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(Re-)Design to Agility using the Concept of Organisational Periodicity

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Abstract: The complexity of a production system is caused by two factors: by a time-independent poor design that causes low efficiency (system design), and by a time-dependent reduction of system performance due to system deterioration or to market or technology changes (system dynamics). To optimize the efficiency and changeability of a production system, both factors must be considered. Starting from complexity theory, a procedure is presented in this paper that helps not only to design production systems with low or zero time-independent complexity (focus: flexibility and efficiency), but also to prevent the unpredictable influences of the time-dependent combinatorial complexity by transforming it into a periodic review and adaptation of the system's volume and variant capabilities (focus: changeability). With the help of a practical industrial example the validity of the approach is illustrated.

Keywords: Agility, Complexity Theory, Functional Periodicity

1 Introduction

The recent economic crash and the financial crisis triggered by the subprime mortgage crisis have been leading to another global follow-up recession. Most companies are struggling with overcapacities caused by an abrupt decrease in market demand. But did this crisis really come surprisingly?

The economic cycle is a well-known phenomenon. Often new business opportunities created by a new technology (e.g. GPS – Global Positioning System, smart items, photovoltaic cells, etc.) or some “hypes” such as the “dotcoms” in the late 90s may initiate an economic boom. Initially, wealth is created when growing market demand for new or “hip” products generates new jobs and promotes

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productivity and growth. However, quantitative growth is always limited (Matt 2007) and when it turns to be artificially maintained on an only speculative basis, the economic system is going to collapse. According to Nam Suh, the economic cycle is a good example of time-dependent combinatorial complexity at work (Suh 2005). To provide stable system efficiency, the time-dependent combinatorial complexity must be changed into a time-dependent periodic complexity by introducing a functional periodicity. If the functional periodicity can be designed in at the design stage, the system will last much longer than other systems. This way the system becomes “agile”.

2 Literature Review

Many similar terms like flexibility (De Toni and Tonchia 1998), reconfigurability (Koren, *et al.* 1999), agility (Yusuf, *et al.*, 1999) and more recently changeability (Wiendahl and Heger 2003) or mutability (Spath and Scholz 2007) have been defined in many different contexts and often refer to the same or at least a very similar idea (Saleh, *et al.*, 2001). Nyhuis, *et al.* (2005) even state that changeover ability, reconfigurability, flexibility, transformability, and agility are all types of changeability, enumerated in the order of increasing system level context.

Flexibility means that an operation system is variable within a specific combination of in-, out- and throughput. The term is often used in the context of flexible manufacturing systems (Raouf and Ben-Daya 1995) and describes different abilities of a production system to handle changes in daily or weekly volume of the same product (volume flexibility) to manufacture a variety of products without major modification of existing facilities (product mix flexibility), to process a given set of parts on alternative machines (routing flexibility), or to interchange the ordering of operations (operation flexibility) on a given part (Suarez, *et al.*, 1991). Reconfigurability aims at the reuse of the original system's components in a new manufacturing system (Mehrabi 2000). It is focused on technical aspects of machining and assembly and is thus limited to single manufacturing workstations or cells (Zaeh, *et al.*, 2005). Changeability, in contrast, means the ability of an operation system to alter autonomously the configuration to meet new, previously unknown demands e. g. from the market as quickly as the environmental changes (Blecker and Graf 2004). Agility is an enterprise-wide concept incorporating product design as well as manufacturing systems design and aiming at lean and often dislocated manufacturing processes. In this paper it is supposed that the ability to transform and adapt a company or a production system to new circumstances, generally claimed by more recent definitions of changeability, is too narrow and passive to describe today's companies' necessity to proactively adapt to changing technologies and market requirements. Thus, in the following short literature review the focus will be given to the concept of agile manufacturing and agility.

