through the operations of "**division**" and "**combination**";

– at the **control level** of the element: whether it is a centralized system or not, a network or not, the control can be supervised or controlled by a coordination element. It follows that we will have elements characterized by "**autonomy**" or "**dependence**";

– **at the activity level**: the functions or programs provided by each element will be expressed or inhibited depending on the environment. Like active sites located on a genome in the field of proteomics, we will have two states: "**life**" and "**death**";

– at the **nature of the program level**: the element or cell will have to adapt to its environment or may remain generic. It is said that there is "**specification**" (specialization) or "**generalization**".

The first two criteria play a role in the structure, architecture or even the configuration of the upper assembly thus achieved. The last two criteria correspond to the notion of function and make it possible to organize and ensure the functional role of aggregation at a higher level. For example, and in a simplified way, the synthesis of macromolecules is subject to the process of *complexification of a category, according to a given strategy* (external elements "to be absorbed", set of objects and links "to be deleted", etc.). This explains **the appearance of more complex objects** during the development of a system, during its "growth" and later during its evolution. However, this *complexification* is carried out according to a set of constraints: economic means with the lowest material, temporal, computer and energy costs.

1.3.2. *The complexification process*

The complexification process can be repeated, and successive complexifications lead to the appearance of a hierarchy or heterarchy forming a most complex set. The construction, or **evolutionary growth** of the complex assembly, is done in stages and can be applied to the evolution of the universe as well as to the development of biological or social systems. In the case of a neural system subjected to a simple stimulus, learning neurons will be activated. The resulting recognition (or convergence) activity will allow for classification.

More generally, the development of a complex body is done with cells – or differentiated elements – belonging to very specific categories of the environment. These can change over time (problem of acquisition and intuition). As we have seen in biology, the successive levels we encounter will be able to ensure a set of increasingly elaborate global functions until the constitution of higher order mental objects and cognitive processes.

1.3.3. *The smoothing property of chaotic characteristics*

In this section, we propose to make the link between Laplacian determinism, according to which "*nothing new can happen unless it is already contained in the initial conditions*" and deterministic chaos which stipulates that very simple systems give rise to very complicated trajectories and unpredictable evolutions. In the case at hand, the problem is whether a chaotic or turbulent phenomenon at a microscopic level generates a coherent and stable state at a higher level.

To explain this fact, we recall the work of E. Lorenz who highlighted the phenomenon of exponential sensitivity compared to initial conditions: the size of the disturbances doubles each time the time spent increases by a given unit [ROB 01]. Thus, two initially neighboring points on a phase diagram have rapidly separating trajectories; they diverge and their behavior over time is different. In the same way, Hadamard has shown that the movement of a marble on a negative curve surface is exponentially unstable (horse saddle problem). It is therefore impossible to calculate the trajectory of the ball after a very short time. This problem can be found in a billiards game as well as in the perfect fluid model: the problem of hydrodynamic instability is reduced to that of calculating a curvature. This problem is also that of the SIC (Sensitivity to Initial Conditions) which has led us to rethink the world in terms of "deterministic chaos" or "fractal chaos", with the famous example of the butterfly effect that illustrates the complexity of systems with its notions of unpredictability.

But what is the problem here? When modeling a simple system, new statistical phenomena that may arise when changing scale (e.g. from micro to meso level) and moving from a small to a larger number of degrees of freedom are generally not taken into account. To illustrate this problem with Boltzmann's experience:

– if we study the movement of a gas composed of a few molecules in a closed elastic enclosure, we will be able to put the system into an equation; however, due to elastic collisions, we join the problem previously described and we cannot predict the trajectories of each molecule in the long term, therefore the overall evolution of the system;

– on the contrary, if we focus on global and "integrated" variables, such as the average value of gas density or the average value of gas pressure, we know that these variables are calculable – they are determined statistically – and we know how to predict that the pressure, for example, will remain uniform throughout the enclosure and will increase by this or that value according to temperature.

Thus, between the microscopic and macroscopic levels, the same variables are not used. In the first case, they are the coordinates of a trajectory. In the other case, they are observable global variables. We generally do not know how to "move" from the microscopic to the macroscopic level, although the links are strong and underlying: each level has its own geometry (classical geometry and fractal geometry).

