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Behavioural Analysis of a Complex System

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Recent works have shown that well-known models used for the analysis of human behaviour, in economics and in production–distribution contain unsuspected regimes of deterministic chaos. This paper is intended to study and analyse such behaviour in manufacturing and assembly shops.

We have shown how deterministic chaos could be produced by human decision making: the equations built from decision rules generally applied in a complex manufacturing system, lead to chaotic behaviour in a realistic region of parameter space. Also, we have implemented a methodology with associated tools to verify the nature of a production system and to highlight the above assumptions. Such target systems concerned by a deterministic chaos cannot be controlled through conventional management systems.

Dynamic modelling analysis of different production systems including delays, multiple-feedback loops, environmental and intrinsic disturbances, enables the induction of the management rules to be implemented for improving the control of such complex and chaotic systems.

Keywords: Complexity; Control system; Deterministic chaos; Dynamic behaviour; Non-linear dynamic modelling; System dynamics

1. Introduction

A model is basically a simplification or an abstraction of the real world. Until now, only the quantitative aspect has been considered when describing and modelling a system. The Galilean principle, on which this approach is based, consists in determining parameters and variables, then in defining and measuring their values and numbers. These numbers are linked together with mathematical formulae; they are organised in equations. Solutions to these equations enable us to predict the future. This principle supposes that the system is predictable and that there is absence of ambiguity.

This is in agreement with the deterministic approach, as defined by Laplace: "If we know, at a given time *T*, the location and the speed of any particle in the sky, then we are able to know all the future of the Universe." If we apply this principle to planning and scheduling fields, we could say: "If we know the location and process status of any part, in a production system, then we are able to determine the future and the evolution of this manufacturing system, based on the routeings and/or the technical description of the product/process."

Unfortunately, if we consider a multi-product, multi-process production shop involving thousands of steps and operations, with hundreds of parts, associated with a particular management system, submitted to various inputs, we cannot calculate and predict what will happen in time, that is to say: what the WIP will be, or the location and the status of any parts. We are not able to determine future and the dynamic evolution of the production system. This is due to the volume of information we have to handle and also to the application of the Uncertainty Principle as defined by Heisenberg. In the following, we will address the complexity of a production system and we will see why, and how, we have to introduce a new paradigm.

2. Complexity

2.1 Preliminary Definitions

For many years, industrial systems, and more generally production systems, have been evolving in a continuous way: they are comprised of more and more complexity. At the beginning, they were related to the assembly, or manufacturing, of simple products based on elementary operations. Later on, they were organised and combined together to form more complex products. To produce such products, a great number of sophisticated operations is then necessary and their associated routeings become longer and more varied.

For instance, in a typical semi-conductor manufacturing line, many local, complex routeings are involved in thousands of operations. The production system is multi-product (with several 10*2 P/Ns), multi-process (each one related to a family of products) and it is difficult to describe or to model

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such a system with general algorithms and conventional programming. The complexity is high, even without considering any change in the priorities which disturb the system rather than providing a good balance of flow of parts.

Here, the complexity is a function of the structure of the involved objects and cells and of the associated procedures. In the case of a study using modelling and simulation, the complexity will be expressed by the cost of the model build-up (length of coding, number of formulae, run time, ...). For example:

In an MRP system, the structure, capacity, and sophisticated local rules are not always considered. In this case, the complexity is low and the scheduling system is governed by simple programs.

In a PULL system, the management of production is simple, but the implementation of the strategy implies considering a flow of information associated with a physical flow of products.

Now, more and more mixed push+pull strategies are applied. When they are not well defined and applied (i.e. inconsistent clustering of the process, buffers and "kanban" not well adjusted), anything can happen to the WIP and TAT.

2.2 Different Types of Complexity

In fact any production system is subject to several possible phenomena. The following are some examples associated with three types of complexities, as generally considered:

1. Structural complexity of the system itself.

Here, the complexity is related to the structure of the products:

Assembly: in this case we have several levels in the bills of material structured as a tree. Problems are related to the synchronization of the parts flow and to the large volume of various technical data to be managed.

Parts manufacturing: main problems are related to the scheduling of the resources and the organisation of the means to be involved.

Complexity is also related to the nature and the size of the production system in which different kinds of relationships exist between the cells. In a manufacturing plant, the shop is often organised similarly to a Bill of Materials (BOM) with tree structures. The cells will be clustered in consistent sectors and the routeing of the products, which may be simple for some, may be very complex for others. Nevertheless, the complexity can be more or less important according to the constraints of synchronisation and also according to the complexity of the products (quantity of assembly levels, links, ...). We have few "states" for the target system under study, but computations needed for this type of model are much more complex and can be prohibitive.

2. Ill-defined complexity.

Sometimes, an accurate and reliable numerical model does not exist, or is only partially reliable: very often in process control, we have to reason with partial or incomplete information. This type of problem is also encountered in economic modelling or in diagnosis, where the degree of uncertainty increases. Here, the systems become much more difficult to understand and hence to reason on. The only way to make precise and relevant statements is to abstract the support set until consistent associated relations are shown (principle of incompatibility, Zadeh 1973).

3. Dynamic complexity of the deterministic chaos.

In any case, the complexity is first structural, then it becomes progressively behavioural. A production system, even with few cells and subject to a simple strategy, may be subject to unexpected events or to an unusual behaviour. Something simple may well lead to something complex. In this case, the complexity involves either an instability or a great quantity of various "states" that the system may have.

2.3 Consequences

Constructionism fails when faced with the difficulties of scale and complexity. Many production systems are difficult to model. Consequently, the analysis of their behaviour and their predictability is limited or difficult with actual tools, techniques and technologies.