Agile manufacturing emerged after lean production and can be defined as an enterprise level manufacturing strategy of introducing new products into rapidly changing markets and an organisational ability to thrive in a competitive environment characterized by continuous and unforeseen change (Groover 2001). A study in 1991 observed that the pace of change in technologies and markets had suddenly gotten ahead of the typical enterprise's ability to keep up (Nagel, *et al.*

1991). Flexible systems that could respond in multiple pre-planned ways had become inadequate (Matt 2005). The nature of future requirements could not be sufficiently predicted to have a preplanned response on hand. The new approach of agile manufacturing focused on the extension of the useful life of existing manufacturing systems, re-tasking them rather than replacing them, reconfiguring them rather than redesigning them (Dove 2006). An agile manufacturing system shifts quickly among product models or between product lines, ideally in real-time response to customer demand (Yusuf, *et al.*, 1999), using a toolbox of well-known techniques and methods such as lean manufacturing, Total Quality Management TQM or Business Process Engineering (Zach, *et al.*, 2005). The concept of agile manufacturing involves more than just manufacturing. It addresses a company's organisational structure, the impact of people and information, partnerships with other organisations and relationships with customers (Goldman, *et al.*, 1995). Thus, it might be more appropriate to talk about "agility" (Groover 2001).

However, agility acts too loosely with concerns of production systems. The suggested method to combine various concepts is not generally being expected to work in practice (Gunasekaran, *et al.*, 2002). The claimed ability for operations, to adapt quickly on changes also focuses only on the change in customers' needs. Contrariwise, operations also have to (re-)act to changes in the technological and competitive environment. Nonetheless, the objectives of agile manufacturing are valid. But they are too widespread on different functions within the enterprise. Agility is much concerned with effectiveness, but in practice a combination of TQM, MRPII, CIM, and Business Process Reengineering would be costly and surely not efficient. Therefore, a concept for the implementation of rapid changes is necessary, that also respects efficiency concerns in the operation system.

The objective of this paper is thus to present an integrated and comprehensive approach for a system "(re-)design to agility" which provides the system designer with a good guidance and the right questions rather than a collection of different tools and methodologies.

3 The Mechanisms of System Complexity

Unlike flexible systems, agile ones are expected to be capable of actively varying their own structure. Due to the unpredictability of change, they are not limited to a pre-defined system range typical for so called flexible systems but are required to shift between different levels of systems ranges (Spath and Scholz 2007).

3.1 The Principles of Axiomatic Design

According to the principles of Axiomatic Design (Suh 2001), the flexibility range can be described by a set of functional requirements in the so called functional domain, represented by a vector {FR}. In the design domain, the design parameters express how to satisfy the functional requirements. They are also described by a vector {DP}. The Design Matrix [DM] describes the relationship between FRs and DPs in a mathematical equation:

$$\{\text{FR}\} = [\text{DM}]\{\text{DPs}\} \quad (1)$$

The goal of a production system design decision is to make the system range inside the design range (Suh 2006). The information content I of a system with n FRs is described by the joint probability that all n FRs are fulfilled by the respective set of DPs. The information content is measured by the ratio of the common range between the design and the system range (Suh 2001).

A production system can be defined as a dynamic system, because it is subject to temporal variation and must be changeable on demand (Cochran, *et al.*, 2000; Matt 2006). Market and strategy changes will influence its system range of functional requirements and therefore impact the system's design (Reynal and Cochran 1996). The complexity of any dynamic system is determined by the uncertainty in achieving the system's functional requirements (Suh 2005) and is caused by two factors (Matt 2007): by a time-independent poor design that causes a system-inherent low efficiency (system design), and by a time-dependent reduction of system performance due to system deterioration or to market or technology changes (system dynamics).

3.2 The Elements of System Complexity

Thus, the methodology presented in the following provides two steps based on the AD complexity theory (see also Fig. 1): First, the system is designed to fulfil the time-independent requirements of efficiency and flexibility within a "predictable" planning horizon of 6 to 24 months (Rother and Shook 1998; Matt 2006).