Thus, in an industrial system, when we ask to determine, on the basis of local objectives and behaviors, the global objectives and behaviors of a system, we sometimes respond, due to lack of experience: "*It is a complex system: I don't know how to do it, we'll have to think about it!*" Similarly, on a very small scale, an agent will behave in a chaotic manner; causing local turbulence in the immediate vicinity and then on a large scale and coherent orders and structures will emerge. But which ones?

Rather than increasing the number of degrees of freedom, which makes it impossible to model a complex system, two levels of description of the movement or evolution of the system should be considered. In the case of the flow of a fluid, we know how to calculate for an element of the fluid in motion, to pass to the level of detail from turbulent chaos to whirlwind, but we cannot currently go beyond this level of aggregation: even with IBM computers at 140 Teraflops, we remain limited and must, here again, proceed differently. The macroscopic level ignores details and these generate more noise than relevant information at this level. Global models, statistical or stochastic types, will be used, knowing that the disorder level will be characterized by the **entropy of the system**. This entropy is all the higher the more stable the microscopic states are. We will look for the most probable stable macroscopic states: these are the ones that correspond to the maximum entropy; it is also according to this situation that we will be able to determine the parameters and variables of the system's functioning, therefore its objectives! This brings us back to the Boltzmann gas problem.

The study of sensitivity to initial conditions in simple systems and the resulting local fractal chaos is a source of self-organization at a higher level and therefore of form emergence, sometimes coherent thanks to synchronization phenomena. However, at the higher level, the growth of the disturbance energy in a coherent structure is most often linear because it responds to the general laws of statistics (normal law, law of large numbers, etc.). More rarely and in extreme cases, such as in high technology or geophysics, etc., hyperbolic or exponential distributions, therefore power laws, are used; the assertion is then no longer valid because the system can switch from one state to another (critical case, fork or disaster) but this is not the case here.

In summary, when the evolution of a system or its divergence is linear, the forecast error does not double at each time unit: it is proportional to a constant and longer-term forecasting becomes very possible. This is important because, in the case of sets consisting of a large number of elements or having a large number of degrees of freedom, it will be possible to make **predictions** on “macroscopic” variables and on statistical averages representative of the system. Thus, the notion of unpredictability is quite relative.

1.4. Analysis of some industrial dynamic systems

1.4.1. *Introduction*

In the field of complexity, the presence of deterministic chaos in electronic circuits and signal processing is known to many automation engineers [MIR 95]. These include: looped systems with pulse modulation, or networks with switching elements, manipulators performing repetitive tasks, nonlinear recursive prediction, adaptive control and monitoring, etc.

In all these cases, the control and management methods of a system subjected to a chaotic phenomenon cannot be similar to those of a stable system; either stabilizing devices or disturbances are then introduced. The approach depends on the precise nature of their behavior.

In macroscopic and industrial engineering industrial systems, the basic assumptions and approaches used are still conventional. However, an interest is beginning to emerge around the “chaos” phenomenon because, between the order and turbulence phases, there is a poorly exploited area with interesting properties. We will describe some classes of situations in production systems where such phenomena may occur:

– a network of workshops driven by MRP production management systems;

– a flexible multi-product, multi-process workshop;

– the distributed processing of information.

In order to qualitatively predict the evolution of these so-called “complex” systems, simulation models are often used, as we have already seen, based on a strong assumption: product and information flows are uniform and regular on a large scale. However, these have strong inhomogeneities that are also distributed over time according to particular density functions [MAS 97b]. This translates into very specific characteristics or phenomena that we have observed and that we summarize:

– the distributions used are often of a known statistical type. However, as shown, the available data have no statistical significance and must be studied using new approaches (e.g. Levy distribution);

– the magnitude and recombination phenomena related to feedback loops highlight the presence of deterministic chaos as well as large-scale fluctuations that lead to the emergence of order structures;

– depending on the origin of the fluctuations manipulated, different classes of models must be used; what is valid and observed at the living level, or at the material level, what must be taken into account in an industrial system. For example:

- the notions of **initial quantum fluctuations** taken into account at the agent level (such as those found in particle physics) can lead, during a phase of inflation and by propagation to its close neighbors, to the formation of simple and diluted aggregates [MAT 96a]. By placing themselves within an industrial system that is itself an assembly of agents, fluctuations in product flow do not correspond to strong initial disruptions and result in "apparently" random groupings at the end of the line,

- typological defects related to **phase transitions** are due to symmetry breaks between fundamental interactions. However, these phenomena exist in chaotic systems where fluctuations are amplified and/or inhibited by feedback loops in order to generate clusters. This, of course, has a significant effect on product propagation times (product exit horizon) and therefore on the distribution of cycle time or T.A.T. ("Turn Around Time"). Similarly, a local defect will have a direct effect on close neighbors and more widespread effects on a global level due to the more or less strong interactions that may occur at long distances.