In this sense, we will apply, in the field of scheduling, the principles as defined by P. Anderson: "The behaviour of the complex aggregates of elementary particles cannot be understood by extrapolation of the one related to a small number of particles. At each level of complexity, new characteristics appear and they have to be studied and modelled through quite different and specific ways in order to understand the behaviour of the whole system". This is in contradiction to the commonly used approach which consists of developing submodels to describe and analyse the local behaviour of a system, then assembling all the submodels to study the global behaviour (as a result of the interactions between the different local behaviour).

As we cannot satisfactorily describe a complex system as an assembly of objects or components associated with local and elementary laws, a different approach, based on complexity, has to be designed, implemented and applied. In this paper, we will mainly focus on the dynamic complexity of a system we will call also behavioural complexity.

3. Behaviour of a Complex System

Chaotic dynamics is a new area of mathematics applicable to the complex dynamics field. The complexity of the behaviour results from simple mathematics. A small change in a control variable can turn an ordered flow of parts from a tap into a highly complex chaos of vortices.

As we will see in this section, a subsequent order emerges from that chaos.

3.1 Initial Conditions Necessary for a Chaos

Chaos is not necessarily generated with a large amount of data: simple systems, submitted to few nonlinear rules, and very sensitive to initial conditions will be unpredictive and they are generally governed through Lorenz attractors.

Now, we are going to detail two characteristics, very common in a complex system, which are prerequisites for any chaotic behaviour.

1. Sensitiveness
Sensitiveness is a characteristic present in many closed-loop systems involved with either feedback loops or effect amplifiers.

For instance, if we consider a production system in which we denote the WIP by X and the Turn Around Time (TAT) by Y, X and Y will be very sensitive to repair. As an example, we consider first a simple operation (or a set of simple operations) as described in Fig. 1. In this case, D% represents the yield and X_0 the initial demand.
The WIP is expressed by: $X = X_0/(1 - D)$
The TAT, called Y, compared with the raw process time, Y_0, follows the same rule: $Y = Y_0/(1 - D)$, when it is stabilised. When D is varying and is near to "1", the WIP, X, becomes very "high". Nevertheless, after a transient period of time, the throughput, called Z, remains constant.

2. Nonlinearity
For easy calculation of the "curve" of the system, and then to obtain a predictive system, the corresponding parameters and variables have to be expressed through linear equations or through linear relationships.

For instance, the variables X, Y and Z at a given time T, must be used in proportional relations to the power of "1". They have to be combined linearly in a formula. In reality, the variables are sometimes multiplied or divided together.

A set of such equations may not have a possible "algebraic" solution. Because of this, we are not able to predict the curve of the system then its sensitiveness and reaction to some initial conditions.
Here are some detailed examples:

In a manufacturing line, the throughput is expressed by a ratio:

$Z = X/Y$, where X is a quantity of product and Y is a time duration.

To implement the continuous flow manufacturing (CFM) concepts, the demand $E = X_0$ to be sent at the previous operation is a combination or a selection of the two following values (see Fig. 2):

$$X_{01} = \mathrm{Min}(X_1, X_2) = Q_{\min} \text{ or } X_{02} = MAQ = Q_{\max}$$

The information related to X_0 is determined when the WIP reaches a maximum allowable quantity (MAQ).

Also, in a very flexible manufacturing system, some nodes are quite autonomous and are controlled or managed through behavioural rules such as: $X = F(X_1, X_2, \ldots)$.

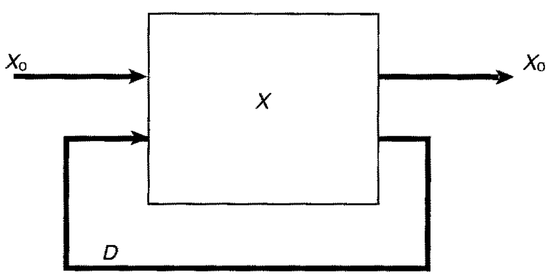

Fig. 1. Basic cell.

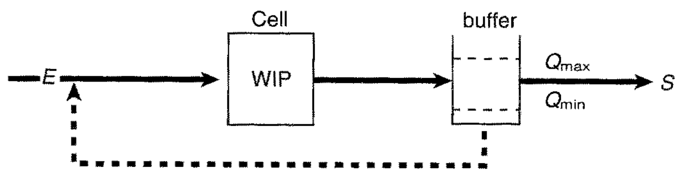

Fig. 2. Nonlinear basic cell.

Such management rules are nonlinear and they make the mangement system more complex.

3.2 Mathematical Analysis of Chaos

In a flexible shop, or manufacturing line, some cells are devoted to several operations and parts are sent back to an identical or different cell in the manufacturing line.

Similarly, in many complex assembly lines involving several hundred operations, some of them are replicated several times all along the process and could be performed tens of times on the same product. Here, we intend to analyse the evolution of the state variables.

Basically, we are faced with a process subjected to nonlinearities and feedbacks. The state variable, or the set of state variables, is called X. We will adopt a dynamical point of view, with the aim of establishing a relation, or "rule", to generate the new value of X_{n+1} (for instance the WIP or TAT) from the previous value X_n. The mathematical expressions describing how a set of state variables $\{X\}$ evolves in time are given by:

$$\mathrm{d}X/\mathrm{d}(t) = F_n(X,L)$$

Here, we want to express the idea that evolution is influenced by the variation of some parameters present in the problem that can be modified by the external world. We call these entities, or problem parameters: control parameters, and we denote them $\{L\}$. Whatever the form of F_n, when an equilibrium or non-equilibrium steady state is reached, this corresponds to the solution of: $F_n(X,L) = 0$.

These relations impose certain restrictions because any physical system cannot always be reduced to simple mathematical formulae. However, we will use them to model part of a process regarded as more typical or generic, from the mathematical point of view.

