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Application of Axiomatic Design principles to control complexity dynamics in a mixed-model assembly system: a case analysis

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Dominik Matt is a Full Professor at the Faculty of Science and Technology at the Free University of Bolzano, Italy. He studied Mechanical Engineering at the Technical University of Munich and achieved a Ph.D. in Industrial Engineering at the University of Karlsruhe. In 1994, Matt became Assistant Professor at the Institute of Machine Tools and Production Science (wbk) at the University of Karlsruhe. In 1998, he worked as project manager for an US company in Boston (MA), USA, where he developed a template model for the fast configuration of supply chain software. In 1999, he entered the Research and Engineering Center (FIZ) of the BMW Group in Munich, where he worked in different management positions and projects in Germany and UK. In 2004, he was appointed to the post of a Professor for Production Systems and Business Economics in the School of Industrial Engineering and Management at the Polytechnic University of Turin, Italy. In 2008, he accepted a call of the Free University of Bolzano to a tenured professorship at the Faculty of Science and Technology. Since 2010, Professor Matt is also Head of Fraunhofer Innovation Engineering Center (IEC) in Bolzano. Moreover, he is member in various national and international scientific organizations. His current research activity focuses on different innovative applications of Axiomatic Design theory and organizational complexity management, with a special focus to industrial production systems. His main research objective is to gain a better understanding of organizational complexity mechanisms in order to design and manage efficient, reconfigurable and agile industrial systems, as a potential cornerstone for a complexity- based theory of the firm. His research work has been published on internationally renowned conferences and in some of the most highly rated international journals in the field of Industrial Engineering.

Application of Axiomatic Design principles to control complexity dynamics in a flexible assembly system: a case analysis

The purpose of this paper is to test the validity of Axiomatic Design (AD) based complexity theory as an explanatory construct and as a methodological guidance for the early detection of need for change in flexible manufacturing systems in order to maintain competitiveness even in turbulent environmental conditions. The AD approach postulates that there are general design principles that govern the behaviour of a system. This proposition is empirically investigated for a flexible mixed-model assembly system by the examination of a long-term study conducted in a medium-sized industrial company. The findings of the long-term study suggest the introduction of a company specific cycle of functional periodicity in combination with a set of functional requirements working together as a regular trigger to detect whether the system range is moving away from the once defined manufacturing system's design range. The paper extends the research work made in the field of Axiomatic Design by focusing on mechanisms that help to control the effects of time-dependent complexity in manufacturing (re)design. Examples of methods and lead measures are given that can be used by organizations in early detecting and controlling complexity driven efficiency losses in manufacturing systems.

Keywords: axiomatic design; flexible assembly; manufacturing systems; design of production systems; complexity theory; functional periodicity

1. Introduction

Durable goods manufacturing has undergone almost constant change over the past two decades. Globalization of markets has driven this industry to leave the security of mass production in favor of lean and flexible manufacturing models. However, these concepts have already become state of the art in modern manufacturing system design. Their implementation is no longer a unique competitive advantage, but has become a vital prerequisite in global competition. Today's challenges for manufacturing go beyond these concepts. Since sales figures can hardly be forecasted, it is necessary to conceptualize not only flexible but highly adaptable systems which can be upgraded by more scale-economic solutions during product life cycle, even under extremely difficult forecasting conditions (Spath and Scholz 2007). Unlike flexible systems, changeable ones are expected to be capable of actively varying their own structure (Nyhuis *et al.* 2005). Due to the unpredictability of change, they are not

1
2
3 limited to a pre-defined system range typical for so called flexible systems but are
4
5 required to shift between different levels of systems ranges (Zaeh *et al.* 2005). As
6
7 modern manufacturing systems are increasingly required to be adaptable to changing
8
9 market demands, their structural and operational complexity increases, with a
10
11 negative impact on system performance (Nyhuis *et al.* 2010). However, literature
12
13 review shows that although many authors have investigated complexity mechanisms
14
15 and the related interactions between the production system and the surrounding
16
17 market environment, no suitable frameworks or measures have been developed to
18
19 track and control the dynamic evolving complexity of a manufacturing system in
20
21 order to promote and facilitate its changeability. The qualitative understanding of
22
23 complexity presented in this paper is based on Suh's (2005) Axiomatic Design (AD)
24
25 based definition of complexity as the uncertainty of (sustainably) fulfilling a system's
26
27 functional requirements. Like other important research works on complexity theory, it
28
29 differentiates between two classes of complexity: the time-independent, structural or
30
31 static complexity and the time-dependent, operational or dynamic complexity
32
33 (Frizelle and Woodcock 1995; Calinescu *et al.* 2000; Blecker *et al.* 2004), where
34
35 time-independent complexity is associated with the variety embedded in the static
36
37 system and time-dependent complexity is attributed to the uncertainty of the dynamic
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39 system.
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48 The purpose of this paper is to investigate the mechanisms of dynamic
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50 complexity in terms of internal and/or external drivers and the impact on a flexible
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52 manufacturing system's performance. As a result, a framework for monitoring and
53
54 controlling of dynamic complexity can be derived that helps to anticipate operational
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56 performance losses by a timely definition and implementation of measures for a
57
58 focused system redesign.
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3 Therefore, this research work retraces a series of manufacturing system
4 redesign initiatives in a medium-sized durable goods manufacturing company along a
5 ten year time period that timely helped to maintain and improve the firm's
6 manufacturing system's competitiveness in terms of time, cost and quality even in
7 turbulent environmental conditions. The objective of the case analysis is to test the
8 validity of Axiomatic Design (AD) based complexity theory as an explanatory
9 construct and as a methodological guidance in order to develop a decision support
10 system for the early detection of need for change in a flexible manufacturing system.
11 Since this is a perennial retrospective case study of continued manufacturing system
12 redesign interventions "before" and "after" variations of the system will be examined.
13 The study has been motivated by a best practice example of a specific industrial case
14 focused on a mixed-model assembly of durable goods but it encourages believing that
15 the findings can be extended to other manufacturing systems and industries as well.
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34 The paper is organized as follows. Section 2 reviews literature on
35 manufacturing related complexity theory and on the application of Axiomatic Design
36 principles in manufacturing system design. In Section 3, the research methodology is
37 developed from the literature and the hypotheses are described. Section 4 illustrates
38 and discusses the results of the case analysis. The concluding Section 5 discusses the
39 implications of the research findings and further research work.
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49 **2. Literature review**

