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THE POWER OF SIMPLICITY: DESIGN OF FLEXIBLE, CHANGEABLE AND EFFICIENT ASSEMBLY SYSTEMS THROUGH SYSTEMATIC COMPLEXITY REDUCTION

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ABSTRACT

The complexity of an assembly 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 an assembly system, both factors must be considered in order to reduce the system's entire complexity [1]. The presented approach provides methodological guidance in the systematic complexity reduction and in the development of efficient, flexible and changeable assembly systems. Thus, it accelerates the planning process and increases quality of the planning results. With the help of practical applications in different industries and the obtained results, the validity of the approach is illustrated.

Keywords: Complexity reduction, assembly systems, system design.

1. INTRODUCTION

Modern assembly systems are increasingly required to be flexible and adaptable to changing market demands, which adds to their structural and operational complexity. One of the major challenges at the early design stages is to select an assembly system configuration that both satisfies the production functional requirements and is easy to operate and manage [2], especially in terms of its adaptability to changing environmental factors.

2. LITERATURE REVIEW

The term complexity is basically discussed in connection with the system theory and is referred to as a system attribute [3]. A system consists of subsystems or elements and the existing relationships between them [4]. The complexity of a system is defined with respect to the complexity variables, namely number, dissimilitude and states' variety of the system elements and relationships [5]. These variables enable one to make the distinction between static and dynamic complexity. Whereas static complexity describes the system structure at a defined point in time, dynamic complexity represents the change of system configuration in the course of time. Considering 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 [6]. 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 [1].

There are two general ways to attack the problems associated with complex systems. The first is to simplify them, the second to control them. Leanness is about the former in that it advocates waste removal and simplification [7]. 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. Changeability is the ability to transform and adapt a production system or assembly system as a part of it to new circumstances caused by market or environmental turbulences [8]. 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 Changeability 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 [9]. 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 [10]. The methodology provides process boxes, which describe manufacturing or assembly processes following the flow principle, with now material stoppages within their borderlines. In [11], these process boxes are defined as production modules. Accordingly, in the specific case of in assembly systems the single assembly process boxes can be defined as assembly modules. 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 [12]. To define the functional requirements of an assembly system and to transform them into a good system design, Axiomatic Design (AD) is proposed to be a very helpful tool [13]: 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 [10]. 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 an assembly system design, also the time-dependent side of complexity has to be considered. However, most research work in the area of lean manufacturing and assembly system design falls into one of two main categories. On the one hand, there are several works presenting high-level ideas and concepts about what makes a manufacturing system "lean" [15], [16], [17], [18]. On the other hand, some papers examine a few very specific issues involved in designing cellular systems, generally treating the cell design process purely as the selection and grouping of machines into cells [19], [20], [21]. As more and more turbulence factors become important, the problem of adapting an existing system design to continuously changing market and environmental requirements opens the need for a methodological support.

This paper investigates how the total complexity of an assembly system can be reduced. Thus, it considers both: the time-dependent and the time-independent complexity of an assembly system.

3. PROPOSED MODEL

According to Nam P. Suh, most complexity theories deal with the complexity of a system in its physical domain [14]. The physical domain contains the design solutions or design parameters (DPs) to satisfy the functional requirements (FRs) that describe the design goals for the system. Complexity problems can be difficultly solved in the physical domain, because every change of the elements and their relationships aiming at the reduction of the system's complexity might influence the overall system's behavior in an uncontrollable way due to the system designer's lack of understanding of the system's architecture. To provide a general theoretical framework for solving complexity problems in engineering and in production related areas, Nam P. Suh defined complexity narrowly as a measure of uncertainty in achieving a set of design goals that a system must satisfy. Thus, complexity must be measured in the functional domain.

The underlying hypothesis of AD is that there exist fundamental principles that govern good design practice. The main components of AD are domains, hierarchies, and design axioms. Two basic axioms are distinguished:

Axiom 1. Maintain the independence of the functional requirements.

Axiom 2. Minimise the information content of the design.

The design world consists of four domains: customer, functional, physical and process. Through an iterative process called zigzagging, the design process converts customer's needs (CNs) into Functional Requirements (FRs) and constraints (Cs), which in turn are embodied into Design Parameters (DPs). DPs determine the Process Variables (PVs). The decomposition process starts with the decomposition of the overall functional requirement – in practice this should correspond to the top system requirement. Before decomposing to a lower level, the DPs must be determined for that level in the physical domain.

FRs and DPs are represented by vectors, their relationship by an n-dimensional matrix. In the special case of a one-to-one direct relationship between FRs and DPs, this matrix is reduced to a purely diagonal matrix which guarantees that every single DP just fulfils one FR. In an ideal system design, these elements are autonomous, they have no interrelations. Such a design is called an uncoupled design. The off-diagonal elements are represented by arrows. They show that the fulfilment of the diagonal element at the start of the arrow influences the elements at the end of the arrow. The worst case is a circular independence. This is the case in a coupled design and it means a bad system design [22].

In the case of a triangular matrix circular independence does not exist and therefore the design might be potentially good, although not an ideal design. This case is called a decoupled design. It is obvious that it is very difficult or sometimes quite impossible to really obtain an ideal design.

3.1 Procedure

The first step towards the design of flexible, changeable and efficient assembly systems through a consequent focus on complexity reduction is the development of a suitable procedure to reduce or eliminate time-independent and time-dependent complexity. Again, AD is used to do this in a very systematic and straight-forward way. First, the functional requirements are defined:

FR1: Reduce or eliminate the time-independent complexity of the assembly system
FR2: Reduce or eliminate the time-dependent complexity of the assembly system

The relative design parameters mapped by functional requirements are:

DP1: Design the system according to the Independence Axiom
DP2: Make a periodical check whether the design range has moved outside the system range. Eventually reinitialize the system.