Again, let us consider a simple closed-loop system (Fig. 3), which describes a nonlinear behaviour linking the steady state value (X) to the control parameter C, at stages (n) and (n+1). In this graph, $F(X_n,C)$ acts as an amplifying factor.

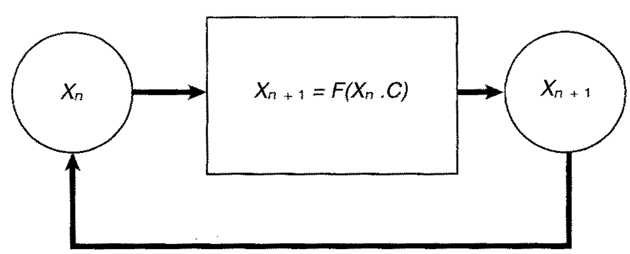

Fig. 3. Closed loop system.

This nonlinear function, in some conditions, may lead to chaos.

In both cases, (n) is the index representing the number of passes of the flow of parts in a given cell (or set of manufacturing cells). $F(X_n,C)$ corresponds to a dynamic system which successively propagates an initial X_0 value into the points X_1, X_2, ..., X_i ... This sequence of points to which the value X_0 is sent may be called the path, or orbit, of X_0. If the path is ordered, we may speak of ordered dynamics; if not, it is described as chaotic dynamics.

After several successive backwards loops or recyclings, in the production process, the quantity of parts present in a cell is defined by: $X_n = (1 + R)n\ X_0$, where X_0 is the size of the initial batch in the cell.

In reality, this exponential growth will not occur because of several reasons:

The processing capacity of an involved cell is limited to a maximum value X_m.

The yield, leading to R, is controlled, and many change with time or circumstances so that it is generally improved: the rate always drops from R to a lower value, when the population approaches X.

The resources, and consequently the efforts, assigned to a manufacturing system are sized to the "criticality" of the situation. Then an "autoregulation" phenomenon always applies. This introduces the concept of self-control which we will develop later.

In a practical way, each time the growth of the population becomes too high, the solutions offered may be of three kinds, as follows:

1. Limitations by the "MAQ":

The maximum allowable quantity (MAQ) enables regulation or limitation of a flow of parts in a shop: the input of the parts, in a cell, is limited thanks to a buffer control approach. When the cell is full of parts, the upper limit of the WIP is reached, then parts from the previous cells are not accepted. If the WIP is denoted by X, then the evolution of X is mathematically represented by: $X_{n+1} = ((1 - A) + R)X_n$, where: $A = C_1X_n$ and $C_1 = 1/X$. C_1 is defined so that input is 'O' when X is equal to X_n. In this case we have the general formula: $X_{n+1} = (1 + R - (1/X)X_n)X_n$.

At the steady state, when the limit is reached, the WIP becomes: $X_{n+1} = X_n + X_n(R - X_n/X)$.

By appropriate alteration of the units of measurement, the formula is then simplified as follows:

$$X = (1 + R)X - X_2$$

The graph of the trajectories is shown in Fig. 4. As we can see, the behaviour of the cell is a deterministic chaos. This situation appears as soon as $R \geqslant 2$, that is to say for a yield lower than 50% ($D \leqslant 0.5$).

Symmetry-breaking bifurcations:

First bifurcation is found when $F(X) = X$.
In this case, 2 solutions are possible: $X = 0$ and $X = R$.
Then $F'(0) = 1 + R$ and $F'(R) = 1 - R$.
With $R > 0$, $X = R$ only is valid.

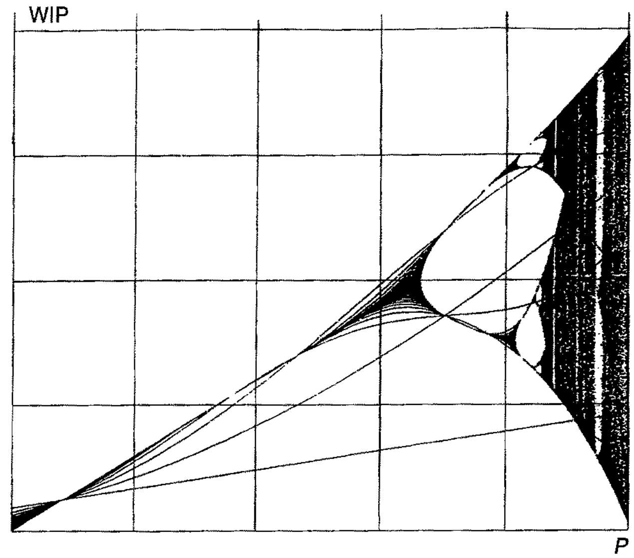

Fig. 4. Phase plane trajectories (MAQ).

Bifurcation is reached when abs$[F'(X)] = 1$ that is to say when: $R = 2$ and $X = 2$.
Second bifurcation is given by $F^2(X) = X \Rightarrow -X^2 + (R+2)X-(R+2) = 0$.
Then $X_1 = ((R + 2)+((R^2 - 4)) \times 0.5)/2$,
and $X_2 = ((R + 2)-((R^2 - 4) \times 0.5)/2$.
We can easily deduce: $R = 2.45$, $X_1 = 0.517$ and $X_2 = 2.931$.

This also addresses the manufacturing lines where some set of operations are duplicated several times in a process.

2. Limitations through "dispatching rules":

In order not to affect the main flow of parts, the dispatching rules may be changed, giving lower priority to recycled and repaired parts in the cell.

In this case, the variable growth rate R, used in the previous mathematical expression, will be limited by a threshold and is now replaced by: $R - C_2 X_n$, where $C_2 = R/X$.

This expresses that the growth of the population becomes zero when:

$X_n = X_m$ (X_m being the upper possible limit of X).
Thus: $X_{n+1} = (1 + R - C2\ X_n)X_n$.
When C_2 is replaced by its value, we get:
$X_{n+1} = X_n + R\ X_n(1 - X_n/X)$.