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51 This section starts with the review of the existing research work done in the field of
52 manufacturing related complexity theory. It will explain the reasons why the AD
53 based complexity theory seems to be most suitable to fulfil this paper's purpose. In a
54 next step, the literature regarding the application of AD principles in the field of
55 manufacturing systems will be reviewed.
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2.1 Complexity theory

Complexity is difficult to define precisely. A general definition of complexity is that a complex system is one, which has a large number of elements, whose relationships are not simple (Simon, 1962). These variables, namely number, dissimilitude and states' variety of the system elements and relationships, allow differentiating 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 (Blecker et al., 2004). When both complexities are low, then the system is simple; when both complexities are high, then the system is said to be extremely complex (Ulrich and Probst, 1988).

Manufacturing's systems are complex. They have many elements with obvious, but non-simple relationships to each other. Frizelle and Woodcock (1995) argue that systems with higher complexity have more problems than systems with lower complexity, and that measuring manufacturing complexity provides a useful metric for improvement.

In order to understand how factors like product variety, changing quality requirements or varying customer demand regarding packaging or delivery service complicate manufacturing processes and in turn impact the performance of production systems, some research work has been conducted mainly in the investigation of the static manufacturing system complexity.

Deshmukh et al. (1998) derived an information-theoretic entropy measure of complexity for a given combination and ratio of part types to be produced in a manufacturing system. ElMaraghy et al. (2005) proposed a code-based structural complexity index to capture the amount of information in the manufacturing systems as well as another complexity measure to represent the probability of a manufacturing

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2
3 systems success in delivering the desired production capacity. In Zhu *et al.* (2008) and
4
5 Hu *et al.* (2008) the variety induced manufacturing complexity in manual mixed-
6
7 model assembly lines is considered where operators have to make choices for various
8
9 assembly activities. The authors propose a complexity measure called “operator
10
11 choice complexity” to quantify human performance in making choices.
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13

14
15 Through three case studies, Frizelle and Suhov (2008) proposed methods to
16
17 quantify the system’s immanent complexity while considering the data uncertainty
18
19 that is due to measurement noises. Jenab and Liu (2010) presented a graph-based
20
21 model to measure the relative manufacturing complexity and the manufacturing
22
23 similarity of products in job shop manufacturing systems in order to support assembly
24
25 and production cost estimation, and to provide a guideline for creating a product with
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27 the most effective balance of manufacturing and assembly.
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31 Little research, however, has focused on how to describe manufacturing
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33 system performance in terms of whether it is capable to handle and control the market
34
35 and product demand induced dynamic complexity. Sivadasan *et al.* (2002) developed
36
37 an entropy-based methodology to measure the operational complexity of supplier-
38
39 customer systems associated with the uncertainty of material and information. Other
40
41 research has recently explored new entropic-related complexity measures to describe
42
43 the uncertainty induced by the rescheduling of the production (Huaccho Huatuco *et*
44
45 *al.*, 2009). However, these studies do not provide any guidance and mechanisms to
46
47 install a continuous monitoring and controlling of a manufacturing systems dynamic
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49 complexity in order to maintain or even enhance its performance over time.
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51

52
53 Suh (2005) defined the complexity in the context of manufacturing system
54
55 design “as the measure of uncertainty in achieving the FRs (functional requirements)
56
57 due to a poor design or to the lack of understanding and knowledge about the system”.
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3 The author introduces the Axiomatic Design (AD) based complexity theory as a
4 comprehensive approach to describe the mechanisms of a manufacturing system's
5 static and dynamic complexity and illustrates the concept of functional periodicity in a
6 scheduling problem of a machine cluster to control the system's time-dependent
7 combinatorial complexity. Apart from the described example of a scheduling problem
8 which handles dynamic complexity only in a given tolerance range of a
9 manufacturing system's flexibility, no research work has been done so far to use the
10 AD approach in the context of an already flexible manufacturing system's (re)design
11 to changeability.
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26 ***2.2 Application of AD principles in manufacturing system design***

27 The following papers are good examples of design of manufacturing systems based on
28 Axiomatic Design principles (Kulak *et al.* 2010).
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30