Based on these remarks, the following strategies can be formulated.

1.4.2. *Interactions in industrial workshops*

On the functional and logistical level, an industrial system has a network structure, as found in ecosystems or biology, with medium-sized non-hierarchical aggregations. At the information system level, this system contains positive and negative feedback loops: this is the case when several activity centers (workshops) are interconnected to form a complete plant. Such a system, with its interaction and feedback loops, is presented in Figure 1.1.

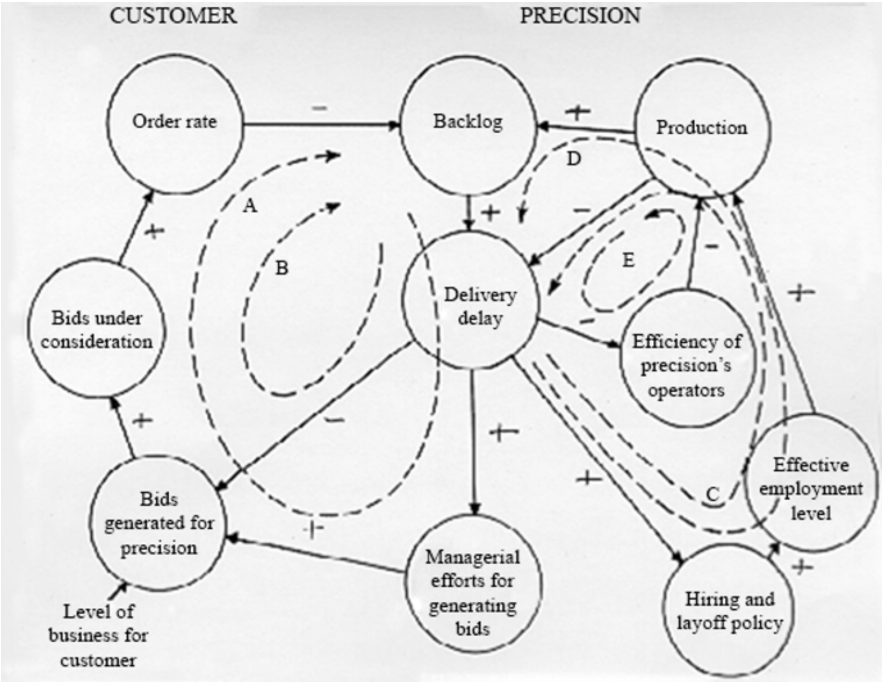

Figure 1.1. *An industrial MRP system with its feedback loops*

More formally, it is a cybernetic system with strong interactions between distributed functions: a given function will influence the activity or "inhibition" of a neighboring function. The problem involves analyzing the overall behavior resulting from such a system; a **systems dynamics** approach is appropriate. We have applied it to study the dynamic influence of interactions between various manufacturing plants of the type: Semiconductor – Electronic boards – Computers.

This set is subject to stepwise requests, at the final product "computers" level. The objective here is to analyze the impact of disruptions (demand level, yield variations, "over-reaction of production agents") on the evolution of inventories and work in progress upstream, at the card and then semiconductor level. Modeling in the form of differential equations was carried out in a simple way on such systems, and it was possible to easily integrate the parameters and variables (size of buffer stocks, response times, etc.). In this case, it has been shown [MAS 95c] that the variation in component stocks, i.e. upstream, becomes chaotic when the system is subjected to simple control variations. As the capacity of the production system is limited, some products are penalized compared to others. This situation occurs more precisely when the flow of information is amplified and when we try to “recover” the drifts because the production agents tend to anticipate disruptions. On the contrary, in the case where the input variable is chaotic, it has not been possible to demonstrate with certainty that the system was chaotic: because of the buffer stocks (number, size, response time, etc.), the results can be smoothed, attenuated or even amplified. When the size of the buffer stocks is large and the yields are low, it has been found that the system can even diverge: in this case, the noise is amplified and directly influences the evolution of the system. However, this is also not possible due to the lack of sufficient reliable data.