As stated above, the formula yielding a stationary state value becomes:

$$X = X + R\ X(1 - X)$$

The representative graph is shown in Fig. 5.

Again, the behaviour of the cell is a deterministic chaos:

First bifurcation appears when $F(X) = X$, then $X = 0$ or $X = R$.
We can define: $F'(0) = 1 + R$ and $F'(R) = 1 - R$, consequently: $R = 2$ and $X = 2$.
Second bifurcation is obtained with $F^2(X) = X$,
Then: $-X^2 + (R+2)X - (R+2) = 0$ gives X_1 and X_2 as before.

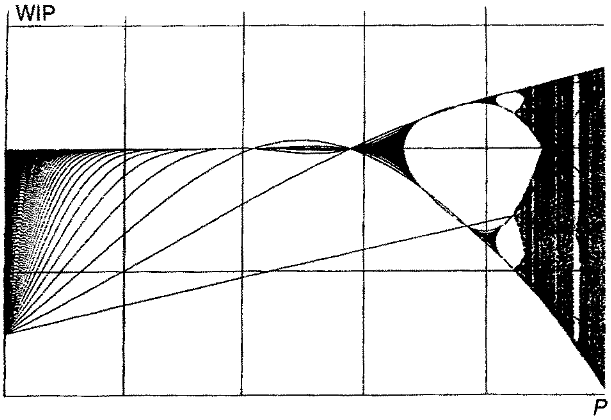

Fig. 5. Phase plane trajectories (dispatching).

With $R = 2.45$, we can calculate $X_1 = 0.619$ and $X_2 = 1.197$.

These formulae are similar to the very well-known equations defined in 1845 by P. F. Verhulst.

3. Bottleneck management
In some recent manufacturing and assembly shops, for instance in semiconductor plants, the process involves hundreds of products, described by different routeings, each one involving hundreds of operations. The process is often repetitive because of the similarities of some operations: mask, exposure, clean, burning. The equipment at these stages is frequently sophisticated and expensive. Consequently, they are limited in quantity. This explains why we have some bottlenecks owing to hardware limitations. Generally they are solved through management of the product flow, in the shop itself.

The usual way to handle such a bottleneck is to apply the following strategy: "If a given operation is a congesting one, never leave it unloaded. As soon as the queue length is below a threshold, load the shop with the products having the highest processing time at the bottleneck ... even without a demand!"

Let us call X_b and T_b, respectively, the values of the WIP and of the threshold at this bottleneck.

The value of the total WIP, along the time is defined by:

$$X_{n+1} = X_n + K(T_b - X_b) - X_b \quad \text{with } K = F(1/X_b)$$

This formula can also be expressed by: $X_{n+1} = X_n + C(1 + X\ T/X)$, where C is a constant, acting as a control parameter. In a stationary state, this leads to the more general formula:

$$X = X + C/X\ (X_2 + X - T)$$

Here again, according to the form of the formula, the resulting behaviour of the WIP will be chaotic.

4. Validation of the Concepts

In the previous section, chaotic behaviour was demonstrated, based on modelling of simple cells. In fact, modelling of a complete production system is complicated: many overlapping cells have to be considered and mathematics are not sufficient.

The objective is now to validate our assumptions and to prove the presence of such a behaviour in a real production system. For that purpose, a set of simulation tools, image analysis techniques and tests have been set up in order to:

Check the presence of any chaotic phenomena in a production system.

Measure and visualise these phenomena in the system under study.

4.1 Detection of a Chaos in a Production System

Mathematical Methods

Mathematical methods can be used for detecting the chaotic behaviour of a dynamic system. Most of them are qualitative and are able to determine with a high level of confidence if the system under study is chaotic. Among these methods that we have implemented and experimented on real systems, we can quote:

Spectrum analysis. We have developed an FFT program to analyse a large set of observed data.

Phase graph analysis (with a 3D visualisation tool called Galaxy, implemented on a RS/6000).

Poincare map.

Sugihara May test.

Comments: All these approaches can describe the characteristics of a possible chaotic system. However, during our experiments, we were not able to confirm clearly and to prove the chaotic type of a dynamic system. Best results were obtained with FFT: we could analyse a time series representing daily deliveries of TCM products; existence of continuous spectra were observed.

To Improve the Behavioural Analysis

To improve the behavioural analysis of a dynamic production system, a different and more quantitative approach was implemented. It is based on Lyapunov exponents. This approach, thanks to specific and precise calculations, enables us to predict the situation of a dynamic system, by measuring the deviation of the trajectory near the attractor.

In the following, we will not detail the formulae and calculations principles which are quite complex, but remember that the condition of a system can be specified by the value of two exponents:

IF Lambda and Sigma are positive, THEN the system is chaotic.

IF Lambda and Sigma are negative, THEN the system is steady.

Considering the complexity of calculations to determine the values of the Lyapunov coefficients, two methods have been implemented:

Use of the set of differential equations describing the system.

Use of a set of data coming from observations related to the system.

Comments: a reliable analysis of a production system requires a large set of data (about $10/30^D$, D being the dimension of the attractor). For our experiments we could not collect a reliable set of data large enough to validate our assumptions: the Montpellier plant is involved with the assembly and test of TCM modules and large systems; here, the information system collects and stores the quantity of products manufactured every day in the production system. As the lifetime of a product is around three years, we had time series consisting of around 1000 values. Under these conditions, it was very difficult to confirm reliably the evidence of chaos in our production system.