31
32 Suh *et al.* (1998) presented the first study using AD principles for a
33 manufacturing system design based on the independence axiom. Cochran *et al.* (2000)
34 proposed a method based on the principles of lean management and the independence
35 axiom of axiomatic design principles which converted production system to small,
36 flexible, and non-central production units to design a production system that could be
37 managed more effectively. Kulak *et al.* (2005) presented an approach to transform
38 traditional production system from process orientation to cellular orientation, based
39 on axiomatic design principles. Houshmand and Jamshidnezhad (2006) proposed an
40 axiomatic design modelling of lean production system design. Nakao *et al.* (2007)
41 used the independence axiom in order to shorten the lead-time of tailor-made products
42 by eliminating couplings. Matt (2008) described a template approach based on the
43 independence axiom to give guidance to manufacturing system designers in the fast
44 and efficient design of lean and flexible manufacturing systems.
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4 Using only the independence axiom which describes the time-independent part
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6 of AD based complexity theory, none of the research works performed in the field of
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8 AD application in manufacturing system design considered the impact of system
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10 dynamics so far. Therefore, this research is motivated to develop a suitable
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12 methodological framework on the basis of the Axiomatic Design related complexity
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14 theory to track and control the dynamic evolving complexity of a flexible
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16 manufacturing system in order to promote and facilitate its changeability.
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21 **3. Research methodology**

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23 The methodology applied in this research has two main components: First, a theoretic
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25 framework for the explanation of a manufacturing system's dynamic complexity
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27 drivers and their control is developed basing on the principles of AD related
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29 complexity theory. Its practical relevance is then investigated on the basis of a long-
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31 term study carried out at a durable goods manufacturer, here onwards referred to as
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33 "the company".
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39 **3.1 Axiomatic Design based complexity theory**

40 According to Suh (2005), most complexity theories deal with the complexity of a
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42 system in its physical domain which contains the design solutions or design
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44 parameters (DPs) to satisfy the functional requirements (FRs) that describe the design
45
46 goals for the system. However, complexity problems can be difficultly solved in the
47
48 physical domain, because every change of the elements and their relationships aiming
49
50 at the reduction of the system's complexity might influence the overall system's
51
52 behavior in an uncontrollable way due to the system designer's lack of understanding
53
54 of the system's architecture. To provide a general theoretical framework for solving
55
56 complexity problems in engineering and in production related areas, Suh (2005)
57
58 defined complexity narrowly as a measure of uncertainty in achieving a set of design
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3 goals that a system must satisfy. Due to its time-dependency complexity must be
4
5 measured in the functional domain: as technical and socio-economic conditions
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7 change over time, also the objectives and driving forces for manufacturing system
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9 design have changed. While in the early twentieth century labor productivity was the
10
11 most important factor for measuring manufacturing performance, this objective
12
13 started to change when automation began to play a dominant role and much more
14
15 effort was dedicated to capital cost reduction. Currently, we are facing a general trend
16
17 towards increasingly fluctuating market demand as consumers are asking for more
18
19 individualized products and services. In the next future, probably shortages in raw
20
21 material supply and increasing energy costs may drive the change in a manufacturing
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23 system's set of functional requirements. It can be noticed that the complexity of
24
25 manufacturing systems depends on the functional requirements that are relevant at a
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27 given moment in history and thus their regular (re-)design is becoming one of the
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29 most important factors in determining industrial competitiveness (Suh 2005).
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36 The underlying hypothesis of AD is that there exist fundamental principles
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38 that govern good design practice. The main components of AD are domains,
39
40 hierarchies, and design axioms. The Axiomatic Design world consists of four
41
42 domains: customer, functional, physical and process. Through an iterative process
43
44 called zigzagging, the design process converts customer's needs (CNs) into
45
46 Functional Requirements (FRs) and constraints (Cs), which in turn are embodied into
47
48 Design Parameters (DPs). DPs determine the Process Variables (PVs). The
49
50 decomposition process starts with the decomposition of the overall functional
51
52 requirement – in practice this should correspond to the top system requirement.
53
54 Before decomposing to a lower level, the DPs must be determined for that level in the
55
56 physical domain. Two basic axioms are distinguished (Suh, 2001):
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- **Axiom 1 – 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 – Information Axiom:** Minimise the information content of the design. The Information Axiom is defined in terms of the probability of successfully achieving FRs.

3.1.1 The First Axiom: The Independence Axiom

FRs and DPs are represented by vectors, their relationship by an n-dimensional matrix. For example, a 3-dimensional matrix the design equation can be written as follows:

$$\begin{Bmatrix} \text{FR}_1 \\ \text{FR}_2 \\ \text{FR}_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \cdot \begin{Bmatrix} \text{DP}_1 \\ \text{DP}_2 \\ \text{DP}_3 \end{Bmatrix}$$

In terms of its elements, the above equation may be rewritten as follows:

$$\text{FR}_1 = A_{11}\text{DP}_1 + A_{12}\text{DP}_2 + A_{13}\text{DP}_3$$

$$\text{FR}_2 = A_{21}\text{DP}_1 + A_{22}\text{DP}_2 + A_{23}\text{DP}_3$$

$$\text{FR}_3 = A_{31}\text{DP}_1 + A_{32}\text{DP}_2 + A_{33}\text{DP}_3$$

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 optimal system design, these elements are autonomous, they have no interrelations. Such a design is called an uncoupled design as the single equations can be solved independently. In any other case, the off-diagonal elements can be also 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 dependence. This is the case in a coupled design and it means a bad system design (Lee and Jeziorek 2006).