Conventional management systems are essentially “planning”: they are intended to prepare a production system but not to manage it as well as possible. In some cases, they are even useless because they are too restrictive, sometimes unable to control a complete production system. In addition, they are subject to the normal reaction of a planning agent who reacts in the opposite direction to certain trends in an attempt to compensate for variations. In this case, the overly “planning” and “rigid” management system leads to dangerous, unexpected and unpredictable variations, such as changes and jolts that are amplifying disturbances. On another level, conventional production management systems are not designed to handle chaotic programs. In such production systems, reactive management tools can only degrade their overall performance. We therefore deduce that planning management systems, which are so reassuring and very useful in other respects, are costly in terms of procedures (many steering meetings, production readjustments, multiple planning steps, etc.) and are not the best suited to certain types of dynamic behavior.

According to the well-known principles of stability, it is sufficient to introduce compensation loops or decision-making centers whose action will change the direction of variation, positive or negative, of the product or information flow. It is also possible to control unstable systems by injecting “noise” and uncertainty into control parameters as well as stimuli and input variables. This allows the possibility of compensating or even eliminating knocks and counteracting the effects of pumping. For example, it is common for decision-makers to introduce noise: they can constantly modify product priorities in the workshop, depending on changes in the situation and conflicting demands. In fact, the stimuli generated are based on their perception of the problem and tend to create more disruptions and blows.

1.4.3. *Product flow in a flexible production system*

Consider a flexible multi-product and multi-process workshop with duplicated equipment, feedback loops and complicated ranges.

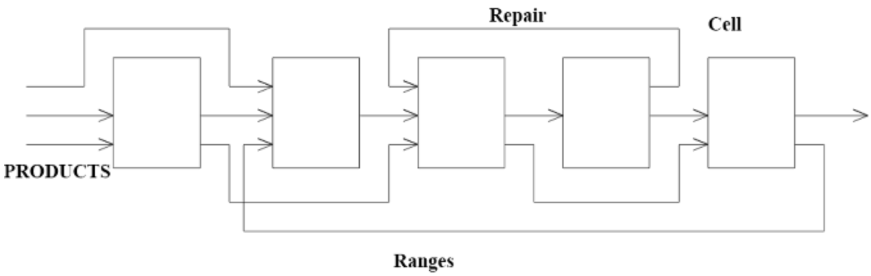

Figure 1.2. *A flexible production system*

Each node or cell has its own control system and behavioral procedures. We are in a "local" environment with a limited proximity; the production rules used here concern priority management, order sequencing, alarm management (in economy and finance: alert management) in case of problems, etc.

Such a production system has been studied [BAR 96] in terms of the organization to be put in place to compensate for the disruptive effects of chaos (in the sense that they are unpredictable). Here, the chaos is essentially due to interactions between cells: oscillations created by calls, supply orders that propagate from cell to cell, going up the "line" of manufacture. They are also production or launch orders from the production management system, which will spread from one cell to another and vice versa. This will generally be done from downstream to upstream, if we operate in a pull flow. When these orders respond to nonlinear functions or influences and the phenomena are amplified, making the system sensitive to initial conditions (SIC), this induces many possible states for the production system, which can be the result of deterministic chaos. This is observed, for example, in the dynamic variation of stocks (WIP or Work In Process) throughout the "line". The cause is due to the sequencing and amplification effects specific to the physical and logical structure of the production system. We will call this the **caterpillar** effect. Under these conditions, we cannot predict the behavior of such a system. Moreover, the model corresponding to a real workshop is relatively complex and cannot integrate all the parameters and assumptions: it cannot be used for steering purposes. Simulation can therefore be used to "gauge" a complex system, to evaluate trends and define the least bad strategies.

In terms of the strategies adopted, one of them consists of returning the production system to a stable state, which amounts to placing it in an area of the known and "reassuring" phase space corresponding to an area of weak bifurcations.

However, its adaptability is reduced because, to reconfigure it and bring it into a new given state, it will require a lot of energy (since its inertia is greater). On the contrary, we will recommend exploiting the chaotic nature of such a system. More generally, we must seek conditions that place the production system at the limit of stable and unstable states. In an area of "weak chaos", which is easy to achieve in nonlinear workshops, its flexibility is maximum. These concepts formed the basis of an international project called GNOSIS-VF (EU ESPRIT 28448 project) as part of the Intelligent Manufacturing Systems (IMS) program with Japan.