Information and Results

To obtain information and results on the production system involved, one solution consists in modelling then simulating the system. Simulation is a good and realistic way to represent complex systems with much more detail and behavioural rules than would be possible with mathematical methods. Again two approaches have been defined:

Dynamic simulation language (DSL): this is a high level language enabling continuous simulation of a production system. DSL is based on the resolution of differential equations. It comprises many functions to represent some behavioural methods in a dynamic system. DSL is fully adapted to transient analysis and we could simulate all the production systems we intended to study.

NETSIM: this tool was developed to model and simulate a network. Each node of the network can be a piece of equipment or a cell and the nodes are linked together with a procedure which defines the management methods between two cells, the values of the parameters. NETSIM is an object oriented, easy to use, tool. It is written in Smalltalk.

Comments: DSL and NETSIM are very useful for generating large sets of data, well-fitted to different types of production systems. These data are the inputs of the Lyapunov program, to calculate the exponents associated with the dynamic system under study.

Figure 5 shows some outputs we get with NETSIM: we could verify, as we did in the real system and according to the values of the control parameters, that we had cycles with 16, 24 and 32 periods of time.

4.2 Methodology

Determination of the nature of a dynamic system may require several studies through the various tools we have developed. We found it is possible to define a chaining between the tools and associated methods, according to the characteristics and the nature of the observations and also depending on the structure of the production system. This can be summarized on the diagram depicted in Fig. 6.

This methodology has been succesfully used in several studies we have recently conducted. Each time the quantity of observed data is not large enough, simulation based on DSL has to be used. The difficulty is to select the most significant parameters related to the modelling of the production system. The definition of the equations is not the most difficult work.

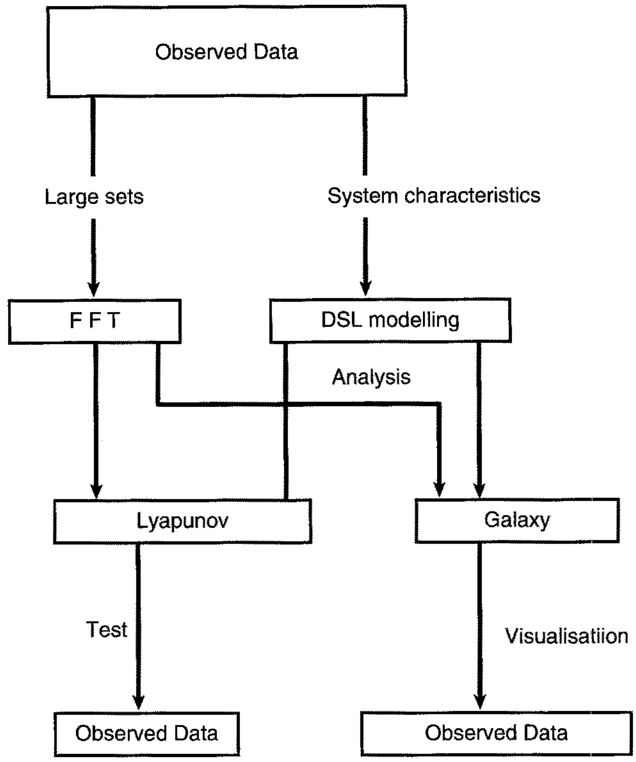

Fig. 6. Methodology.

FFT is a good tool for analysing the response spectrum. However, the proof of the existence of a possible chaos must be based on Lyapunov exponents testing.

Finally, visualisation is interesting, as a qualitative tool, to demonstrate how the variables of a dynamic system are arranged and to represent a periodic trajectory in pseudo-phase-space coordinates.

4.3 Application to a Production System: Results

Several production systems have been studied theoretically and experiments have been conducted over a long period of time.

On some of our production systems, we analysed the WIP and found it was quite impossible to predict future events and to determine any cycle on the WIP variations. Mathematical modelling of such systems has demonstrated a chaotic behaviour. In that case, the demand remains constant and the variables we considered were: the WIP and the throughput; the control parameter being the size of the kanban's. We selected these characteristics as they are easily visualisable. Moreover, in case of validation of some assumptions, a partial display of the attractor is sufficient as a first approach.

Based on experiments and observed values we could only demonstrate firmly that a chaotic behaviour exists in some of our production systems. The reasons are as follows:

The yield which implies feedbacks is variable with time.

The number of state variables depending upon the complexity of the dynamic system is changing regularly because of modifications in the process and/or in the routeings.

As explained before it was difficult to collect a large set of data. In many cases we had a strong belief that the chaos was there but we could not state that fact with a high level of confidence.

A simple approach consisted of highlighting on bifurcations: we could observe double the number of states when the control parameters were changed (one stable, steady, state, then 2, 4, 8, ..., till non-predictable variations).

As said before, we could check the evolution of the system towards a chaotic behaviour. However, we can consider that reliable and regular measurements are difficult and this could lead to some caution.

When checking the real sets of data, we could detect some anomalies due to, for instance, the introduction of random events, like failures, which disturb the set of observed data.

As a conclusion, the mathematical approach shows that chaos occurs in our production systems. The validation of such assumptions is difficult, but we have a strong belief that such behaviour often exists and we will consider that fact in the design and the implementation of future management and control systems.

5. Analysis of Manufacturing Control Systems

5.1 General

In the previous section, we have seen that chaotic behaviour could exist in some production systems. The aim of this section is to study two families of control systems widely used in the industry and often described in the CIM field. Their characteristics will be highlighted and a classification will be deduced accordingly. The objective of this classification is to help the decision maker in choosing the type of strategy he has to apply when he faces a given situation. In the following, the production system under study is submitted to an input variable, called DM, the nature of which is either a stochastic or a deterministic chaos.

5.2 Case Study 1: Planified System

First, let us consider a shop conventionally controlled through an MRP system; it comprises feedback loops of information. Moreover, different shops, like this one, are connected together to make up a complete facility. Such a system is similar to the one we have studied for the French Manufacturing Headquarters: The problem consists of analysing the behaviour of a complete production system in the computer industry. For this purpose we have used industrial dynamics techniques to study the interactions and behaviour between the different shops: CHIP ↔ CARD ↔ BOX.

