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COMPLEXITY CONTROL, FLEXIBILITY AND THE COHERENCE OF PRODUCTION

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Abstract. – *The essential hypothesis of this paper is that the control of complexity depends intrinsically on flexibility. Greater flexibility induces increased complexity arising from the growth of potential combinations a production system can handle. This growth of complexity leads to a need for operational and managerial principles which can be helpful to master a process' complexity.*

Problems of integration of different types provide a wide range of solutions to controlling complexity. In particular, the paper investigates as a special case the definition, use and impact of "group technology classification methods".

Keywords: Complexity, flexibility, production.

Résumé. – *L'hypothèse essentielle de cet article est que le contrôle de la complexité dépend intrinsèquement de la flexibilité. Une plus grande flexibilité induit une plus grande complexité due aux combinaisons potentielles que la flexibilité permet. La croissance de la complexité requiert toutefois des principes opérationnels de gestion qui peuvent aider la maîtrise de la complexité. Des outils d'intégration de systèmes tels que la technologie de groupe est proposée et utilisée pour contrôler la complexité en particulier.*

Mots clés : Complexité, flexibilité, production.

1. FLEXIBILITIES

"Flexibility" is a multi-dimensional concept which requires a precise and operational definition. Consequently, we shall both attempt to understand its many facets and point out to the appropriate tools for its analysis. For example, we can distinguish between static and dynamic flexibility. The former emphasizes the existence of an instantaneous potential, omnipresent flexibility while the latter emphasizes a sequential flexibility, revealed over time.

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Static flexibility depends on the **set of opportunities available at a given time**. It expresses a reaction to particular qualities of the environment such as situations where the environment is expressed in terms of probabilistic events (1).

Static flexibility of a production system is necessarily characterized for example by the presence of excess capacities or through alternative sourcing. In services or industrial activities which face seasonal productions, this excess capacity enables industrial managers to avoid excessive inventory costs. Similarly, for production processes perturbed by uncertain incidents but with identifiable probability, it may be worthwhile to set up emergency backups (for example, one may install a spare generator to avoid possible power cuts).

This type of flexibility is similar to the potential choices imbedded in the construction of a portfolio. In such cases, one can use mean-variance criteria. This type of flexibility remains largely compatible with the « Taylorian-Fordian » model since it is only a juxtaposition of several processes which follow a conventional production logic. In this case, static flexibility will normally generate additional costs. These costs explain the often encountered dilemma between static flexibility and productivity as opposed to dynamic flexibility (2) which is described below.

Dynamic flexibility is the ability **to react continuously over a period of time** to environmental changes. It is a response to changes which result from unknown laws. Here, the decision-maker faces **uncertainty** through an adaptive learning process. As a result, the decision maker transfers from one period to another a « **portfolio of optimal lines of actions** » in order to enable him to keep a maximum number of possible responses to perceived changes of his own situation which allows one to react as quickly as possible and to match the speed at which the environmental parameters are changing (3).

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(1) Sometimes this variability may even be certain (probability equals 1). For instance, the case of Électricité de France seasonal tariffs.

(2) *Cf.* J. C. Tarondeau, *Produits et technologies*, Dalloz, 1982.

(3) In other words, the search for static flexiblity is generally a reaction to the law of "required variety" stated by Ashby: "The necessary condition for a system of variety A (the firm) to be in a position to control a system of variety B (the environment) is that A's variety must be at least equal to B's variety". As for the quest for dynamic flexibility, it follows the principle of "required time" stated by Apter according to which "in order to be able to adapt the environmental changes, the corporate reaction time must be of a similar importance as the modification time of this environment", *cf.* Apter, *Maîtriser la flexibilité de l'entreprise*, Masson, 1985.

For a firm, dynamic flexiblity requires the control of time at various production steps and their sequence. The objective function which such a strategy logically implies is the **response time** compared to an environmental variation. This variable has at least two characteristics:

In the short run, this response time which is an expression for the degree of flexibility, can be estimated by **the production delay**. When it is a response to an order for a product or to a **set-up time** for switching from one production line to another (the interruptions due to changes of tools are then included in the production time) (4).

– **In the mid and long runs** one may use **the process adaptation time** which reflects an ability to renew the products and therefore to transform the production processes and their organization. This adaptation time also reveals the ability to integrate easily technological changes. We shall deal with these points separately.

In terms of dynamic flexibility, a qualitative threshold is reached when the production time becomes inferior to the commercial deadline acceptable by the customer. Then the pace of production can match the pace of the firm orders and not the estimated or presumed ones. This example underlies the importance of the reaction time.

