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Axiomatic design of Agile manufacturing systems

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1. Introduction

The trend of shifting abroad personnel-intensive assembly from Europe to foreign countries continues. Manufacturing systems widely differ in investment, demand and output. Since sales figures can hardly be forecasted, it is necessary to conceptualize highly flexible and adaptable systems which can be upgraded by more scale-economic solutions during product life cycle, even under extremely difficult forecasting conditions. 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.

Modern manufacturing systems are increasingly required to be adaptable to changing market demands, which adds to their structural and operational complexity (Matt, 2005). Thus, one of the major challenges at the early design stages is to select an manufacturing system configuration that allows both – a high efficiency due to a complexity reduced (static) system design, and a enhanced adaptability to changing environmental requirements without negative impact on system complexity.

Organizational functional periodicity is a mechanism that enables the re-initialization of an organization in general and of a manufacturing 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 organization.

Starting from the Axiomatic Design (AD) based complexity theory this chapter investigates on the basis of a long-term study performed in an industrial company the effects of organizational periodicity as a trigger for a regular organizational reset on the agility and the sustainable performance of a manufacturing system.

Besides the presentation of the AD based design template which helps system designers to design efficient and flexible manufacturing systems, the main findings of this research can be summarized as follows: organizational 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 years, sub-periods are defined that trigger the re-initialization of a manufacturing system's set of FRs and thus establish the system's agility.

2. Agility – an Answer to Growing Environmental Complexity

The actual economic crash initiated by the subprime mortgage crisis has been leading to another global follow-up recession. Most enterprises are struggling with overcapacities caused by an abrupt decrease in market demand, and our industrial nations – traditional sources of common wealth in our "old world" – are groaning under the burden of mountains of debts. But did this crisis really come surprisingly?

The answer is no, although nobody could exactly determine its starting point in time. In fact, the economic cycle is a well-known phenomenon. Often new business opportunities created by a new technology (e.g. digital photography, GPS, smart items, photovoltaic cells, etc.) or some "hypes" such as the "dotcoms" in the late 90s may trigger an economic boom. Initially, wealth is created when growing market demand for new or "hip" products generates new jobs and promotes productivity and growth. However, quantitative economic growth is limited (Matt, 2007) and when it turns to be artificially maintained on an only speculative basis, the economic system is going to collapse.

Analyzing analogical behaviors in natural and other systems, we understand that the reason for this lays in the interaction of a system's elements in terms of causal or feedback loops (O'Connor & McDermott, 1998). System growth is driven by positive (or escalating) causal loops (Senge 1997). Even an exponential growth of a system is limited, either by the system's failure or collapse (for example, the growth of cancer cells is limited by the organism's death) or by negative feedback loops (for example, a continuous growth of an animal population is stopped by a limited availability of food, see Briggs & Peat 2006).

To maintain stability and survivability, a growing system needs to establish subsystems that are embedded in a superior structure (Vester 1999). Life on earth has not been spread all over the earth ball as a simple mash of organic cells but started to structure and differentiate, that is to grow qualitatively. A randomized cross-linking of the system components will inevitably lead to a stability loss. Thus, a system can overcome its quantitative growth limits only by qualitative growth, establishing a stabile network structure with nodes that are subject to cell division as soon as they reach a critical dimension.

2.1 The Mechanisms of Complexity

A system's ability to grow depends to a considerable extent on its structure and design. Its design is "good" if it is able to fulfill a set of specific requirements or expectations.

An entrepreneur or an investor for instance expects that a company makes profit and that it increases its value. The entrepreneurial risk expresses the uncertainty that these targets or expectations are fulfilled, especially over time when environmental conditions change and influence the system design. The complexity of a system is determined by the uncertainty in achieving the system's functional requirements (Suh 2005) and is caused by two factors: 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).

To enable a sustainable and profitable system growth, its entire complexity must be reduced and then be controlled over time. To reduce a system's complexity, its subsystems should not overlap in their contribution to the overall system's functionality, they must be mutually exclusive. On the other hand, the interplay of system components must be collectively

exhaustive in order to include every issue relevant to the entire system's functionality. Finally, this procedure has to be repeated over time as changes in the system's environments might impact its original design and thus lead to a loss in efficiency and competitiveness.