Modelling

The model, developed with Dynamo, was submitted to a step function, in terms of demand (DM), at box level. The purpose was to analyse the consequences of the variations on DM at chip and card level and the evolution of the WIPs.

The equations used to process the flow of information were simple. The parameters on which we could react were: the size of the buffers, the "rates" and the delays (response times) introduced in the formulae.

In that case, the total WIP of chips evolved as shown in Fig. 7: when the demand "DM" changes, the WIP is subject to decreasing variations. Nevertheless, for some values of the control parameters, these variations may persist in time, and in some cases, we can observe an oscillation or an increasing oscillating curve. In these conditions, the system is said to be "PUMPING". In addition, these oscillations, due to feedback loops, are either amplified or absorbed according to the values of the different parameters. Although the system is modelled with simplified equations, it is difficult to control the system in a stable way, but we could not demonstrate that it was a chaotic one.

Chaotic demand

This example is related to the analysis of the behaviour of the TCM BAT manufacturing line, in the Montpellier plant. This production system has been modelled and simulated with RESQ.

Now, let us consider, as the input stimuli, a real set of values for DM (see Fig. 8). Contrary to appearances, this initial demand is not "random": for several reasons we will not detail here, the vector DM issued from a history in the BAT shop has a "memory effect" of previous events and situations. In fact, DM is the result of a deterministic demand modified by several and successive simple laws, fits and starts, generated by different decision makers. In this study, we did not have sufficient available data, whatever the product, to demonstrate firmly that the DM vector is a "chaotic" one; nevertheless there is a strong belief that we should made such an assumption.

Curves, showing the evolution of the different parameters are shown in Fig. 8. The production is represented by the curve (PC). We may observe that the evolution of the order file (CC) and of the WIP (ST) follows the input (DM). However, according to the quantity of buffers, their size, the delays, etc. the results are either smoothed, attenuated or amplified (pumping effect). When the buffers are too big,

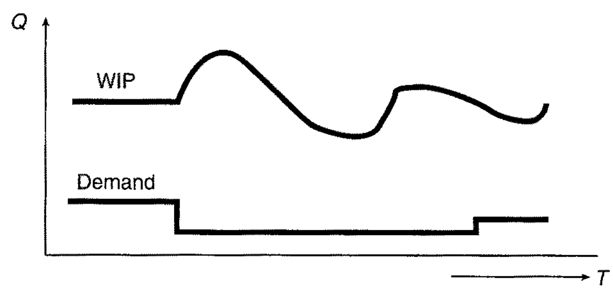

Fig. 7. Stable production system.

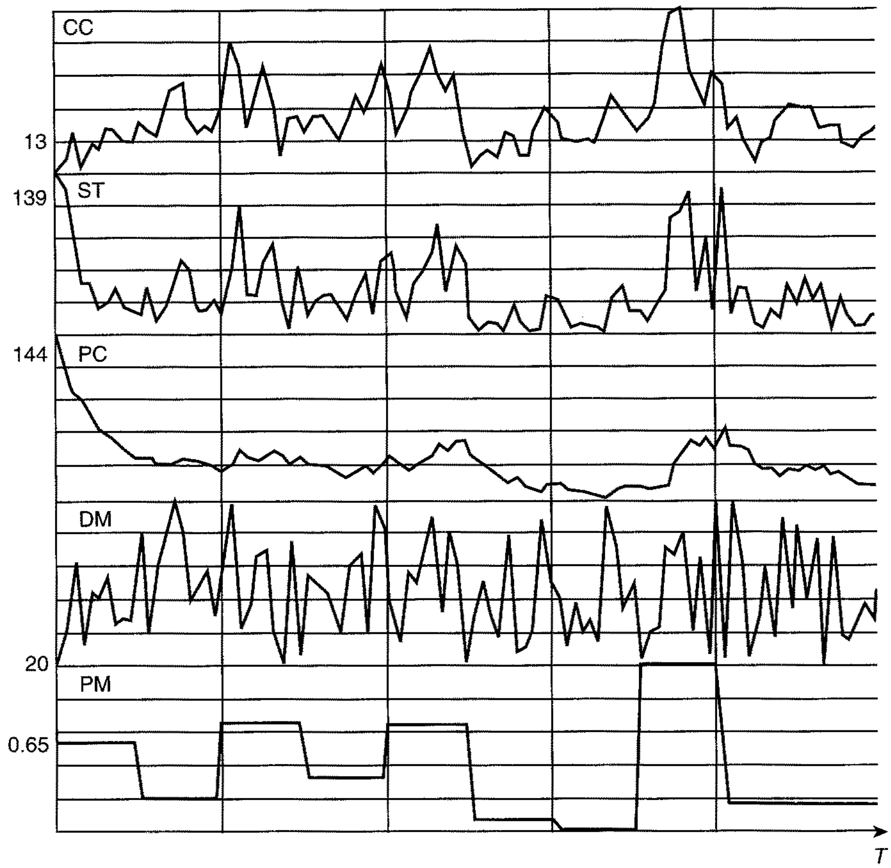

Fig. 8. Behaviour analysis of the TCM production system.

and corrective factors in the feedback loops too high, the system may diverge; it creates and amplifies the noise.

With a more planifying system, we get a "dangerous system" with unexpected evolutions. The resulting performance parameters evolve by "fits and starts". A control system is not generally designed to process a chaotic demand. In such a condition, it degrades the overall performance of the production system. Then, a planified system is not adapted to react to a varying demand like this one.