Our distinction between static and dynamic flexibility remains analytical however, introducing a dichotomy in the nature of flexibility, which leads to fruitless debates if it is ignored.

2. FLEXIBILITY AND COMPLEXITY

The growth of flexibility is equivalent to increased interaction between a system's components and the environment. Thus, it also creates and increases complexity. We shall attempt to demonstrate that this concept is itself closely related to the design of a production process as a network of interacting units. The analysis of these interacting units will constitute the potential organizational frameworks a production process organization can assume and which can be selected according to the effects and the environmental conditions.

More precisely, **complexity** can be defined as « an intrinsic quality of the system, characterized by some combination of the number of system components, the nature of their interconnection, the dynamical flows of

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(4) *Cf.* P. Pecquet, 1986.

information between the parts and the interaction between the various hierarchical levels comprising the system » ([5]). This definition gives rise to two remarks:

– For a given type of firm, a « Taylorian-Fordian » (therefore sequential) production process is not as complex as a network production process (interactive by nature). Indeed, as soon as the organization potential to change is considered, the difficulty level of the decision making problems increases considerably. Similarly, when we introduce new technologies: they usually require more sophisticated know-how and tend to be more difficult to handle.

– The second remark deals with the relation between flexibility and complexity. **An increase in flexibility implies an enhanced complexity**, since this flexibility deals with an increased variability of the environment. Increased complexity does not arise only to the growth in the number of elements in a system but also from the growth of their interactions and their adaptation to new elements circumstances (dynamic flexibility).

We believe that this type of complexity is the mechanism altering new production processes. In the « Taylorian-Fordian » model, one always thinks in terms of **constant complexity**. For example, investments in a production system do not by themselves change the organizational process. Thus, investments in a production system which does not alter the organizational process, does not alter either the level of complexity. However, a new organization, based on a greater dependency between the corporate organization and environmental change, can lead to a growth in complexity. The level of complexity then becomes an endogenous variable which must be controlled. When a process' flexibility increases we can distinguish a greater interaction between the process and its environment. This interaction will, necessarily increase the required amounts of information for their control and, therefore, led to an added increase in the system's complexity. At least two consequences result from this complexity increase: the first one appears as a "folk theorem" and the second one as an economic fact.

The "folk theorem" ([6]) establishes a relationship between the increase of complexity and the increase of stability in a system "The intuitive

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[5] J. Casti, *Manufacturing as a system determined science*, IIASA, Vienna, 1986, p. 18.

[6] *Cf.* J. Casti (1986), *op. cit.*, p. 19.

argument ... is that greater complexity generates a denser interacting network. A greater "connectedness" results in a greater capability to absorb potentially destabilizing disturbances" (7). In fact, lacking a better definition of complexity, we can neither confirm nor reject this theorem.

The economic facts are simpler to establish: an increased complexity leads to greater managerial difficulties, increased information flows and therefore to increased management cost as well. This growth in costs together with the degree of complexity represent one of the fundamental characteristic of systems which seek to build in flexibility. Firms will thus seek to control complexity in order to reduce these costs. To do this, they may use a number of operational principles based on process and organizational integration of different sorts for example.

3. COMPLEXITY, FLEXIBILITY AND INTEGRATION

In an interactive production system such as as defined here, "connectedness" and interaction enable us to define more clearly the concept of complexity. In order to control such a system, it becomes important to augment and to multiply the "feedbacks loops" in order to adapt the system to its environment. The operational principles which we have studied consist in reducing or in controlling the growing complexity of the production process. Process integration seems to be such an essential tool, but its nature and extent will depend on both the production concept used and the sources of complexity.

3.1. Static flexibility and integration

A particular form of flexibility consists in increasing the redundancy of processes, either to obtain excess capacities for one product or to manufacture a range of products. Such a strategy can end up in unbearable costs. To reduce costs we can reduce the complexity by either eliminating certain phases or steps of the production process or integrate in a single operation two or more consecutive operations. In concrete terms this can result in either a combination (grouping of tasks or sequences of work) or in simultaneous

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(7) *Idem* (*see* note 6).

operations performed by a number of tools. Note in this case, that equipment integrates, at least virtually, this complexity. The complementarity of this static flexibility and integration can easily be analyzed thanks to a very simple model ([8]).