In this example, behavioral complexity is related to the presence and importance of interactions between the different agents that make up the production system. Here, simple deterministic functions applied to strongly linked systems can generate chaos. In this case, it is possible to control its effects by decoupling the cells from the system through a double Kanban system; this way, the value of the work in progress can be limited while leaving each cell its own elasticity and having disturbances that compensate themselves. With reduced buffer stocks, the adaptation of inputs and outputs is rather rapid thanks to self-regulatory effects; the best strategy is then to let the system evolve freely, maintaining the parameters within certain control limits.

1.4.4. *Message flows in complex information systems*

1.4.4.1. *Distributed information processing*

This case study was taken as a typical example of a situation that many people are familiar with: it is a Global Information System Network of which the Internet, or Intranet, is one of the elements. This heterogeneous network includes a large number of server and client centers. Each center or agent has its own strategies and can perform different routing or control tasks, as shown in Figure 1.3.

Knowledge and information are distributed throughout the network [MAI 94]. The evolution and growth of such a system with tens of thousands of nodes cannot be ensured, controlled or planned from a central computer. In such a network there is an "apparent" anarchism; each node (agent) is an autonomous computer system: it has the possibility to direct traffic according to predefined rules and the saturation state of the network. It can also manage information flows according to their nature and the state of nearby cells. Indeed, and as we have seen, even though some cells, or a group of cells, have chaotic behavior, there is often a smoothing of chaos at the global level.

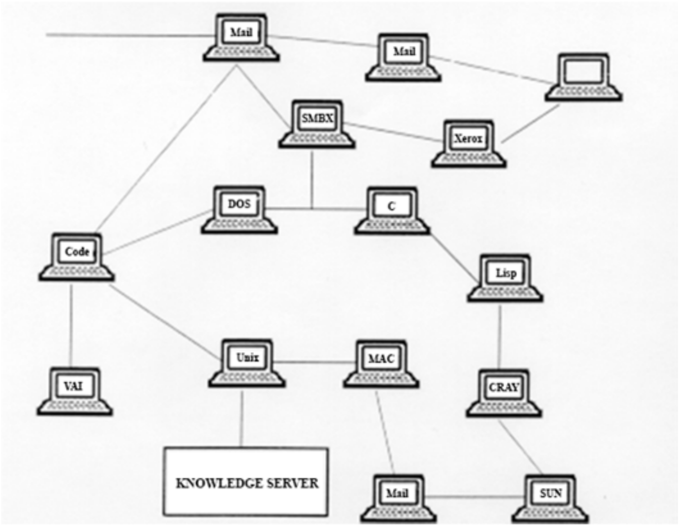

Figure 1.3. *A dynamic industrial system with nonlinear interactions*

In this figure, we see that it is cellular automata (CA) with independent but interacting agents who do not have knowledge of the overall consequences of their actions. The probabilistic data and incomplete or inaccurate information they manipulate, combined with processing delays, result in the emergence of various attractive states such as fixed points, oscillations or even deterministic chaos and auto-catalytic mechanisms that converge them into particular collective states and behaviors. There is the emergence of a collective "intelligence" that cannot be predicted and controlled in advance and that highlights the fact that reductionist approaches cannot be referred to. For these industrial, dynamic and nonlinear interaction systems, the development of models based on evolution equations makes it possible to characterize and study them.

1.4.4.2. *Emergence of collaborative work*

As already mentioned, chaos and fractals are part of the same field of mathematics and underlie the principles of autonomy and self-organization. These properties are exploited in cellular automata, involving stochastic functions; solutions can therefore emerge from systems composed of communicating entities and functions that rapidly evolve into simple – periodic or quasi-periodic – and strange attractors. Their properties can therefore directly influence control systems, management methods and organization. The impact on new skills requirements, people's education, structure and social aspect in the firm have been particularly studied in industry in Germany [WAR 93].