Moreover, as we are not faced with a planified demand, the only way to limit the pumping effect is to react with noise rather than linearly. Introducing "noise" and uncertainties in the control parameters and in the values of the calculated inputs enables compensation or even suppression of the pumping effect as well as the "coughs" and their unexpected results.

Comments

Most of the time, the "planifying systems" are not useful: they have too many constraints. They do not perform an adequate regulation of the production system: variations and variance on performances can be out of control and it is difficult to monitor the complete system. Now the questions are:

What organisation can we propose?

What type of modelling has to be designed to analyse a seasonal or varying demand?

Whatever the level of complexity embedded in the model of such a system, we cannot represent everything in a model at the risk of generating noise. Also, the manager, in a shop, is always introducing "bad noise": he modifies, permanently, the priorities of the products to be manufactured, according to situation changes or contradictory requests. He still creates more disturbances and "coughs". Then, the capacity of a manufacturing shop being limited, some parts are more penalised than others which are prioritised. Consequently, the "buffer" effect is always increased.

The only way to monitor such a system is to build a simple model, with small buffers, with an "output follower" control system to correct the inputs. Finally, in order to integrate the "history" (memory effect) of the inputs and results, the model will have smoothing and moving average capabilities, completed with a precise scheduling system, at cell level only.

5.3. Case Study 2: Flexible Manufacturing System

Let us consider a very flexible manufacturing system: multi-products, multi-process, duplicated equipment, feedback loops, etc. with several and complex routings (Fig. 9). Such a flexible manufacturing system may have a chaotic behaviour. Each node, or cell, in this network (production system) has its own control system with dispatching and behavioural rules.

Here, the chaos is due to the interactions between the cells and it may happen with only a few cells: oscillations, created

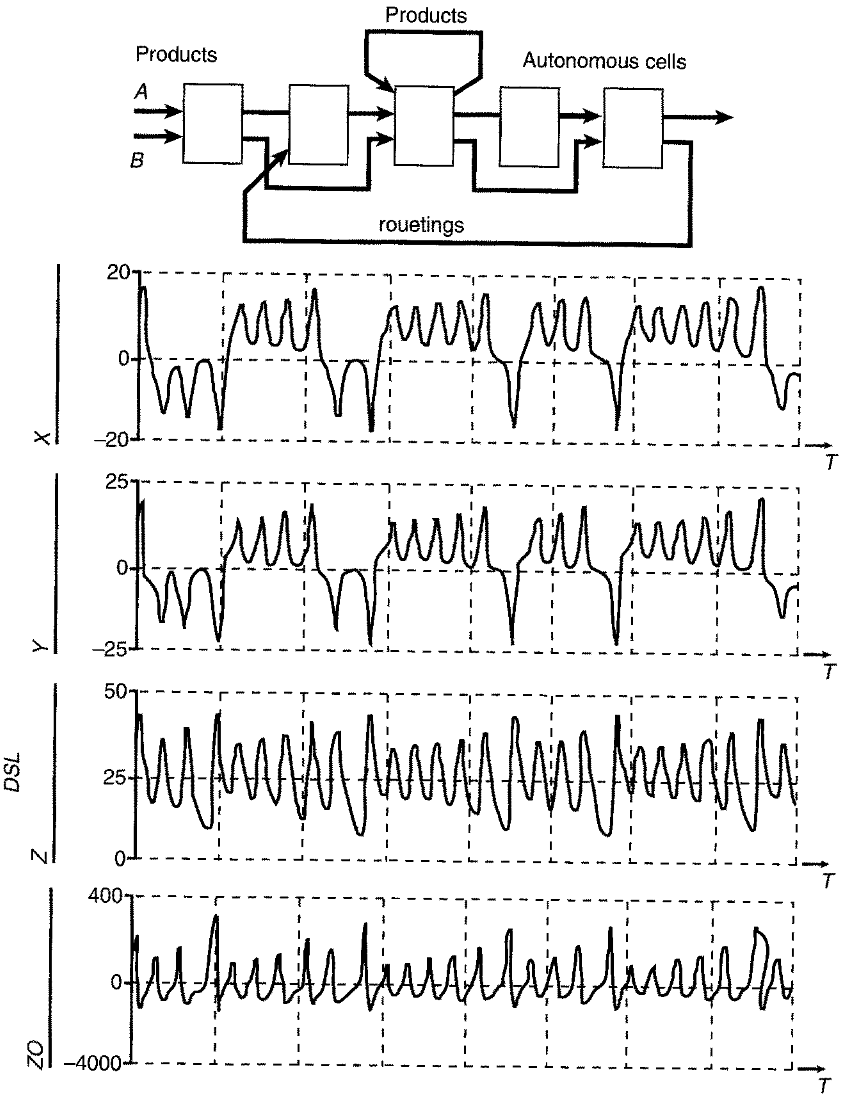

Fig. 9. Flexible manufacturing system.

by the "calls" of the buffer management system, are propagated from one cell to another and vice versa. In practice, this induces the presence of many possible states for each cell. When this phenomenon is amplified and subject to nonlinear functions, it becomes a chaos. This is due to the "chaining effects" of the physical and logical structure of the production system. We will call it: caterpillar effect.

Under these conditions, we cannot predict the behaviour of the system. The model, a very complex one, cannot integrate all the parameters and assumptions: it is not usable for management purposes. In terms of effects, the cells have their own "elasticity", and the disturbances are reduced, and they are smoothed. With small buffers, the adaptation of the outputs to the inputs will be quite fast. Then, the best way to manage the system is to leave it "free": it will regulate itself thanks to self-organisation effects.

Here again, we have to build up a model conditioned by the inputs, or following the inputs, to be able to determine which global strategy has to be applied in the production system. Anyway, we will look for situations between stability and instability for best flexibility. This corresponds to a kind of "weak chaos", which is common to many linear production shops. This will be studied later on in a more detailed way. *Note*: in the previous sentence, the word "linear" is related to the linearity of the product routeings, the structure and the layout of a production system.