A production model

For simplicity, performance will be measured in terms of reliability ([9]). Given a production system composed of n successive stages, each with reliability p_{ji}: $j = 1 \dots n$, $i = 1, 2 \dots m_j$ where m_j denotes the number of components in parallel at the jth stage. Then, for a simple production line consisting of n stages in series, the system's reliability is knwon to be:

$$F = \prod_{j=1}^{n} \left[1 - \prod_{i=1}^{m_j} (1 - p_{j,i}) \right]$$

Note that this reliability rapidly decreases with the number of production stages. For example, if $p_{ji} = 0.9$ for every i and $j = 1 \dots n$, it is sufficient $n = 10$ stages to reduce the reliability to 0.35. To increase reliability, we can of course increase the system's redundancy. A number of numerical cases are given below.

		Number of productive stages			
		$n = 1$	$n = 3$	$n = 10$	$n = 40$
Degree of static flexibility	$m = 1$	0.900	0.730	0.35	0.01
	$m = 2$	0.990	0.970	0.90	0.67
	$m = 3$	0.999	0.997	0.99	0.96

Figure 1. – F as a function of n and m for $p = 0.9$.

In our case, increasing a system's redundancy is equivalent to introducing a static flexibility at each stage. Thus, we can state that the **more flexible a system, the more reliable it is**.

Another approach to increase reliability can be reached through the reduction of complexity. Within a given level of flexibility, one only

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([8]) This model is one of O. LANGE's models adapted to production, *Introduction à l'économie cybernétique*, Sirey, Paris, 1976.

([9]) The same logic is possible starting with distributions of probabilities on production costs or profitability rates related to each stage. We shall consider here a simplified version of the model.

has to reduce the number of stages to achieve an increased reliability. In other words, **the integration and the reduction of the stages** reduces the complexity of a system.

For example, when we reduce the number of components of an object (a frequent phenomenon when for example materials are substituted) this results in a reduced complexity of the assembling process and a reduced total cost, despite the use of more expensive materials (10).

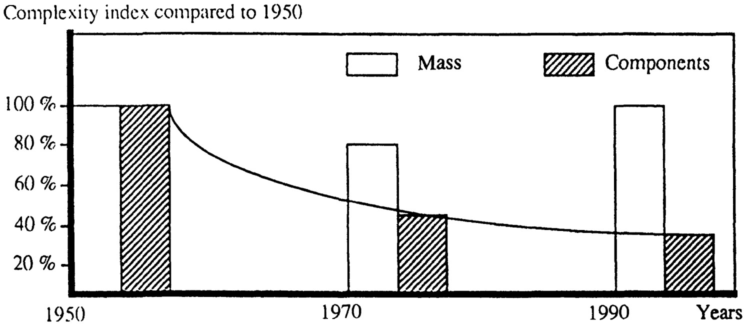

Figure 2. – Evolution of the propelling system of helicopters according to MBB.

Considering the propelling system of helicopters, the firm MBB (11) has been able to work out the evolution of "complexity" (according to the number of components) of this system in time (*cf.* Figure 2).

The purpose of integration (of phases or of parts) is to reduce the complexity of the system, measured in terms of the number of interconnections. Just as for static flexibility (more precisely the adaptability and the versatility obtained by juxtaposing several processes), these integrations remain compatible with the « Taylorian-Fordian » model. The interactions between components are determined, unchangeable and independent of the components considered as exogeneous (*i.e.* out of the decision-maker's reach).

3.2. Dynamic flexibility

Dynamic flexibility can be expressed in terms of new and evolving representations of production processes. The potential to meet a continuously changing environment occurs due to a new weaving of the production systems

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(10) One could show that here, in fact, we have a complexity "allocation": the complexity of the assembling process is replaced by a complexity integrated to the material itself.

(11) MBB, quoted by W. Hartmann and H. Kellerer, *Criteria for the material selection for aircraft structure*, EMRS, Strasbourg, 26-28 November 1985.

in which the corporate organization structure is adaptive. It is then moded by major market forces as well as technological change. In order to sustain such a flexibility **a high level of complexity is, by definition, unavoidable** as it corresponds to environmental variability and the required coherence between this variability and the corporate structure.

However, to fulfill such aims, it is necessary to master this complexity, **the major characteristic of which is the amount and the exchange of information to manage**. The control of complexity can then be reached in different ways. *A priori*, information technologies seem to be an important part of the answer. For example a workshop schedule can be worked out for every conceivable situation, thus responding to changing patterns of demand.

Assume that, in order to set up an operation (on a machine), a computer needs **one** thousand millionth of a second (10^{-9} second). Finding the solutions for 10 operations on one machine will take 4 thousandths of a second; on 3 machines it will take 1500 **years**; on 4 machines it will need 54 million **centuries** ([12]). Thus, the use of computers is not a solution to the "problem of complexity" as it only increases computational power. It is only possible to master complexity through an appreciation and an understanding of the change taking place in the framework of an on-going approach to production.