In the case of a triangular matrix circular dependence does not exist and therefore the design might be potentially good, although not optimal due to the given path

1
2
3 dependency. This case is called a decoupled design. It is obvious that it is very
4
5 difficult or sometimes quite impossible to really obtain an ideal design (Suh 2001).
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7

8 9 *3.1.2 The Second Axiom: The Information Axiom*

10 The Information Axiom is the theoretic funding of the AD based complexity theory.
11
12 In the preceding section, the Independence Axiom was shortly introduced. The design
13
14 process following the rule of the Independence Axiom may produce several
15
16 acceptable design alternatives: uncoupled or decoupled. To determine, which of these
17
18 represents the best solution, the Information Axiom can be applied.
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24 **“Insert Figure 1 about here”**
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27

28 As previously mentioned, the Information Axiom is defined in terms of the
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30 probability of successfully achieving FRs. The probability of success can be
31
32 computed by determining the area of common range between the design range (dr)
33
34 defined by the system designer to satisfy the FRs and the system range (sr) that the
35
36 proposed design can really provide to satisfy the FRs within the specified range (Suh
37
38 2005). The larger this overlap, the lower the system’s complexity (Figure 1).
39
40
41

42 However, in a dynamic system like a manufacturing system, the complexity might
43
44 increase over time as the system range moves out of the once specified design range.
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46
47

48 *3.1.3 Complexity theory based on Axiomatic Design*

49 The complexity of any dynamic system is determined by the uncertainty in achieving
50
51 the system’s functional requirements and is caused by two factors (Suh 2005): by a
52
53 time-independent poor design that causes a system-inherent low efficiency (system
54
55 design), and by a time-dependent reduction of system performance due to system
56
57 deterioration or to market or technology changes (system dynamics). The complexity
58
59 that follows directly from the Information Axiom is the time-independent real
60

complexity which tells whether the system range is inside or partly or completely outside the system's design range. To assure a manufacturing system's flexibility, a certain allowable tolerance regarding variations of the design range have to be defined. In the case of an ideal, uncoupled design, the allowable tolerance for DP_1 can be determined as follows (Suh 2005):

$$\Delta DP_i = \frac{\Delta FR_i}{A_{ii}}$$

Consider now the decoupled design below:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \cdot \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}$$

In the case of that 2-dimensional triangular (decoupled) matrix, the allowable tolerances for the DPs can be expressed as (Suh 2005):

$$\begin{aligned} \Delta DP_1 &= \frac{\Delta FR_1}{A_{11}} \\ \Delta DP_2 &= \frac{\Delta FR_2 - |A_{21} \Delta DP_1|}{A_{22}} \\ \Delta DP_3 &= \frac{\Delta FR_3 - |A_{31} \Delta DP_1| - |A_{32} \Delta DP_2|}{A_{33}} \end{aligned}$$

The total time-independent complexity contains also a second component for those design solutions that are not completely uncoupled: The so called time-independent imaginary complexity results from a lack of understanding of the system design. As it is not of direct relevance for this research, it won't be detailed further. When the system range moves as a function of time, then this is time-dependent complexity at work. There are two types of time-dependent complexity (Suh 2005): The so called periodic complexity exists only 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

1
2
3 systematic research of possible failure sources. The second type of time-dependent
4
5 complexity is called combinatorial complexity. It increases as a function of time
6
7 proportionally to the time-dependent increasing number of possible combinations of
8
9 the system's functional requirements. Leaving the pre-defined flexibility tolerance, it
10
11 may lead to a chaotic state or even to a system failure. The critical issue with
12
13 combinatorial complexity is that it is completely unpredictable. Becoming able to
14
15 control the combinatorial complexity means to obtain not only a flexible but a really
16
17 changeable manufacturing system.
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23 **“Insert Figure 2 about here”**
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28 To control combinatorial complexity, a functional periodicity has to be
29
30 introduced. First, a set of FRs that repeats cyclically must be identified. Among these,
31
32 those FRs and their related DPs have to be identified that may be subject of a
33
34 combinatorial process. To introduce functional periodicity, the selected set of FRs has
35
36 to be reinitialized at a defined (periodically turning) point in time t_2 (Figure 2). How
37
38 this procedure works in practice will be explained within the case study.
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43 **3.2 Case study**

44 The main research question of this paper is: To what extent can Axiomatic Design
45
46 based complexity theory help illuminate the regular redesign of a manufacturing
47
48 system to improve its robustness regarding various changes driven by a time-
49
50 dependent combinatorial complexity that go beyond system flexibility and impact the
51
52 system's efficiency in terms of time, quality and costs?
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54
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56 The research question is addressed by presenting a case study. Case studies are
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58 typically used for deeply investigating dynamic, experiential and complex processes
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60 and areas taking place in a fast-changing and fluid environment (Gilmore and Carson