The **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 behavior. It consists of two components: a time-independent real **complexity** and a time-independent **imaginary complexity**. The real complexity tells if the system range is inside or partly or completely outside the system's design range. The imaginary complexity results from a lack of understanding of the system design, in other words the lack of knowledge makes the system complex. If the system is designed to always fulfill the system requirements, that is the range of the system's functional requirements (system range) is always inside the system's range of design parameters (design range), it can be defined a "good" design. This topic will be treated in more detail in a following section.
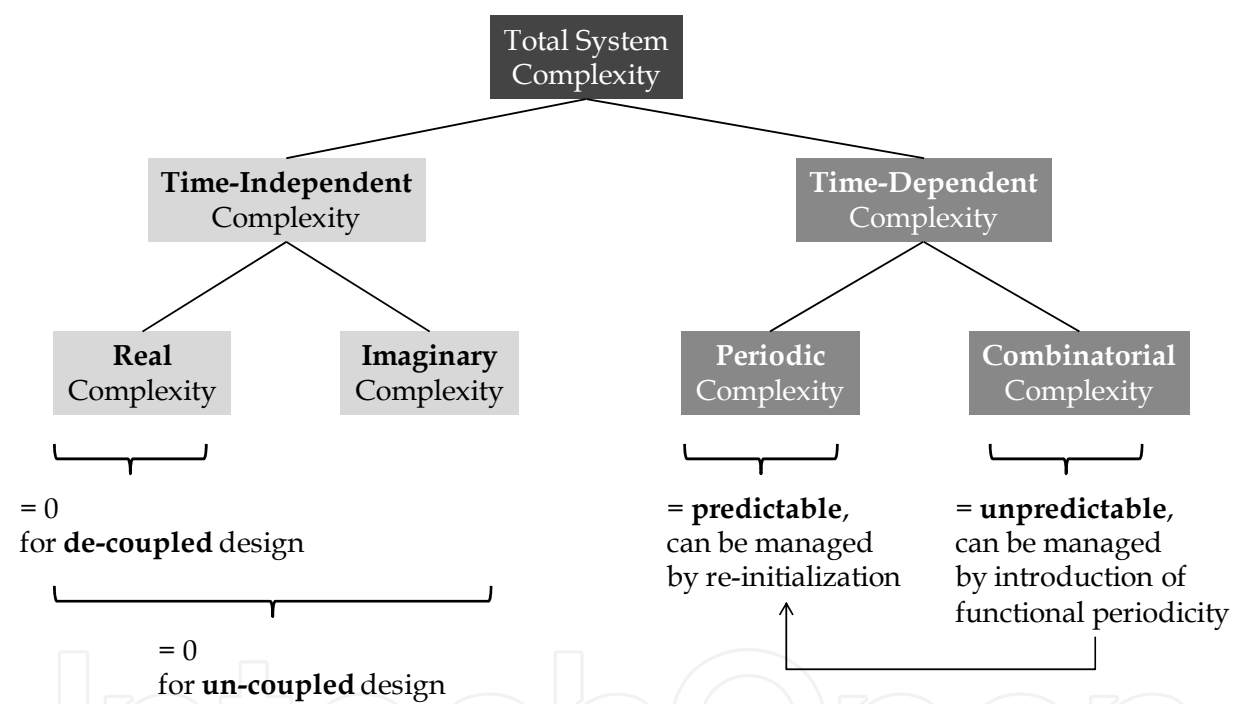

Fig. 1. Elements of the Axiomatic Design Based Complexity Theory

Time dependent system complexity has its origins in the unpredictability of future events that might change the current system. There are two types of time-dependent complexities (Suh 2005): 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.

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. This may lead to a chaotic

state or even to a system failure. The critical issue as to combinatorial complexity is that it is completely unpredictable.

According to Nam Suh, the economic cycle is a good example of time-dependent combinatorial complexity at work (Suh, 2005). To provide stabile 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".

2.2 Agility

In recent scientific publications, terms like flexibility (De Toni & Tonchia, 1998), reconfigurability (Koren et al., 1999), agility (Yusuf et al., 1999) and more recently changeability (Wiendahl & Heger, 2003) or mutability (Spath & 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 and describes different abilities of a manufacturing 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). Agility as the highest order of a system's 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 & Graf, 2004).

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 & Scholz, 2007).

2.3 The Principles of Axiomatic Design (AD)

The theory of Axiomatic Design was developed by Professor Nam P. Suh in the mid-1970s with the goal to develop a scientific, generalized, codified, and systematic procedure for design. Originally starting from product design, AD was extended to many different other design problems and proved to be applicable to many different kinds of systems. Manufacturing systems are collections of people, machines, equipment and procedures organized to accomplish the manufacturing operations of a company (Groover, 2001). As system theory states, every system may be defined as an assemblage of subsystems.

Accordingly, a manufacturing system can be seen as an assemblage of single manufacturing stations along the system's value stream (Matt, 2006).

The Axiomatic Design world consists of four domains (Suh, 2001): the customer domain, the functional domain, the physical domain and the process domain.

The customer domain is characterized by the customer needs or attributes (CAs) the customer is looking for in a product, process, system or other design object. In the functional domain the customer attributes are specified in terms of functional requirements (FRs) and constraints (Cs). As such, the functional requirements represent the actual objectives and goals of the design. The design parameters (DPs) express how to satisfy the functional requirements. Finally, to realize the design solution specified by the design parameters, the process variables (PVs) are stated in the process domain (Suh, 2001). For the design of manufacturing systems the physical domain is not needed (Reynal & Cochran, 1996).