1.5. Applications of new concepts in industrial systems

1.5.1. *New features and functionalities to consider*

In the field of complexity, the presence of deterministic chaos in electronic circuits and signal processing is known to many automation engineers [EEA 95]. Without going into detail, we have simplified the representation of the new paradigms to be implemented and positioned them in a graph. The aim here is to switch from the "standard" system to "OKP" (One-of-a-Kind Production). In this context, the concepts developed above will have an impact on the methods and tools used to control and manage production systems. As indicated in Figure 1.4, there is an opposition of characteristics, resulting in a conflict between capabilities and goals.

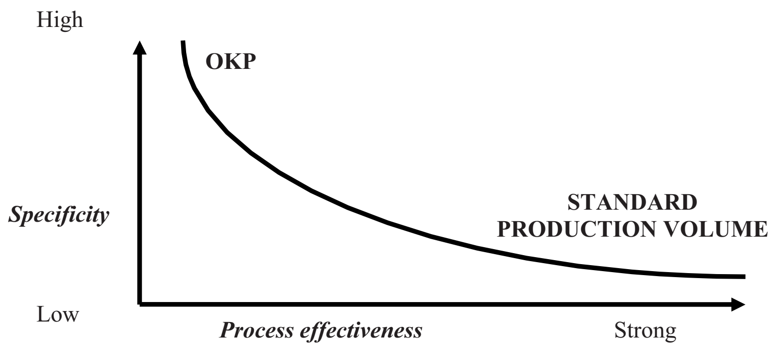

Figure 1.4. *Positioning of paradigms in production management*

In view of the new constraints observed in industry and the changing needs of consumers, it will be necessary to increase both the possibility of producing specific devices, also known as "attributes" (and no longer "finished products"), personalized, in small quantities and on demand, with maximum efficiency.

In short, and this is a change, clients are becoming inflexible, while production systems and products must be more flexible and adaptable. In case of difficulties, we will even say that it is a supply crisis and not a demand crisis. The initial approach consists of developing and using information technologies as a factor of innovation and resolution. However, these only concern process automation and are based on concepts and information theories that have certainly evolved and led us to JIT (Just-In-Time), CIM (Computer-Integrated Manufacturing), FMS (Flexible Manufacturing Systems) and so on. Thanks to robotics too, we have been able to improve the flexibility of production systems, scheduling techniques, etc.

Processes have therefore benefited from these developments and have seen their performance increase. However, as systems evolve towards greater **complexity** and these evolutions have their limits, it follows a simple observation: the difficulties we encounter are not technological in nature, but involve, when they are resolved, a change in logistical and organizational approaches. In fact, it will be necessary to introduce a paradigm shift such as fractal chaos or self-organization.

1.5.2. *Design of complex industrial systems management tools*

When we consider the new structure of production workshops, we must instead speak of **production networks** because production systems are, in fact, made up of cells and resources that communicate and interact with each other in such a way as to constitute self-configuring systems. Such systems have been extensively studied at the VTT Laboratory in Helsinki, Finland [RAN 93].

Autonomy and self-organization are essential characteristics of future production systems. Combined with these concepts, and to produce customized products, with a high reactivity to meet demand, it is important to implement new principles of planning, scheduling, piloting and control. However, limiting the ability of systems to be flexible and adaptable through the improvement of their operation or production control functions leads us to play on other potentialities such as interactions between functions, autonomy and system dynamics. This is mainly due to the increasing difficulties encountered in solving problems of scheduling, synchronization and development of the right ranges: as everyone knows, it is indeed very difficult to determine good scheduling in multi-product processes and multi-processes under conditions of nonlinearity and uninterpretable discontinuities.

Of course, there has long been an attempt to simplify processes and improve their flexibility by developing increasingly complicated strategies and algorithms (in a study conducted in 1993 in the industry, more than 430 scheduling algorithms corresponding to specific problems had been identified, around the production control community, by our team in IBM. Some of them are now considered as algorithms for AI; this demonstrates the many various approaches in machine learning and solution elaboration in planning and scheduling). The question then is: should we continue to try to solve each new problem in a traditional way? How far will we go in the level of complexity to be understood? Can we not work on new and more original approaches? Can we not take better advantage of the intrinsic properties of the systems concerned? How can we exploit new architectures or properties? Here again, we are tackling a new paradigm, which will be part of the familiar domains to come and which are called: fractal factory, virtual factory, agile manufacturing, etc.