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2
3 1996; Ghauri 2004; Perren and Ram 2004; Halinen and Törnroos 2005). Another
4
5 strength of case studies is that the necessary data can be collected over a long time
6
7 period. Consequently, the researcher can go much further than a cross-sectional
8
9 snapshot of a process (Johnston *et al.* 1999; Stuart *et al.* 2002; Ghauri, 2004).
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13 The empirical basis of this paper is a single case study involving the
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15 production plant of a medium-sized Italian producer of durable goods. The case
16
17 analysis refers to a long-term period of ten years starting from the year 2000. It aimed
18
19 at identifying and analyzing the factors influencing the operational performance of
20
21 manufacturing over an extended timeframe. Three main sources of data were used: a)
22
23 semi-structured interviews with staff at the company, b) direct observations on the
24
25 shop floor, and c) collection of documents and historical data from electronic
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27 databases/spreadsheets and documents such as production schedules, expected
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29 deliveries and actual deliveries records, and the related development of product
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31 variety.
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36 37 **4. Results**

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39 The results of the long-term study will be shown and discussed in the following
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41 section.
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43 44 **4.1 Identification of the FR-DP-set**

45
46 The processes affected by system redesign were those related to company internal
47
48 value stream from the procurement of materials and components to shipping, focusing
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50 however on the two sequential processes of (1) the mixed-model assembly and (2)
51
52 packing process connected to each other by a decoupling buffer line. In terms of the
53
54 long-term analysis subject to this research, the company's management emphasized
55
56 two aspects for redesign. First, they aimed to maintain or even improve operational
57
58 performance in terms of labor productivity with the constraints of an increased
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60

number of product types and variants. Second, flexibility had to be increased in terms of responsiveness to short-term customer requirements and volume changes, maintaining however a minimum of 95% delivery capacity.

Within the analyzed manufacturing system “assembly process – buffer line – packing process”, the following FR can be derived from defined redesign objectives:

- FR₁: Produce to demand at best achievable operational efficiency

The design parameters mapped by the functional requirements are:

- DP₁: Design of flexible assembly (*or packing*) operations focused on customer demand pace and value added work

As this represents a one-FR-design, the Independence Axiom is always satisfied at this level. To bring the design task onto an implementable level, the design has to be further decomposed:

- FR₁₁: Produce to the customer demand
- FR₁₂: Ensure flexibility to accommodate capacity increments at lowest cost
- FR₁₃: Ensure flexibility to accommodate future products and variants

For the case study’s system, the corresponding DPs were stated as follows:

- DP₁₁: Takt-time calculation based on real average customer demand
- DP₁₂: Multiple single-station mixed-model assembly and packaging cells designed to focus on value added work; number of assembly and packing stations are determined on the basis of their average cycle time and the required customer takt-time
- DP₁₃: Movable and reconfigurable stations to enable new cell redesign

The design equation and matrix is:

$$\begin{Bmatrix} \text{FR}_{11} \\ \text{FR}_{12} \\ \text{FR}_{13} \end{Bmatrix} = \begin{bmatrix} \text{X} & 0 & 0 \\ \text{X} & \text{X} & 0 \\ 0 & 0 & \text{X} \end{bmatrix} \cdot \begin{Bmatrix} \text{DP}_{11} \\ \text{DP}_{12} \\ \text{DP}_{13} \end{Bmatrix}$$

This is a decoupled design and thus satisfies the Independence Axiom. For the purpose of this research work, no further decomposition will be needed at that stage.

According to the Information Axiom, in the next step the design will be analyzed regarding its information content. In this case study, set-up times and time for planned stand stills can be neglected. Thus, for the fulfillment of FR_{11} , in DP_{11} the takt-time can be determined according to the following simplified formula:

$$T_{\text{takt}} = \frac{P_{\text{ap}} \cdot A \cdot S \cdot H}{Q}$$

with Q = daily average customer demand, P_{ap} = yield of good units produced by the system, A = average availability of the manufacturing process, S = number of shifts per day (shifts/day), H = hours/shift.

Any variation to demand represented by ΔQ has a direct impact on ΔDP_{11} . It can be compensated by ΔH or by extra shifts. However, in our case example extra shifts are not a solution to be considered and thus the equation can be written with $S=1$ as follows (see also section 2.1.3), with $A_{111} = T_{\text{takt}}/(P_{\text{ap}} \cdot A)$:

$$\Delta DP_{11} = \frac{\Delta FR_{11}}{A_{111}} = \frac{P_{\text{ap}} \cdot A \cdot \Delta H}{T_{\text{takt}}}$$

According to Italian labor legislation, a maximum of 2 hours of overtime per person and day are allowable and a maximum of 60 hours of overtime per person and year can be shifted for overtime compensation from one to the next year, with a reduced overtime premium of +10% in case of disbursement. However, as demand variation in this case study follows a normal distribution with a standard deviation that allows the achievement of a 95% delivery capacity within overtime flexibility, these constraints do not need to be considered. Furthermore, an average value of $P_{\text{ap}} \cdot A = 0.95$ can be assumed in this case study.