Similarly, dynamic flexibility requires that we adapt to environmental variability. For example, the management of complexity requires the control of switchover times. In this sense the objective of a strategy seeking to reduce the **reaction time** is to integrate the switchover and production times into a strategy that will result in the control of complexity. The Just in Time production technique emphasizing flawless flows through the application of SMED is a case in point.

3.3. Complexity control and integration

In general, the control of complexity implies the control of information by an information system. This is seen in **the integration of corporate functions**: integration of conception with programming, of conception with manufacturing, of manufacturing with production management in order to attain an "integrated factory" (CIM). Such integration multiplies and reduces the feedbacks delays, reducing thereby the organizational complexity required to formalize and "**standardize**" **interconnections** between the various functions: conception, management, manufacturing, control, marketing, etc. For example, compatibility problems between materials and network

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([12]) *Cf.* J. Bernad, M. Paker, *Les plannings*, Les Éditions d'Organisation 1985, p. 351.

development such the MAP (Manufacturing Automation Protocol) by General Motors are symptomatic of **the process of integration** and the problems it encounters.

A whole series of production techniques (computer aided or not) are applied to reduce the information volume to be dealt with and thereby deal with the system complexity. By grouping parts according to their type production is facilitated. For example, parts standardization and modularity are developing at the same time and the same place as diversification and final products variety are being developped. To a diversity of items there corresponds a standardization of components, on the one hand increasing complexity and reducing it on the other. This logic is still applied when parts use existing production references as soon as they are devised: why should we devise an entirely new part if an already existing part is just as satisfactory?

Four types of integrated organization are defined (*see* Figure 3), where A and B are for example two departments in a company). In a Taylor type organization each subsystem takes decision in order to reach its own objective depending of the level of decisions.

Nowaday most of the companies faced with integration of their functions have organization such as the one defined in Figure 3b. Few have really integrated decision systems however (Figure 3c). Integrating all decision systems is probably a utopia, but for some large subsystems such as with production systems, some integration is attempted (through simultaneous engineering, concurrent engineering). Further, considering the application of CIM, there seem to be different concepts of integration according to the approach adopted. S.K. Das (13) has put forward a classification of nine types of integration grouped together under resources and activities.

Resources directed integration

The objective of such integration is to ensure that each resource is accepted by the global production system:

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(13) S. K. Das (1992), A scheme for classifying integration types in CIM, *Int. J. Computer for Incl.*, *5*, n° 1.

IMS: Intelligence Manufacturing System.

CE: Concurrent Engineering.

IMS: Integrated Management System.

CAPP: Computer Aided Process Planning.

JIT: Just In Time.

TQM: Total Quality Management.

CIM-OSA: Computer Integrated Manufacturing Open System Administration.

– Integration through computer networks: concerns the transmission and reception of data to or from a center of activity. Proposed solutions are DBMS, LANS, etc.

– Integration of equipment: concerns the design and the selection of equipment like material, handling, storage and retrivial devices, etc. with different workstations and different products.

– Integration of materials: concerns the definition of consumer specifications for the choice of materials, their characteristics, their delivery delay, etc.

– Integration of resources: refers to the identification of material flow, the organization of production into manufacturing cells, the posting according to qualification of employees to workstations, etc.

Sequential system: decision are taken independently (a).

Integrated system: each department takes its decision but according to information from other department (b).

Integrated system decisions are taken according to A and B (c).

Simultaneous engineering no individual decision (d).

Figure 3. – Various levels of integration in a production system.

Activities directed integration

Activities integration seeks to realize a maximum profit with a minimum of effort in carrying out of these activities. These include:

– Integration of products: tallies the design of products and manufacturing. The objective is to simplify manufacture, quality control, assembly, scheduling, etc.

– Integration of processes: consists in designing manufacturing operations, which minimize the transfer of parts, the number of tool changes, which integrates operator know-how, etc.

– Integration of information: aims at making data accessible to the various decision making centers (transaction), and comprehensible for users (transformation into each user language).

– Integration of decisions: consists in using decision making tools and methods that allow coherent objectives to be optimized at each stage of the production process.

– Integration of controls: deals with supervision and control of information processes in a firm through automatic control systems, project management tools, supervisory systems, etc.

Thus, integration reduces complexity by increasing the coherence of resources and/or activities:

– Integration of equipment reduces handling tasks, reduces the number of machines, tool fixtures, jiggs varieties, manufacturing, data, etc.