Most system design tasks are very complex, which makes it necessary to decompose the problem. The development of a hierarchy will be done by zigzagging between the domains. The zigzagging takes place between two domains. After defining the FR of the top level a design concept (DP) has to be generated.

Within mapping between the domains the designer is guided by two fundamental axioms that offer a basis for evaluating and selecting designs in order to produce a robust design (Suh, 2001):

- **Axiom 1: The Independence Axiom.** Maintain the independence of the functional requirements. The Independence Axiom states that when there are two or more FRs, the design solution must be such that each one of the FRs can be satisfied without affecting the other FRs.
- **Axiom 2: The Information Axiom.** Minimize the information content I of the design. The Information Axiom is defined in terms of the probability of successfully achieving FRs or DPs. It states that the design with the least amount of information is the best to achieve the functional requirements of the design.

The FRs and DPs are described mathematically as a vector. The Design Matrix [DM] describes the relationship between FRs and DPs in a mathematical equation (Suh, 2001):

$$\{FR\} = [DM]\{DP\} \tag{1}$$

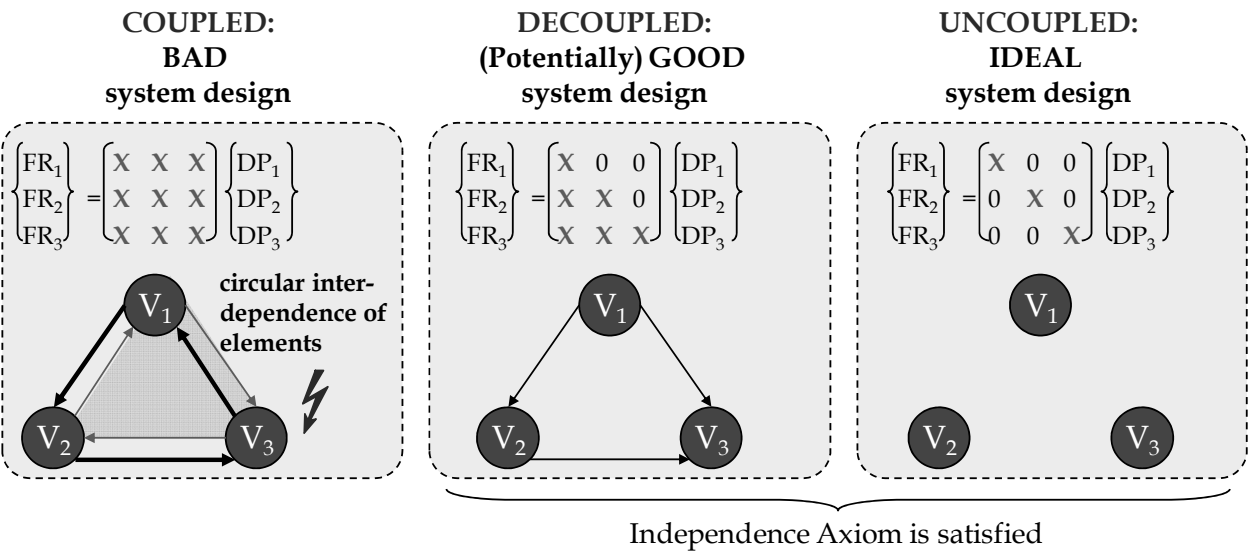With three FRs and three DPs, the above equation may be written in terms of its elements as:

$$
\begin{aligned}
FR_1 &= A_{11}\,DP_1 + A_{12}\,DP_2 + A_{13}\,DP_3 \\
FR_2 &= A_{21}\,DP_1 + A_{22}\,DP_2 + A_{23}\,DP_3 \\
FR_3 &= A_{31}\,DP_1 + A_{32}\,DP_2 + A_{33}\,DP_3
\end{aligned}
\tag{2}
$$

The goal of a manufacturing 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). To satisfy the Independence Axiom, the design matrix must be either

diagonal or triangular (Fig. 2). When the design matrix is diagonal, each of the FRs can be satisfied independently by means of exactly one DP. It represents the ideal case of an uncoupled system design where the design range of every single DP perfectly meets the system range of exactly one FR, irrespective of the sequence of the fulfillment of the functional requirements. This means, that the design equation can be solved without any restrictions. In this case, the above equation (2) may be written as:

$$
\begin{aligned}
FR_1 &= A_{11}\,DP_1 \\
FR_2 &= A_{22}\,DP_2 \\
FR_3 &= A_{33}\,DP_3
\end{aligned}
\tag{2.1}
$$

Both components of the time-independent complexity – the real complexity and the imaginary complexity – are zero, in other words: the total time-independent complexity of the system is zero (see also Fig. 1).