For the fulfillment of FR_{12} , in DP_{12} the number of necessary stations K will be determined according to the following formula:

$$K = \frac{T_c}{T_{\text{takt}}}$$

with T_c = average station cycle time and

$$K = \begin{cases} \frac{T_c}{T_{\text{takt}}} & \text{if } \frac{T_c}{T_{\text{takt}}} \in Z \\ \left[\frac{T_c}{T_{\text{takt}}} \right] + 1 & \text{if } \frac{T_c}{T_{\text{takt}}} \notin Z \end{cases}$$

As already outlined in section 3.1.3, the allowable tolerance for DP_{12} may be written as follows, with $A_{121} = A_{122} = T_c$:

$$\Delta DP_{12} = \frac{\Delta FR_{12} - |A_{121} \Delta DP_{11}|}{A_{122}} = \frac{\Delta FR_{12}}{A_{122}} - |\Delta DP_{11}|$$

with

$$\frac{\Delta FR_{12}}{A_{122}} = \frac{(K_{\text{max}} - K) \cdot H \cdot A \cdot P_{\text{ap}}}{T_c}$$

In the above term, $|\Delta DP_{11}|$ represents the “tolerance” of the system – in this specific case in terms of overtime flexibility – which enables the system to balance “normal” variations in demand within a certain delivery capacity limit. However, as overtime is expensive and thus impacts FR_{12} , it is suitable only for short term leveling of capacity peaks. A variation in demand can be managed only to a certain point by this type of flexibility. As soon as average demand starts to move, ΔDP_{12} decreases. For $\Delta DP_{12} > 0$, no action is needed (green zone). When ΔDP_{12} moves towards 0 or starts to turn negative, then system re-design must be triggered (yellow zone). Latest for $\Delta DP_{12} = -|\Delta DP_{11}|$, re-design has to start (red zone).

4.2 Investigation of the case study system’s long-term behavior

The following Figure 3 and Figure 4 show the behavior of the manufacturing system in the investigated case study.

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8 **“Insert Figure 3 about here”**
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12 In 2001, the new manufacturing system based on manual mixed-model
13 assembly stations connected to the packing station(s) by a buffer line (see Figure 4)
14 was introduced. Since then, the overall production system consists of several so called
15 “assembly-buffer-packing segments” (short: assembly segment), each assigned to
16 always one product family offering a high adaptability to variations in models and
17 variants within the assigned product family; in this case study, we focus on just one of
18 these assembly segments, called “segment C”. Adaptability to demand volumes is
19 guaranteed by the activation of further assembly stations along the buffer line.
20 Furthermore, the single assembly stations are also designed for fast and easy
21 reconfiguration. This design perfectly fits with the above explained functional
22 requirements and offers a very high volume, variant and redesign flexibility.
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42 **“Insert Figure 4 about here”**
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47 The observed assembly segment C started in 2001 with the activation of 7
48 assembly stations and 1 packing station, fulfilling the average daily demand of 600
49 units per day (Figure 3). The system was designed to allow a maximum of 10 stations
50 to be allocated along the buffer line. The review of historical data shows that in
51 2003/2004 volumes would have justified the activation of an eighth station. However,
52 first redesign was done in 2005 after having noticed that demand fulfillment with
53 overtime and stand-by workers where neither sufficient nor very cost-efficient. Thus,
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3 a total of 9 stations were activated in one time. Moreover, the increase in variants and
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5 in demand at the same time caused the packing station to move out of the original
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7 design range so that a second station had to be added. Due to the introduction of
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9 several new products and variants, in 2007 demand and product mix had so much
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11 increased that the activation of the 10th station would not have been sufficient.
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13 Furthermore, the two packing stations had already reached their capacity limit. Space
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15 requirements would not allow allocating 4 packing stations at the end of one assembly
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17 segment. Thus, production management decided to split the segment in two separate
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19 ones with 2 packing stations at the end of each buffer line (Figure 4). In the meantime,
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21 even this latest measure has reached its limits and since 2009, the system is subject to
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23 substantial redesign, similar to the one in 2001. This redesign includes also DP₁₃;
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25 however, no results can be reported so far as this latest initiative has not been
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27 concluded yet.
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35 **“Insert Figure 5 about here”**
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39 As previously outlined, a good way to control combinatorial complexity is to
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41 introduce a functional periodicity. First, a set of FRs that repeats cyclically must be
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43 identified. As assembly stations are de-coupled from packing stations by a buffer line,
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45 two separate sets of FRs must be defined according to the one presented in section
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47 4.1, one for assembly and one for packaging. In this paper, focus is given just to the
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49 assembly part; however, procedure for packaging is similar. All FRs and their related
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51 DPs are subject to a combinatorial process. To introduce functional periodicity, the
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53 selected set of FRs has to be reinitialized at a defined (periodically turning) point in
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55 time. The investigation of the case study system’s long-term behavior shows a cyclic
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57 behavior of redesign activities: with intervals of about 2 years, redesign was
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3 necessary. Figure 5 shows the company's functional periodicity in parallel to an
4 economic cyclic behavior. In future, the FR-set of the investigated company can be
5 regularly reinitialized by a programmed two-year trigger (see also Figure 2).
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8 Presumably, there is a correlation between economic cycles and the company specific
9 functional periodicity: the anticipation of economic trends could be – for example –
10 realized by introducing more cycles with shorter periods. However, prove for this
11 assumption is still missing.
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20 21 **5. Conclusions**

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23 An AD based methodology to monitor and control the time-dependent complexity of
24 manufacturing systems has been developed and illustrated on the basis of a single
25 case study. The use of the AD based complexity mechanisms to investigate the
26 characteristics of manufacturing systems especially regarding their time-dependent
27 behaviour is novel both in its methodology and in the application field. The proposed
28 analysis provides powerful insights on the dynamics of operational complexity and
29 hence provides guidance to organisations in managing manufacturing system redesign
30 more effectively. A key benefit of this measure is identifying complexity hotspots and
31 trigger points to start system re-initialization. Concepts arising from this method are
32 that of internal organisational ability to absorb operational complexity. The validation
33 of the complexity methodology has been conducted through practical application and
34 through confirmed results from a single industrial study carried out at an Italian
35 producer of durable goods. The case study demonstrated that the methodology
36 provides valid and valuable means of identifying and prioritising areas of high
37 operational complexity. The methodology presented in this paper will continue to be
38 developed and validated in further case studies. Areas of further work include:
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- The more detailed investigation of correlations between economic and market cycles and their impact on a company specific functional periodicity.
- The generalization of the case study's findings and the respective evaluation in other case studies
- A more detailed decomposition of FR-DP-relations to derive algorithms for the installation of early detection mechanisms

Work in these areas is under development in collaboration with industrial partners.