Future production systems will not only have to be adaptable, but also have to be able to change the configuration of their own structure as well as the structure and functional principles of the production system itself. Thus, production systems will have to be reconfigurable, self-reconfiguring or scalable, which implies notions of modularity, autonomy and self-organization. This means that they are able to allocate, by their own means, the right resources, the right control and monitoring system, assign the right tasks at the right time to each cell and define the right priorities.

1.5.3. *The contribution of chaos and self-organization*

As we have just read, we emphasize here that the challenges and problems posed by the evolution of economies and industry require the implementation of new metaphors and new organizational models. We know, for example, that the most reactive systems can only evolve and change if they have self-organizing properties. Open adaptive systems are the most promising because they are based on a constant improvement of the principles of optimization and evolution as found in Nature. For example:

– a living natural system is equipped with autonomy. Intelligence is distributed and control, instead of being centralized ("top-down" approach), will be achieved from the bottom up ("bottom-up" approach);

– a system evolves and adapts through diversity, i.e. through transformations, disruptions, disturbances and so on. It is a notion that is strongly linked to that of chaos;

– the most adaptable systems are those that are naturally in unstable situations and in constant search for balance;

– the notion of collective intelligence is based on the emergence of orders and self-organization, which is a key mechanism.

It should be recalled that self-organization can be seen as a corollary of chaos. The problem is therefore how to exploit and implement it. By analogy and with reference to our work, a production system must be managed using devices that use simple rules and/or meta-knowledge. Usually, the practical approach consists of an exhaustive inventory of the various constraints and associated actions and then exploiting them using various optimization techniques (linear programming, deductive systems, heuristics, etc.). In fact, industrial systems, like any social group or living organism, are not governed by a complicated function or a list of programs that follow a specific sequence. In a semiconductor assembly line with 140 operations, production management decisions could be described by only 15 rules. However, the behavior of such systems is unpredictable and non-reproducible. Like genes, we must code the rules to be applied, define organizations or configurations, resources to be implemented, but not focus on describing how to perform the tasks. Similarly, meta rules will be defined that will describe an overall objective as well as the space of functioning or freedom. A production system will then be an open space, with agents and autonomous entities able to freely perform tasks according to a set of predefined constraints.

Within this space, the notion of deterministic chaos can be expressed and bring diversity. This is all the more true since it is a confined space and it is under these conditions that an evolutionary self-organization can be set up. Thus, self-organization consists of delegating and multiplying responsibilities, breaking down tasks and performing them simultaneously at different levels. The notion of unpredictability then takes on its full meaning, but this is not a matter of chance. The industrial system under consideration is then subjected to permanent recomposition phenomena, differentiation, redundancy of operations, inhibition, etc. The very way of carrying out a task may evolve, but, this is important, there is “irreversibility”: the system’s reactions will always be different and this calls into question the content of the orders, which will also change according to the situation and the nature of the agents.

These few notions lead us to define [MAS 91] a two-level production management system:

– **the microscopic level**: this corresponds to the operational level of a production system. It includes control algorithms at the cell level, and allows local optimizations and scheduling and sequencing at the equipment level. It also manages the execution of all elementary tasks. At this level, the rules of the internal functioning of the autonomous cell and the nature of the links that will be established with close neighbors (and will be at the origin of an emerging order or configuration) will also be defined;

– **the macroscopic level**: this includes general strategies, as well as global objectives and meta rules. The operating and performance limits of the system and each cell will be determined, as well as the types of links to be established between the cells. It will also define how the network will operate and its exchange capacities, based on demand requirements, as well as on product specifications, constraints and models. This makes it possible to maintain unity of action and coherence of the entire production system.

As we can see, the mesoscopic level sometimes appears in conventional production management systems and disappears in some ERP (Enterprise Resources Planning) or integrated systems. It is no longer necessary since the microscopic level is reinforced by more autonomy and self-organization possibilities. The usual control scheme is therefore simplified; whole categories of problems are no longer dealt with since it is left to the system to solve them according to its internal dynamics. We will no longer speak of a hierarchically organized and managed production system, but of an autonomous network. However, the principles and concepts of fully distributed and autonomous networks are not yet applied. As a result, the development of predetermined, planned and fixed control and management systems is being challenged. This also explains why the obsolescence of conventional "ad hoc" approaches and systems will always be rapid and ERPs will have to evolve.