Fig. 2. Exemplary illustration of the Independence Axiom (Lee & Jeziorek, 2006)

When the matrix is triangular, the independence of FRs can be guaranteed if and only if the DPs are determined in a proper sequence. In the case of a decoupled design, which design range also fits the system range, the real complexity equals to zero, but the complexity consists in the uncertainty of fulfilling the design task due to different possible sequences. Thus, it depends on a particular sequence and represents a decoupled design creating a time-independent imaginary complexity. In terms of equation (2), this has the following consequence:

$$
\begin{aligned}
FR_1 &= A_{11}\,DP_1 \\
FR_2 &= A_{21}\,DP_1 + A_{22}\,DP_2 \\
FR_3 &= A_{31}\,DP_1 + A_{32}\,DP_2 + A_{33}\,DP_3
\end{aligned}
\tag{2.2}
$$

Any other form of the design matrix is called a full matrix and results in a coupled design.

3. Axiomatic Design of Agile Manufacturing Systems

A manufacturing system is 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 & Cochran, 1996). Considering for example a given production program, all possible product variants that can be manufactured at a certain point in time determine the static system complexity. However, the dynamic complexity is determined by the frequency and magnitude of changes of the production program when new product variants are introduced or eliminated. When both complexities are low, then the system is simple. In the case of a high (low) structural complexity and low (high) dynamic complexity, the system is considered to be complicated (relatively complex). When both complexities are high, then the system is said to be extremely complex (Ulrich & Probst, 1995). On the basis of these definitions, every approach aiming at the reduction of a system's complexity consequently has to focus on the redesign of the system elements and their relationships.

Following the considerations made in section 2.1, two general ways to attack the problems associated with complex systems can be identified. The first is to simplify them, the second to control them. Leanness is about the former in that it advocates waste removal and simplification (Naylor et. al., 1999). It aims at the complexity reduction of a system at a certain point in time. Thus, system simplification is about eliminating or reducing the time-independent complexity of a system. Agility is the ability to transform and adapt a manufacturing system to new circumstances caused by market or environmental turbulences (Zaeh et. al., 2005). Thus, complexity control is associated with the elimination or reduction of a system's time-dependent complexity. To adopt design strategies that consider Lean and Agility principles, it is important to introduce decoupling points. A material decoupling point is the point in the value chain to which customer orders are allowed to penetrate. At this point there is buffer stock and further downstream the product is differentiated. A very helpful tool in this context is value stream mapping, a key element of the Lean toolbox, which represents a very effective method for the visualization, the analysis and the redesign of production and supply chain processes including material flow as well as information flow (Rother & Shook, 1998). The methodology provides process boxes, which describe manufacturing or assembly processes following the flow principle, with no material stoppages within their borderlines. Ideally, a continuous flow without interruptions can be realized between the various assembly modules. However, most process steps have different cycle times and thus buffers (decouplers) have to be provided at their transitions for synchronization (Suh, 2001).

To define the functional requirements of a manufacturing system and to transform them into a good system design, Axiomatic Design (AD) is proposed to be a very helpful tool (Cochran & Reynal, 1999): the authors analyse the design of four manufacturing systems designs in terms of system performance and use the methodology to design an assembly area and to improve a machining cell at two different companies. However, the lifetime of such a design varies from 3 to 18 months (Rother & Shook, 1998). During this period, the design can be supposed to behave in a nearly time-independent way. Afterwards, it is again subject to changes. Thus, to maintain the efficiency of a manufacturing system design, also the time-dependent side of complexity has to be considered.

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

3.1 Efficiency and Flexibility: Reduce the Time-Independent Complexity

One of the major goals of manufacturing system design is to reduce the time-independent real complexity to zero. The real complexity is a consequence of the system range being outside of the design range. If the system design is coupled it is difficult to make the system range lie inside the design range. Therefore, the following procedure is recommended:

First, the system designer must try to achieve an uncoupled or decoupled design, i.e. a design that satisfies the Independence Axiom.

Then, every DP's design range has to be fitted and adapted into the corresponding FR's system range. This way, the system becomes robust by eliminating the real complexity. The imaginary complexity rises with the information content of the design. In an uncoupled design, the information content is zero and so an imaginary complexity does not exist. However, in the case of a decoupled design, the designer has to choose the best solution among different alternatives, which is the one with the less complex sequence.

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 manufacturing systems.

The translation of the 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 manufacturing 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 manufacturing system design can be derived:

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 level

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

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \end{Bmatrix} = \begin{bmatrix} X & 0 & X \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \cdot \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \end{Bmatrix} \tag{3}$$

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).