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25 Figure 1. The area of common range A_{cr} measures a system's time-independent real
26 complexity. It might decrease due to the system's time-dependency (Suh 2005).
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28 Figure 2. The manufacturing system (re-)design process and its relation with
29 functional periodicity.
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31 Figure 3. The initial setup of the manufacturing system foresaw an increase in demand
32 of up to 40%. In 2005, delivery could be maintained only with regular overtime.
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34

35 Figure 4. In 2007, two main factors were driving the need for change above the
36 planned system-inherent flexibility: increase in demand volume and in product variety
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39 Figure 5. The results of the long-term case analysis suggest the introduction of a
40 company specific functional periodicity with a two-year interval
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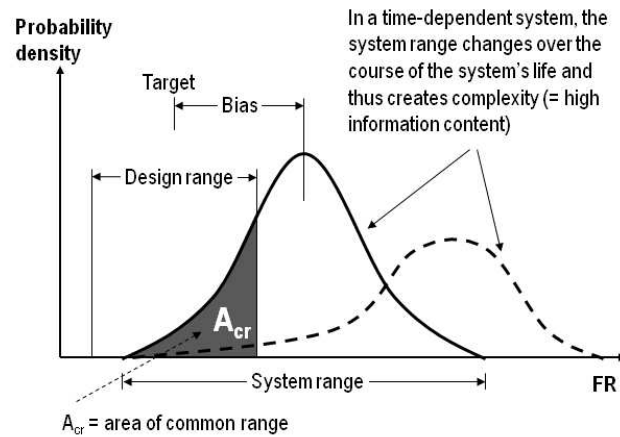


Figure 1. The area of common range A_{cr} measures a system's time-independent real complexity. It might decrease due to the system's time-dependency (Suh 2005).
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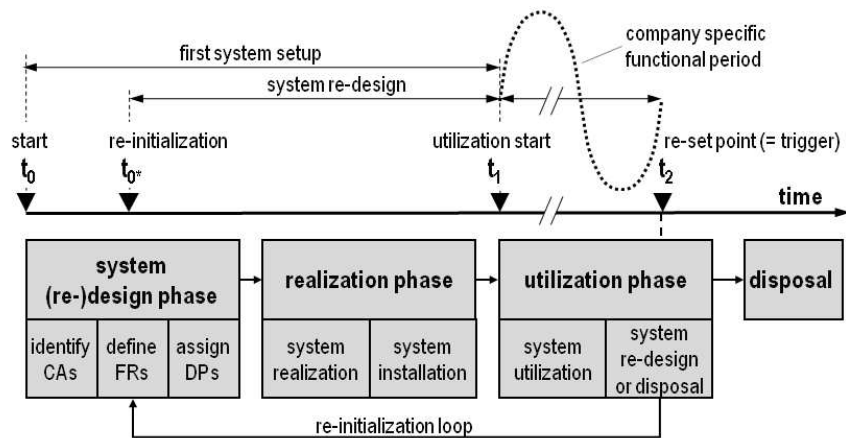


Figure 2. The manufacturing system (re-)design process and its relation with functional periodicity. 254x190mm (96 x 96 DPI)

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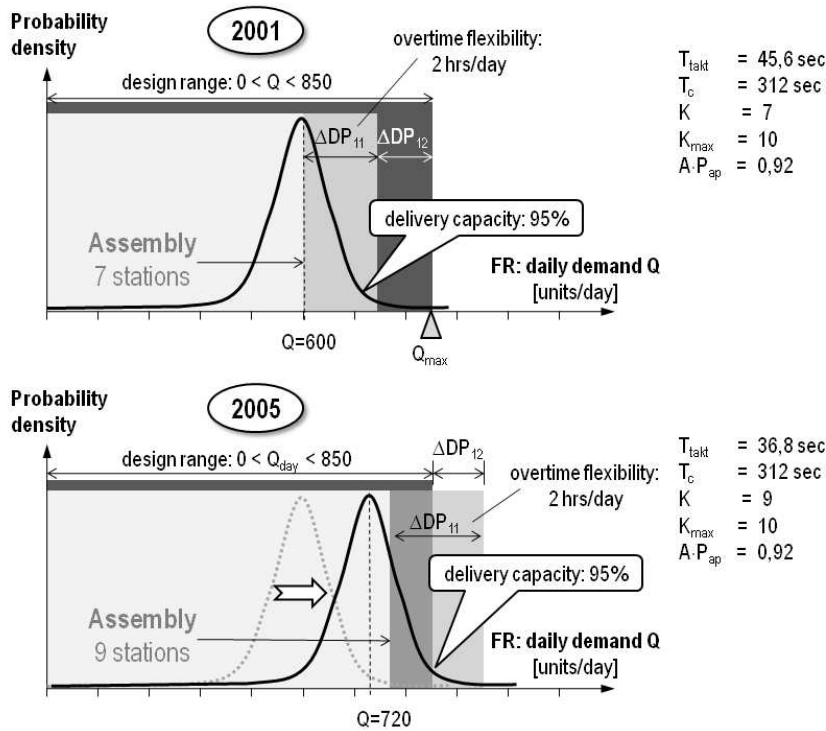