6. Recommendations for Improving a Production Control System

As a result of above, we can deduce recommendations to avoid inefficient management rules:

Adapting the priorities to the demand, or changing the priorities in a cell, according to its performance status, on a real-time basis, is a very disturbing strategy leading to situations which are more difficult to control. Moreover, its effect is quite inefficient as the system is a choatic one.

It is of prime importance to correct an abnormal yield, in order to decrease the value of D (mainly when $D \gg$, because of the raise of a deterministic chaos), and to position the production system at a weak chaos level.

Also to improve or to control a situation, priority must be given to solving any anomaly or discrepancies in the control parameters, then to reducing WIP in the feedback, then to restaring the main flow. For instance:

1. In a turbulent environment, no strategic process may run without strict management and without processing much data related to an everyday or short-term period activity, such as: fluctuations of the demand, varying bills of materials, inputs or production, unstable resources, random failures on equipments.

   This is generally exhibited by a high value of the variance, or standard deviation, of the related parameter. As a consequence, we are unable to predict, plan, and define short-term adaptability. For example, existing scheduling methods are unable to provide, within a short period of time, a good adaptation of the production program in response to a variation of the demand.
2. Tools and techniques in use have to help the management in defining objectives and operational rules. Management should keep the objectives while permanently modulating their implementation depending on:

   The situation of the production system.

   The state of the environment.

   New expectations about the future.
3. In a turbulent environment, the strategic management team cannot permanently adapt its action process without a constant reference to a precise methodology:

   To keep a good consistency.

   To know exactly where the system stands, any time, in terms of chaos, and to deduce consequences compatible with the assumptions.
4. In a turbulent environment, simulation is a good help in elaborating the schemes, because conventional optimisation techniques are subject to uncontrollable and unexpected external constraints. Simulation must lead to:

   Better understanding the environment constraints.

   Detecting, reacting to hazards (quality problems).

   Collective and global vision of the system and its environment.

   This implies numerous interferences between the action process and the research process. This contributes also to the build-up, within an organisation, of a common vision of the genesis of the possible future.
5. The more turbulent the environment is, the more important it is to develop local autonomous tools, to manage short-term difficulties and to reduce the variability of the process.

   The efforts of the executives are concentrated on daily issues and, sooner or later, without strategy, they will face a severe crash crisis. In this case, operations research is a vital counterbalance to define operational rules and directive/strategies, then to limit the effects and disturbances of short-term unexpected events. Unfortunately, the applicability is local, at cell level, and we will have to aggregate a local with a global management system.

7. Conclusion

This paper is related to the analysis and the management of complex target systems. More precisely, an in-depth study has been performed in the field of dynamic complexity. To summarise the content of Section 3, most of the production systems can be subject to a deterministic chaos called either butterfly or caterpillar effect. This leads us to develop a methodology able to detect chaos in a production system. This approach is efficient and such a phenomenon could be observed in real systems, even if it is difficult.

Under such conditions, the conventional management and control systems do not apply. This is why we have developed a methodology aimed at identifying such behaviours. With an environment which is difficult to control and a target system which is unpredictable, we cannot force it to react as we want and a new paradigm as well as a new appropriate approach must be used.

We cannot cope with complexity by more complexity, that is to say with a management system which is too detailed and complex: the more complex a target system is, the more simple its associated control must be.

The conventional approaches are generally based on the products management (flow of parts, scheduling with a given set of capacity limitations, resources constraints) while the emphasis has to be put on the process (tuning, balancing): we cannot dictate a given release of the parts without taking into consideration the process itself.

Instead of being monolithic with a complete set of embedded functions, the management system will be layered. In this paper, we found that two application levels are sufficient. We defined them as the mesoscopic and the microscopic levels. The first one gives the guidelines to be applied to the target system. The second one enables the microscopic level to perform a local control. It is characterised by a given rigidity, leaving some whirlpool at microscopic level. The resulting models have to be modular and, more specifically, the lower level must be able to be adjusted to evolving situations: local rules will take into account the tasks and characteristics of the related cell or workcentre.

In another way, we will pay attention to the microscopic level: it must be in-depth analysed and a precise and local scheduling will be developed accordingly. Scheduling, sequencing and/or dispatching have to integrate real situations subject to uncertainties and nonlinearities (ill-defined complexity). As conventional and analytical techniques are not sufficient enough, we have to study new approaches based on alternate techniques like simulation in which A I, simulated annealing or even genetic algorithm based methods are integrated. The whole production system will adapt itself when faced to new situations, through its self-organisation capabilities, within the framework defined at the mesoscopic level.

With such concepts, we can get a flexible and efficient control of a target system. It will be the basis of future integrated manufacturing systems. Some of these above concepts have been successfully implemented in an application called: line management advisor (LMA). This application is an example of the tools we have developed at Montpellier by the Advanced Technologies Group, to perform dynamic scheduling of a manufacturing shop.

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Glossary

AGV	Automatic guided vehicle
AI	Artificial intelligence
BAT	Bond assembly and test
BM	Bill of material
CRP	Capacity requirement planning
DM	DeMand
DSS	Decision support system
FCS	Floor control system
FFT	Fast Fourrier transform
FMS	Flexible manufacturing systems
GA	Genetic algorithm
KBS	Knowledge-based system
LMA	Line manager advisor
MAQ	Maximum allowable quantity
MCS	Manufacturing control system
MRP	Material requirements planning
NC	Numerical control
NO	Numerical optimisation
PLOOT	Plant layout optimisation
RESQ	Research queuing package
SMS	Shop management system
TAT	Turn around time
TCM	Thermal control module
WIP	Work in process
WMS	Workstation management system