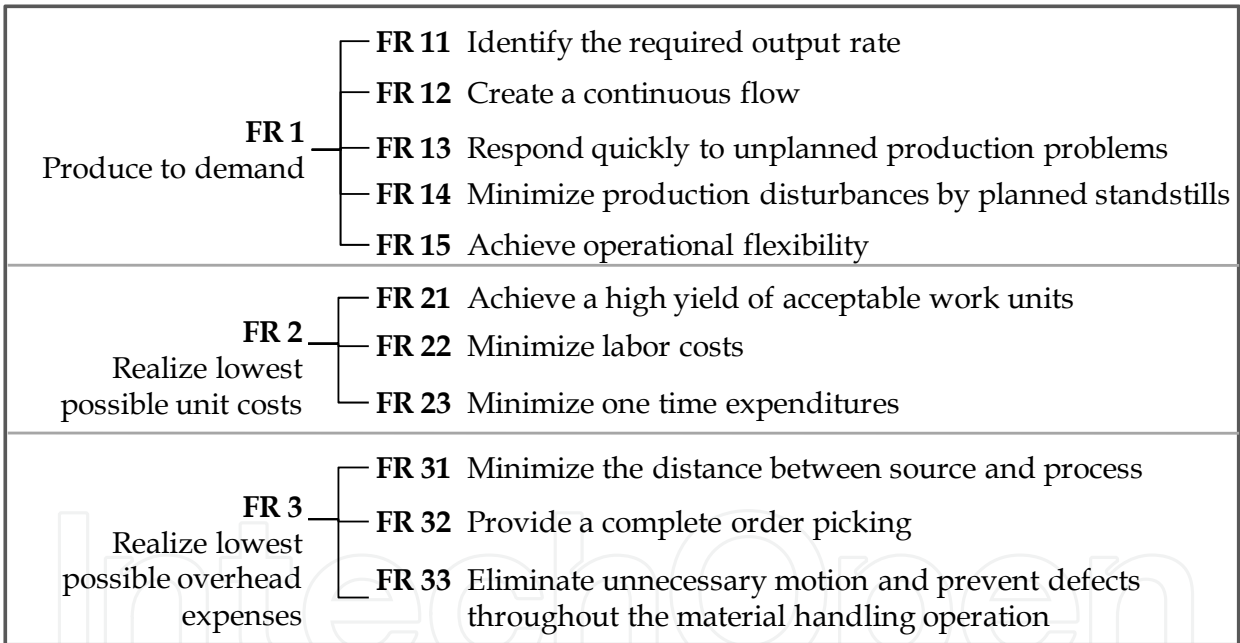|		
FR 1 Produce to demand	**FR 11**	Identify the required output rate
	FR 12	Create a continuous flow
	FR 13	Respond quickly to unplanned production problems
	FR 14	Minimize production disturbances by planned standstills
	FR 15	Achieve operational flexibility
FR 2 Realize lowest possible unit costs	**FR 21**	Achieve a high yield of acceptable work units
	FR 22	Minimize labor costs
	FR 23	Minimize one time expenditures
FR 3 Realize lowest possible overhead expenses	**FR 31**	Minimize the distance between source and process
	FR 32	Provide a complete order picking
	FR 33	Eliminate unnecessary motion and prevent defects throughout the material handling operation

Fig. 3. Second level decomposition of the FR-tree (Matt, 2009/a)

The so developed 2nd level FR-tree is shown in Fig. 3. By doing the zigzagging between FRs and DPs, as done on the first level, the DPs for the second level corresponding to FR-2 can be identified in order to maximize independence (Matt, 2006):

DP-11   Determine and produce to takt time (for details see: Matt, 2006 and Matt, 2008)
DP-12   (a) *Single model case*: no significant variations, sufficient volumes to justify the dedication of the system to the production of just one item or a family of nearly identical items. Introduction of process-principle (multi-station system) if sequentially arranged stations can be balanced to in-line continuous flow.

(b) *Batch model case*: Different parts or products are made by the system. Batching is necessary due to long setup or changeover times

(c) *Mixed model case*: different parts or products are made by the system, but the system is able to handle these differences without the need for setup or changeover.

(c.1) Introduction of process-principle (sequential multi-station system with fixed routing) if sequentially arranged stations can be balanced to in-line continuous flow independent from product variants and their production sequence.

(c.2) Introduction of object-principle if lead times of the single process steps vary widely and cannot be balanced (single-station system, eventually parallel stations if cycle times of the single station exceed the takt time). This is usually the case with a high complexity of the production program with very different variants.