To take better advantage of the characteristics of a production system, i.e. to exploit their flexibility more effectively, it is necessary to take advantage of new properties linked to the very structure of the system, its interactions, etc. Rather than adopting planning strategies, we will exploit the properties of multi-agent systems: we will therefore implement new configurations (logical, virtual or physical) of autonomous and communicating cells, with different initial states, capable of initiating tasks, concurrently, in cooperation or with a spirit of emulation, as can be found in human societies.

It also raises the question of the relevance of current tools and approaches concerning, for example, supply chain management. Indeed, whereas the criteria taken into account in these systems consist of giving priority first to the demand, then to process optimization and finally to physical flow management, the new approach, but which we will not develop here, must first focus on the physical flow, then on the demand and finally on the optimization of the system. The priorities are therefore reversed, but it is at this price that the notions of fractal chaos and self-organization can be integrated into industrial systems.

It follows that the leap to be taken during these rationality changes must be considered from the design and development phase of a process. Finally, as we can see, **intellectual, technological and organizational leaps** will always have to be **integrated and assimilated** into the systems under consideration.

1.5.4. *Consequences*

This section on the study of complex systems has shown how most industrial systems can be subject to deterministic chaos. This is mainly due to feedback loops in product and information flows. These are omnipresent; they accentuate the effects of even simple functions from the outset, introduce delays throughout the system under consideration and effects that are difficult to combine and study as a whole. Chaos is strongly linked to the notions of fractal and self-organization, whose associated properties are essential for the implementation of new paradigms.

As has been suggested, before proceeding to this stage, the presence of chaos should be detected and verified with good reliability. Experience suggests that we should remain cautious: the mathematical approach highlights chaotic behavior, based on models, but given the difficulties of collection and measurement, we do not always have a sufficient and reliable data set to verify these results. The conclusions must therefore always be validated in advance. However, we can say that, in most cases, the probability of chaos is high. It is only recently, in the case of the production (assembly and testing) of electronic modules (called TCM at IBM), that we have been able to highlight almost certainly (probability 1 does not exist), a chaotic behavior.

On another level, the context we have just studied is transdisciplinary and requires knowledge from biology, mathematics, physics as well as cognitive and social sciences. Under such conditions, it appears that conventional approaches and tools for analyzing, managing and steering industrial systems are inadequate because:

– the principle of functional decomposition is not applicable here;

– ways of thinking are compartmentalized;

– conventional modeling and simulation tools cannot be applied because such systems are unpredictable, difficult to control and have specific characteristics, etc.;

– finally, the notion of dynamic "behavior" is essential because it conditions the notions of adaptation and dynamic reallocation of new means, methods and techniques.

Given these characteristics, industrial systems cannot react to certain stimuli and controls according to predefined patterns, and we cannot react to complexity with more complexity because we would engage in an endless spiral. More specifically, some schemes recently highlighted in the Life Sciences must be considered because the mechanisms they use, which are the result of a long evolution, provide some answers to the general problem of flexibility and reactivity of industrial systems.

It is interesting to note the sequence highlighted by biologists to illustrate the evolution of cellular societies: it begins with the notion of diversity at the origin of the convergence of a cell or agent towards an attractor. This then makes it possible to bring into play the notion of complementarity, then interdependence and finally complexity. In terms of functionalities and needs, this corresponds to a specialization of agents (activation or inhibition of specific functions), the emergence of new properties at the global level, and to exploit them, the implementation of a functional organization (and by interlocking fractal type).

On the contrary, based on the fact that only a few simple mechanisms are at the origin of such an approach, the more complex the system is, the simpler the control system must remain. This fundamentally challenges CIM concepts, which, if poorly applied, lead to systems whose information flows are too constrained and too centralized, while we must rely on freer, more autonomous, more distributed systems, systems with strong interactions.

To repeat and clarify what has been previously exposed in industrial systems subject to deterministic chaos, the system is hardly controlled externally. It must therefore have self-organizing properties to adapt to new situations while remaining within a framework of freedom.

Following our observation, some of the approaches described were successfully implemented in the TCM assembly workshop at IBM France, which served as an experimental framework. They have made it possible to define appropriate tools and methods that need to be deployed (here we will simply mention the LMA product: Line Management Advisor, based on artificial intelligence techniques) [BEA 94]. Subsequent studies have further developed the use of recurrent neural networks and cellular automata based on stochastic functions to improve the approaches and results described above.