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

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix}$$

FR-1 is the first FR to be done in order to improve a process; therefore it will be decomposed first to determine what the functional requirements are for reducing the time-independent complexity.

FR11: Reduce or eliminate the time-independent real complexity
FR12: Reduce or eliminate the time-independent imaginary complexity

By doing the zigzagging between FRs and DPs, as done on the first level, the DPs for the second level were identified in order to maximize independence.

DP11: Try to achieve an uncoupled or a decoupled design matrix by choosing the right FRs
DP12: 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, choose the solution among different alternatives with the less complex sequence.

In the next step, DP2 will be decomposed.

FR21: Reduce or eliminate the time-dependent periodical complexity
FR22: Reduce or eliminate the time-dependent combinatorial complexity

The effective design parameters (DPs) are the following:

DP21: Identify periodically repeating system failures and introduce regular prevention measures
DP22: Introduce periodical system checks in order to see whether the system range still fits the system's design range. Eventually, the system has to be redesigned.

3.2 Time-Independent Complexity

One of the major goals of manufacturing system design should be 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 [1]:

(1) First, the system designer must try to achieve an uncoupled or decoupled design, i.e. a design that satisfies the Independence Axiom. In this, the production module template approach [11] can help.

(2) Then, every DP's design range has to be fitted and adapted into the corresponding FR's system range, i.e. the area of common range A_{cr} has to be increased (Fig. 1). This way, the system becomes robust by eliminating the real complexity.

(3) 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.

3.3 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. Thus, it might be defined as system dynamics. According to [14], 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) [1].

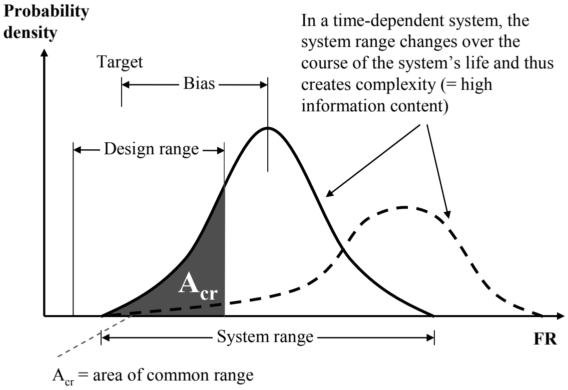

Fig 1: The area of common range A_{cr} [12]

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.

4. ILLUSTRATIVE EXAMPLE

To illustrate the previously described approach, a simple 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. According to the procedure presented in chapter 3, the first step is the elimination or reduction of the time-independent complexity. Thus, the design must first fulfill the Independence Axiom. At the highest level of detail, the following FRs can be identified:

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 Assembly stations are designed for low cost production
DP3 Inventory and coordination related cost is kept at the lowest possible level

The relative design matrix shows an uncoupled design:

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

In [11], a standard template for the decomposition of FR1 and FR2 is proposed. According to this so called production module template approach, the single model case is chosen (interested readers are referred to [11] for more detailed information): 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 decouplers (buffers) between the single stations.

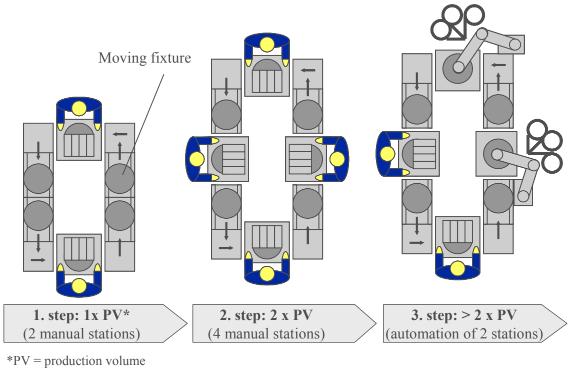

Fig 2: The concept of "moving fixtures" [23]

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 [23]. 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 (see Fig. 2). To decouple the line, several of these moving fixtures form a storage buffer between the single assembly stations.

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 electotechnical 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, regular checks of the screwing device are introduced.

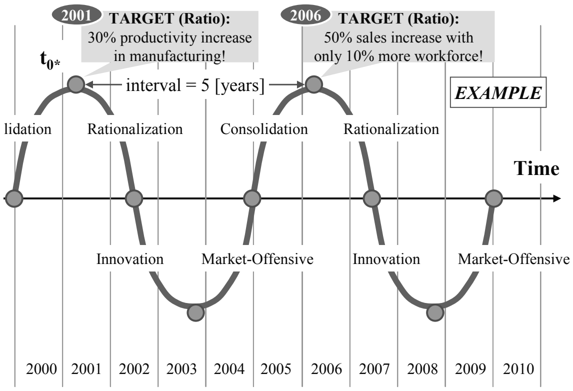

Fig 3: Sinus-Curve-Model for system periodicity [1]

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. Obviously, every economic sector or even every single company has a different cyclic behavior, but only regarding the timeline (Fig. 3). It passes always the following four stages: rationalization, innovation, market-offensive and consolidation. The company individual adaptation is given by the mapping of this generally applicable cycle along the timeline as a sinus curve [1]. The company individual interval can be determined heuristically, i.e. based on data and experiences from past. 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. 2 shows for the present example one possible modular strategy to increase the changeability of the assembly system, either by increasing the number of assembly station modules or by a stepwise automation.

5. CONCLUSION

This paper discusses a concept for the integrated design of efficient, flexible and changeable assembly systems. Starting from the AD based complexity theory, a procedure is 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: changeability). Future research will now concentrate on a more sophisticated determination of the stretching constant in the company individual sinus-curve-model.

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