DP-13   Visual control and fast intervention strategy (Introduction of TPM – Total Productivity Maintenance)

DP-14   Reduction and workload optimized scheduling of planned standstills (TPM)

DP-15   Setup reduction (Optimization with SMED – Single Minute Exchange of Die)

The effective design parameters (DPs) for FR-21, FR-22 and FR-23 are the following (Matt, 2006):

DP-21   Production with increased probability of producing only good pieces and of detecting/managing defective parts

DP-22   Effective use of workforce

DP-23   Investment in modular system components based on a system thinking approach

For FR-31, FR-32 and FR-33, the design parameters mapped by functional requirements are (Matt, 2009/b):

DP-21:   Short distances between material storage location and process

DP-22:   Design equipment and methods that allow handling and transport of the complete order set

DP-23:   Design equipment and methods that allow an effective and defect-free interaction between humans and material

The single level Design Matrices as well as the complete Design Matrix are decoupled. Interested readers are referred to (Matt, 2008) for more detailed information about the above described AD based template approach for manufacturing system design.
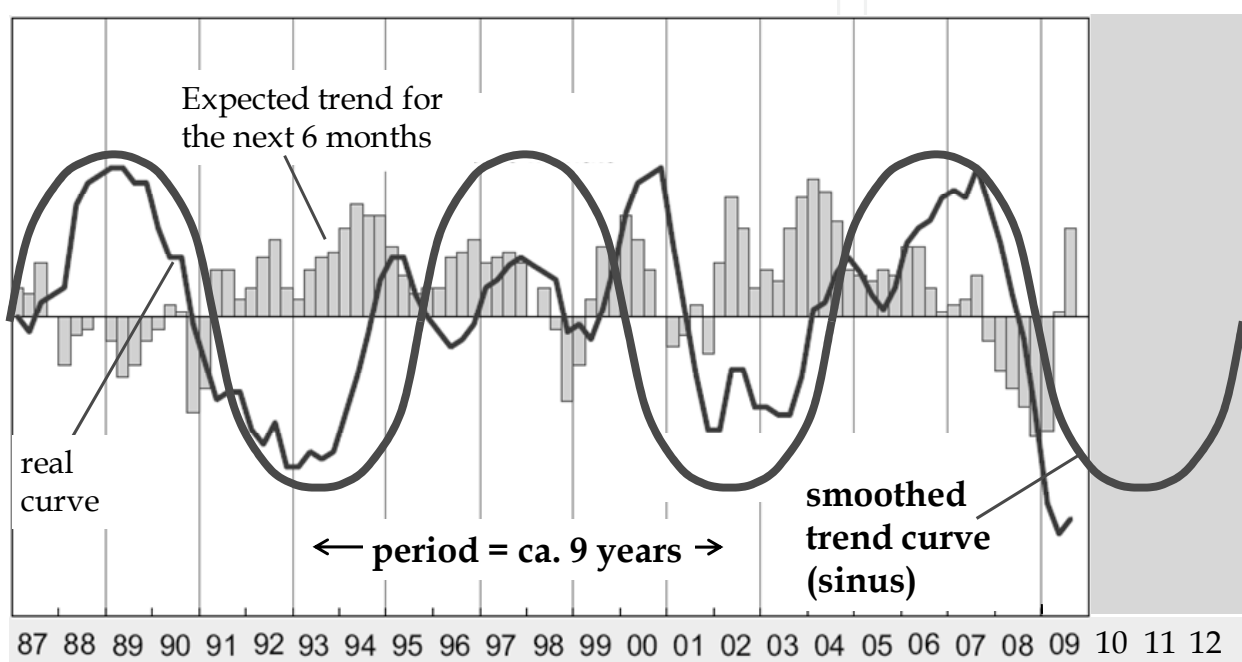
3.2 Agility: Control Time-Dependent Complexity

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 manufacturing 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:

As previously outlined, 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.

The goal of a manufacturing system design is to make the system range lie inside the design range. 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.

Source: ifo World Economic Survey (WES) III/2009

Fig. 4. The economic cycle drives an organization's functional periodicity (Matt, 2009/a)

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. 4 showing the periodicity of our economic system. Organizational systems – e.g. a manufacturing system – need (organizational) 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 manufacturing 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 manufacturing 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 manufacturing system's range of functional requirements.

To design an agile manufacturing 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).

It is important to anticipate the economic cycle in order to maintain competitiveness (Fig. 5). However, the average period of the economic cycle (ca. 9 years) might be too long for the company specific dynamics. The current research results obtained from the observation of good industrial practice show that a possible solution might be to introduce a sinus interval compressed by a 1/n factor (stretching constant), with for example n=2 or n=3. For n=2, this means that the re-organization cycle repeats about every 4-5 years, for n=3 this is 3 years.

4. Illustrative Example

To illustrate the previously described approach, an industrial example of a manufacturer of electrotechnical tools and equipment is discussed. For a recently developed and presented cable scissor, an efficient and flexible assembly system has to be designed: two scissor blades have to be joined with a screw, a lining disc and a screw nut; afterwards, the assembled scissor is packaged together with some accessories.