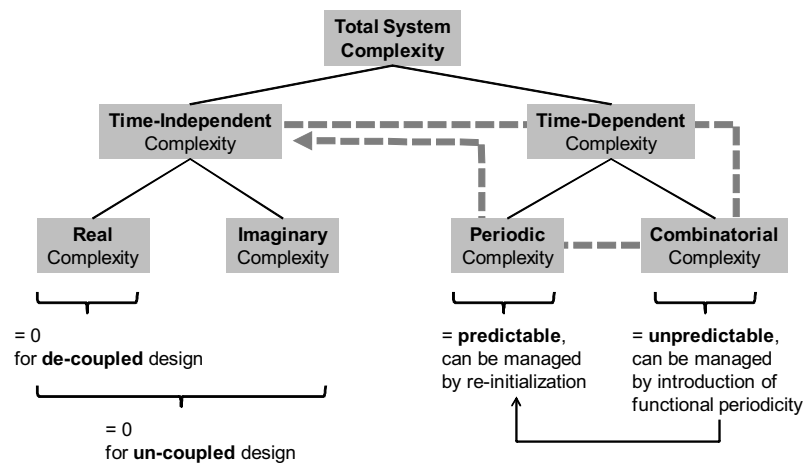


Fig. 1. The structure of system complexity

This design step uses the approach of the production module templates (Matt 2008). In a second step, a (time-dependent) agility strategy is elaborated to allow a quick shift to another (nearly) time-independent system level.

3.2.1 Efficiency and Flexibility: Reduce Time-Independent Complexity

The total time-independent complexity of a system is a measure for a system's ability to satisfy a set of functional requirements without worrying about time-dependent changes that might influence the system's behaviour. Thus, the main target of system design must be the reduction of the time-independent complexity which consists of two components: a time-independent real complexity (shortly: real complexity) and a time-independent imaginary complexity (shortly: imaginary complexity). The real complexity tells if the system range is inside or partly or completely outside the system's design range (see also Fig. 2).

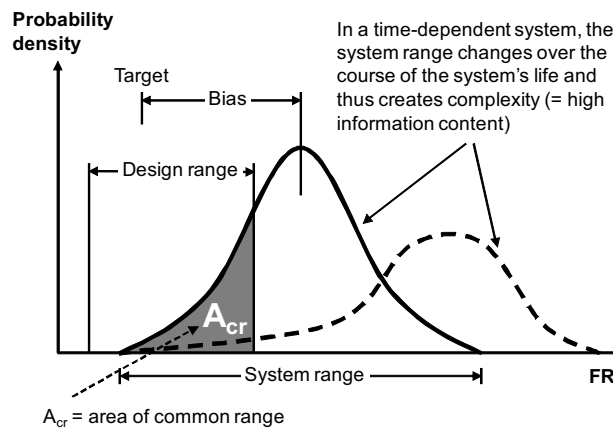


Fig. 2. The area of common range A_{cr} (Suh, 2001)

The imaginary complexity results from a lack of understanding of the system design, in other words the lack of knowledge makes the system complex (Suh 2005).

The probably most important step in Axiomatic design is the definition of the first level of FRs. It requires a very careful analysis of the customer needs regarding the design of the production systems.

The translation of the customer attributes (CAs) into FRs is very important and difficult at the same time, because the quality of the further design depends on the completeness and correctness of the chosen CAs. According to generally accepted notions (Womack and Jones 2003; Bicheno 2004) regarding a production systems objective system, the following three basic CAs can be identified:

- CA1: Maximize the customer responsiveness (according to the 6 "Rs" in logistics: the right products in the right quantity and the right quality at the right time and the right place and at the right price)
- CA2: Minimize the total manufacturing cost per unit
- CA3: Minimize inventory and coordination related costs

Starting from these basic CAs, the following generally applicable FRs for production system design can be derived:

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- FR1: Produce to demand
- FR2: Realize lowest possible unit cost
- FR3: Realize lowest possible overhead expenses

The design parameters mapped by functional requirements are:

- DP1: Only consistent increments of work demanded by customers are released
- DP2: Manufacturing stations are designed for low cost production
- DP3: Strategy to keep inventory and coordination related costs at the lowest possible level

The design matrix provides a decoupled design (triangular design matrix) as shown in the following equation:

$$\begin{Bmatrix} \text{FR1} \\ \text{FR2} \\ \text{FR3} \end{Bmatrix} = \begin{bmatrix} X & 0 & X \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \cdot \begin{Bmatrix} \text{DP1} \\ \text{DP2} \\ \text{DP3} \end{Bmatrix} \quad (2)$$

Since the design solution cannot be finalized or completed by the selected set of DPs at the highest level, the FRs need to be decomposed further. This decomposition is done in parallel with the zigzagging between the FRs and DPs (Suh 2001; Cochran, *et al.* 2002).