Figure 3. The initial setup of the manufacturing system foresaw an increase in demand of up to 40%. In 2005, delivery could be maintained only with regular overtime.
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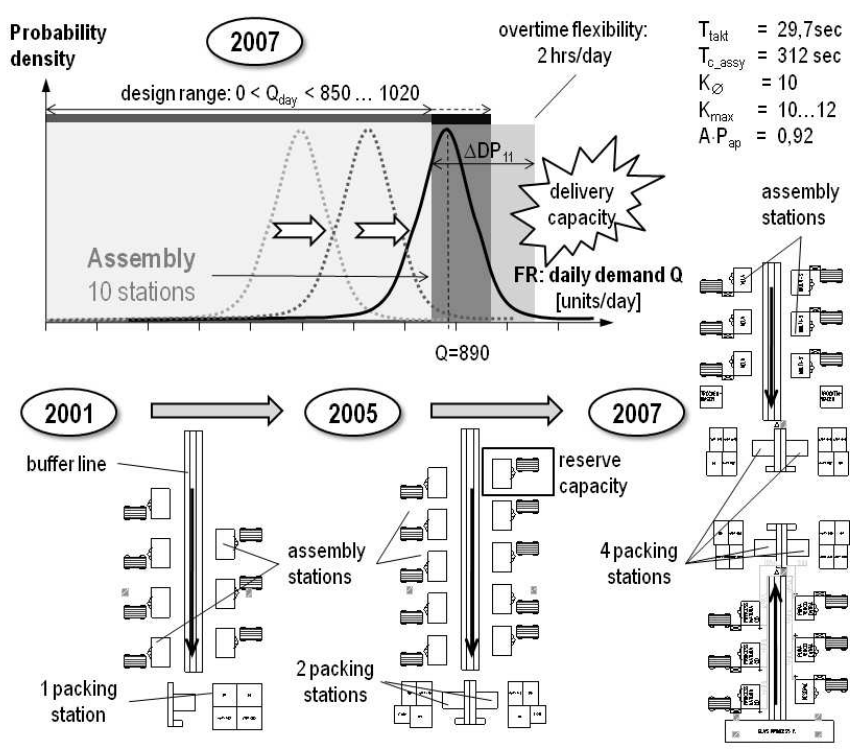


Figure 4. In 2007, two main factors were driving the need for change above the planned system- inherent flexibility: increase in demand volume and in product variety 254x190mm (96 x 96 DPI)

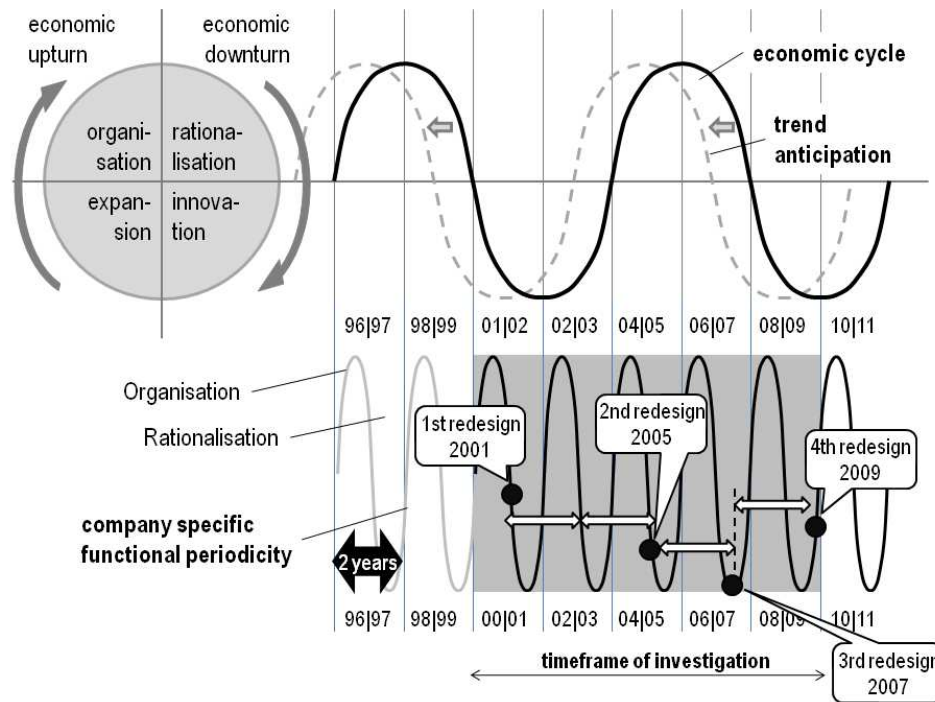


Figure 5. The results of the long-term case analysis suggest the introduction of a company specific functional periodicity with a two-year interval
 254x190mm (96 x 96 DPI)