4.1 Efficiency and Flexibility: Reduce the Time-Independent Complexity

The first step is the elimination or reduction of the time-independent complexity. Thus, the design must first fulfill the Independence Axiom. According to the design template presented in section 3.1, the single model case is chosen: the product has no significant variations and sufficient volumes to justify the dedication of the system to the assembly of just one item or a family of nearly identical items.

To meet the required takt time, a semi-automatic screwing device is provided as first station in a two-station assembly system. However, to create a robust system, the real complexity has to be reduced or eliminated by fitting the DPs' design range to the corresponding FRs' system range. Thus, a dynamometric screwdriver is applied which torque tolerance fits the required system range. To evade the problem of imaginary complexity, the system design has to be uncoupled. In an inline multi-station assembly system, this requirement can be achieved by introducing de-couplers (buffers) between the single stations.

However, buffers have the negative effect to create an increase of handling and therefore a loss in the system's efficiency. A possible solution to decouple an assembly system and at the same time maintain a low level of non value adding activities is the so called "moving fixture" for workpieces (Lotter et al., 1998).

It consists of a base plate with holding fixtures to clamp the single workpieces and is manually or automatically moved on a belt conveyor from one to the next station. To decouple the line, several of these moving fixtures form a storage buffer between the single assembly stations.

4.2 Agility: Control Time-Dependent Complexity

The next step is to reduce and control the system's time-dependent complexity. The new designed 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. This can be done by defining fixed maintenance intervals or by regular or continuous tool monitoring, where the status of the screwing unit is determined and the decision is taken whether to continue production, to maintain or even substitute the tool. In the specific case of the electrotechnical device manufacturer, the design range of the dynamometric screwdriver moves out of the scissors' system range and thus creates quality problems. To reduce or even eliminate this periodically appearing complexity (**periodic complexity**), regular checks of the screwing device are introduced.

However, the most critical aspect in system design is the **combinatorial complexity**. Being completely unpredictable, this type of complexity can be just controlled by transforming it into a periodic complexity. Combinatorial complexity mostly results from market or environmental turbulences that create extra organizational efforts.

As a socioeconomic system, a company is embedded in general economic cycles of upturn and downturn phases (Fig. 4).
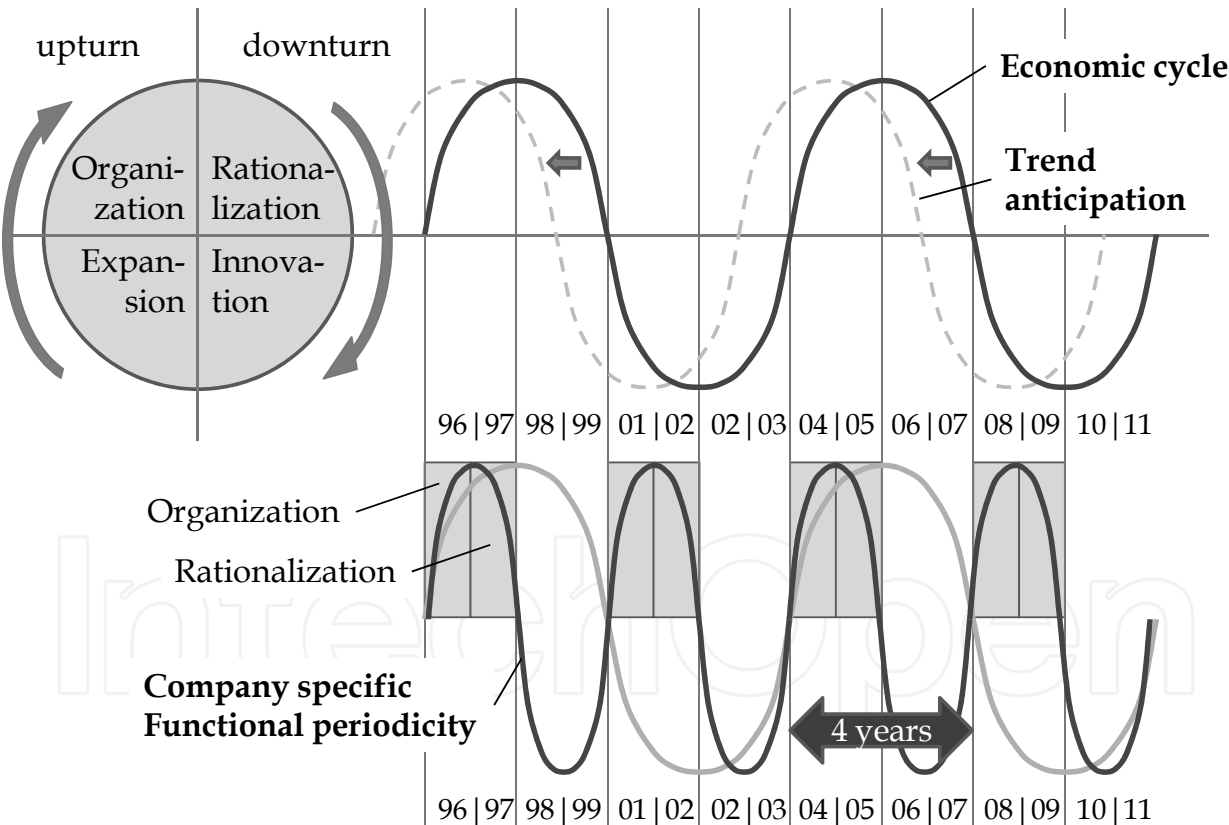