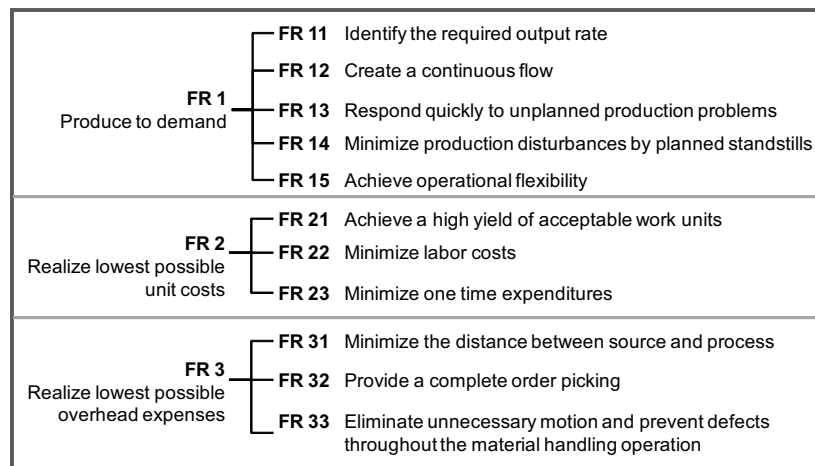


Fig. 3. Second level FR-tree

The so developed 2nd level FR-tree is shown in Fig. 3. It already shows a level of detail which indicates potential areas of time-dependency that will be discussed in the next section. However, interested readers are referred to (Matt 2006, and Matt 2009) for more detailed information about the next FR and DP levels.

3.2.2 Agility: Control Time-Dependent Complexity

Time dependent system complexity has its origins in the unpredictability of future events that might change the current system and its respective system range. The shifting between different levels of system ranges cannot be controlled by the normal flexibility tolerances provided in a production system design. It is subject to system dynamics and thus has to be handled within the domain of time-dependent complexity. According to Suh (2005), there are two types of time-dependent complexities:

The first type of time-dependent complexity is called periodic complexity. It only exists in a finite time period, resulting from a limited number of probable combinations. These probable combinations may be partially predicted on the basis of existing experiences with the system or with a very systematic research of possible failure sources, e.g. with FMEA (Matt 2007).

The goal of a production system design is to make the system range lie inside the design range (see also Fig. 2). The information content I of a system with n FRs is described by the joint probability that all n FRs are fulfilled by the respective set of DPs. The information content is measured by the ratio of the common range between the design and the system range (Suh 2006). However, a system might deteriorate during its service life and its design range will move outside the required system range. In this case, the system's initial state must be established by re-initialization.

The second type of time-dependent complexity is called combinatorial complexity. It increases as a function of time proportionally to the time-dependent increasing number of possible combinations of the system's functional requirements. It may lead to a chaotic state or even to a system failure. The critical issue with combinatorial complexity is that it is completely unpredictable. Combinatorial complexity can be reduced through re-initialization of the system by defining a functional period (Suh 2005).

A functional period is a set of functions repeating itself on a regular time interval, like the one shown in Fig. 3. Organisational systems – e.g. a production system – need (organisational) functional periodicity. When they do not renew themselves by resetting and reinitializing their functional requirements, they can become an entity that wastes resources (Suh 2005).