– Integration of materials reduces the number of suppliers, the inventory volume, increases materials standardization, the frequency and variety of purchases, etc.

– Integration of resources by reorganizing the job shop into manufacuturing cells which simplifies workshop management, scheduling, quality tests, the number of process planning phases, inventory controls, work force management, etc.

– Integration of products through design for production which uses consumer standardized data, by automatic retrieval of previous product drawings, minimize the number of item references, the machine processes, tooling, etc.

– Integration of processes simplifies number of operations by standardization of process planning, assembly, time data base, etc.

If the integration strategy is well conceived this will result in a production system which is both less complex and more flexible.

CONCLUSION

The introduction of information technologies in production has revealed new potential concepts to design and represent production processes. These concepts outpace the "Taylorian-Fordian" scheme which is monoproduct, sequential and based on economies of scale. It sets up a joint multiproducts network system which generates an efficiency arising from an increased dynamic flexibility. This new representation finds its central organizing principle in complexity. Indeed, the evolution of modern production processes can be understood as a quest for minimum complexity. However there remains a constraint to this minimization of complexity: process flexibility must be large enough to provide rapid responses to environmental changes. But, complexity and flexibility grow at the same pace. Thus, it seems that the only viable operational principles seeking the reduction of complexity are associated to the integration of processes. Then, a balance between flexibility and integration can be achieved in order to define the appropriate and manageable degree of complexity of the production system (for instance, components standardization will correspond to products diversity and establish a balance in complexity).

Flexibility and integration are not necessarily incompatible with the "Taylorian-Fordian" approach as some forms of static flexibility and integration follow such a logic. However, when demand becomes increasingly varied and uncertain, a dynamic flexibility augmenting the system

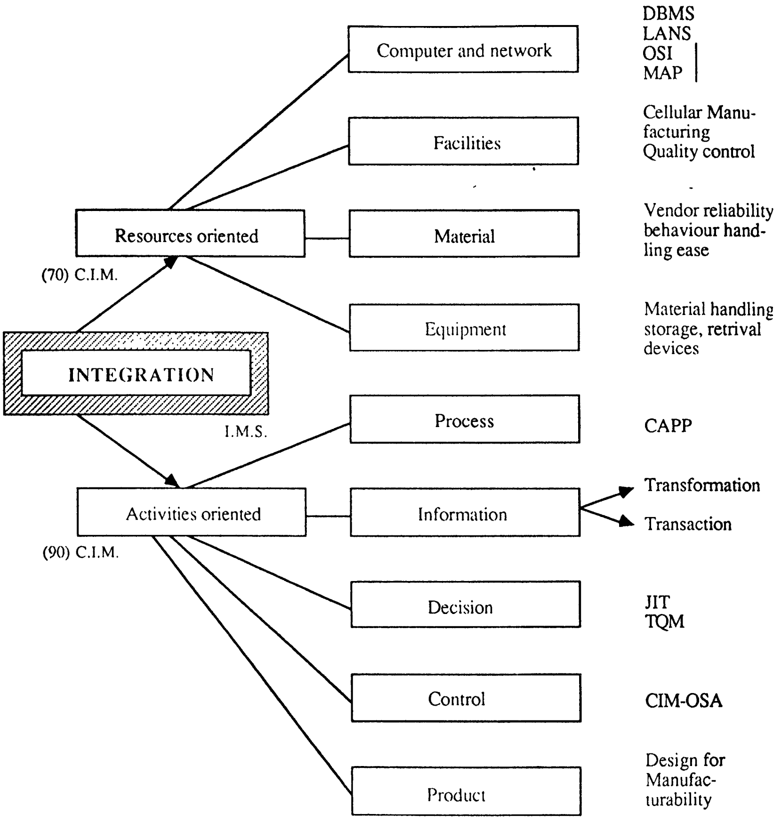

Figure 4. – Integration types in CIM and CE.

complexity becomes necessary. Such systems, of greater complexity, can become efficient only because of the existence of an iterative dynamic between: dynamic flexibility – quality – integration. Indeed, through dynamic flexibility, the firm can adapt to market changes but the resulting complexity requires on the one hand a reactivity of the process physical flows which steers clear of economic catastrophy only thanks to efficient quality management and reliability (by avoiding generalized breakdowns) and on the other, an integration of the corporate functions in order to standardize the interconnections inside the process and achieve an information dissemination. Thus complexity appears once more at the heart of this dynamic process, as its controls allow new gains in dynamic flexibility.