Fig. 5. Company specific functional periodicity of the manufacturing system

Obviously, every economic sector or even every single company has a different cyclic behavior regarding the timeline (Fig. 5). It passes always the following four stages: rationalization, innovation, expansion and organization. The company individual adaptation is given by the mapping of this generally applicable cycle along the timeline as a sinus curve (Matt, 2009/a). The company individual interval can be determined

heuristically, i.e. based on data and experiences from past. In our example, the company specific ideal sinus-interval of the manufacturing system's functional periodicity is 4 years (n=2). As far as research showed, it is determined very much by the average product life cycle and the related company specific innovation cycles.
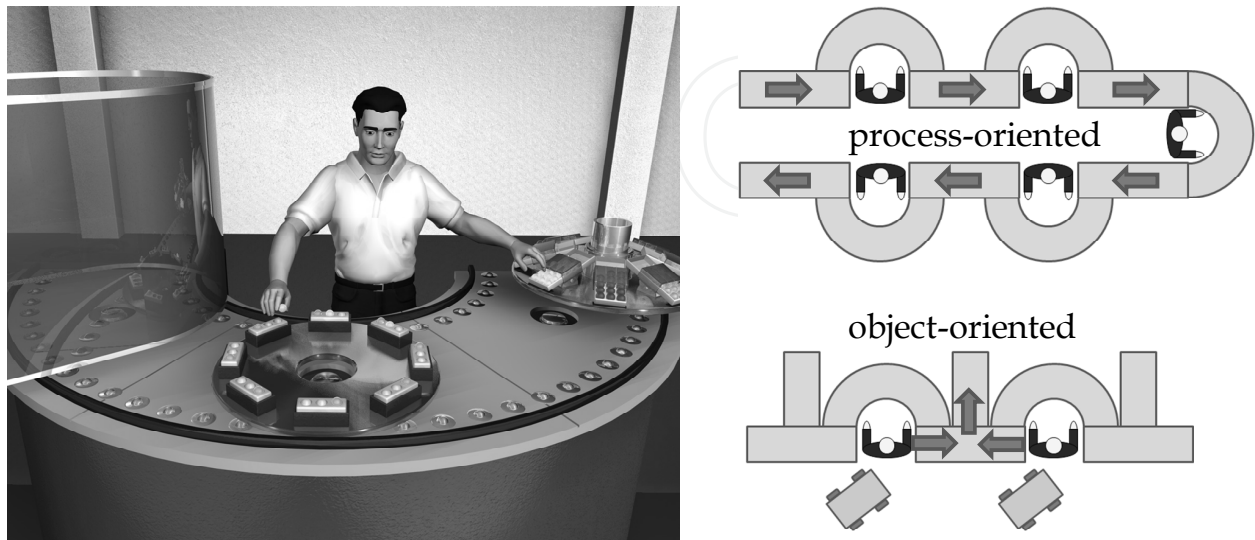

Fig. 6. One-set flow with moving fixtures plates in different flow-variants

Knowing the rhythm of change within a specific industry, suitable strategies for fast volume and variant adaptation can be developed, transforming combinatorial into the manageable periodic complexity. Fig. 6 shows for the present example the re-initialization strategy for the current process-oriented manufacturing system design (Spath & Scholz, 2007): as the number of variants shows a significant increase, a switch of DP-12 towards a mixed-model case c.1 or c.2 is possible.

5. Conclusion

In this chapter, a concept for the integrated design of efficient, flexible and changeable manufacturing systems was discussed. Starting from the AD based complexity theory, a procedure was presented that helps system designers not only to design assembly 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: agility). Future research will concentrate on a more sophisticated determination of the stretching constant in the company individual sinus-curve-model.

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Future Manufacturing Systems

Edited by Tauseef Aized

This book is a collection of articles aimed at finding new ways of manufacturing systems developments. The articles included in this volume comprise of current and new directions of manufacturing systems which I believe can lead to the development of more comprehensive and efficient future manufacturing systems. People from diverse background like academia, industry, research and others can take advantage of this volume and can shape future directions of manufacturing systems.

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