To maximize the operational excellence of a production system in order to provide its transformability to unforeseen changes, the system must be designed to satisfy its FRs at all times. Ideally, such a system has zero total complexity, i.e. both time-independent and time-dependent complexity. Once the production system has been designed according to the above described principles of time-independent complexity reduction, its time-dependent complexity has to be reduced in order to manage unpredictable shifts between different levels of the production system's range of functional requirements. To design an agile production system, the time-dependent combinatorial complexity must be changed into a time-dependent periodic complexity by introducing a functional periodicity. If the functional periodicity can be designed in at the design stage, the system's changeability will be more robust than in any other system (Suh 2005).

4 Practical Example

Starting from the previously outlined Axiomatic Design based complexity theory, a long-term study performed in a medium sized industrial company investigated the effects of economic periodicity as a trigger for a regular organisational reset on the agility and performance of a production system (see Fig. 4).

The sinus interval of the organisational functional periodicity of the production system was first determined on the basis of the analysis of historical data (30 years) and the related events. Due to product program related efficiency losses, a new production system was designed and introduced in the period 2000-2001 (see also Matt 2004). Due to the new design the production system's performance could be increased noticeably.

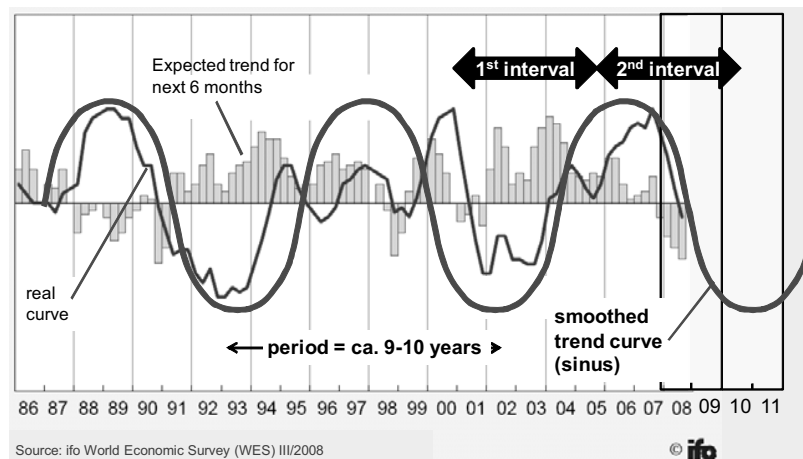


Fig. 4. Economic periodicity drives a production system's functional periodicity

However, due to a market driven explosion of product variants the production system showed a noticeable increase of the average work in progress, quality problems, and efficiency losses already during the first interval of the research period (2000-2005): the system range had moved partly outside the design range due to time-dependent combinatorial complexity. So the decision was taken to make a reset of the cycle for those design parameters, whose functional requirements had been changed over time (FR 11, FR 21, FR 22, FR 31 and FR 33; see also Fig. 3). Due to the redesign of the single assembly-cells walking and handling could be reduced and quality problems were eliminated. As a final result, productivity could be improved by 18% on top of the already high level of performance with nearly no investments and a noticeable improvement of first time quality. The continuous performance monitoring now shows, that from the reset in 2006 to now the system has again lost performance due to changes caused by combinatorial complexity. Thus, it is currently redesigned in order to introduce the next big change in 2010.

5 Summary

Organisational functional periodicity is a mechanism that enables the re-initialization of an organisation in general and of a production system in particular. It is the result of converting the combinatorial complexity caused by the dynamics of socioeconomic systems into a periodic complexity problem of an organisation.

Starting from the Axiomatic Design based complexity theory, this paper investigates on the basis of a long-term study performed in an industrial company the effects of organisational periodicity as a trigger for a regular organisational reset on the agility and the sustainable performance of a production system.

The main findings of this research can be summarised as follows: organisational functional periodicity depends on environmentally triggered socio-economic changes. The analysis of the economic cycle shows high degrees of periodicity, which can be used to actively trigger a company's action for change, before market and environment force it to. Along an economic sinus interval of about 9 to 10 years, sub-periods are defined that trigger the re-initialization of a production system's set of FRs and thus establish the system's agility. Future research will now concentrate on the investigation of mechanisms that determine an industry's or company's individual length of the cyclic sub-periods.

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