

AXIOMATIC DESIGN OF PRODUCTION MODULE TEMPLATES

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ABSTRACT

Since most of today's industrial products are characterized by high complexity and numerous customer-specific variants, flexible and adaptive production system concepts are needed to meet market and customer requirements. At the same time, these production systems have to be highly competitive in terms of cost per unit. This paper introduces a concept for the design of lean and agile production systems with the help of axiomatic designed production module templates. The objective of these generic templates is to help system designers to adapt a production module to their specific requirements in a very fast and efficient way.

Keywords: axiomatic design, customer driven production, production systems, production module templates

1 INTRODUCTION

The principles of Lean Production and Agile Manufacturing have already become state of the art in modern production 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. World-class companies sustain corporate success and a competitive edge not only by introducing lean concepts and by reacting quickly to changing market requirements, but by adapting themselves rapidly within changing global networks of buyer-supplier-relationships. This adaptability requires the resonance between business strategy and operations and thus the fast and direct transformation of strategic requirements into the production system's design. [1]

A production system can be defined as a dynamic system, because it is subject to temporal variation and must be reconfigurable on demand [2]. Market and strategy changes will influence the functional requirements of a production system and therefore impact the system's design.

As already outlined in former publications [3], the concept of innovation families helps in this strategic planning. Innovation families are strategic combinations of products and technologies

that represent the company's actual core competences and project it to the future along the imagined development of market and technology trends. These scenarios help to identify future changes and to consider these trends in the definition of strategic requirements for a company's supply network (level 1) and on the next level of detail for the production system (level 2) as integral part of the supply network (Figure 1).

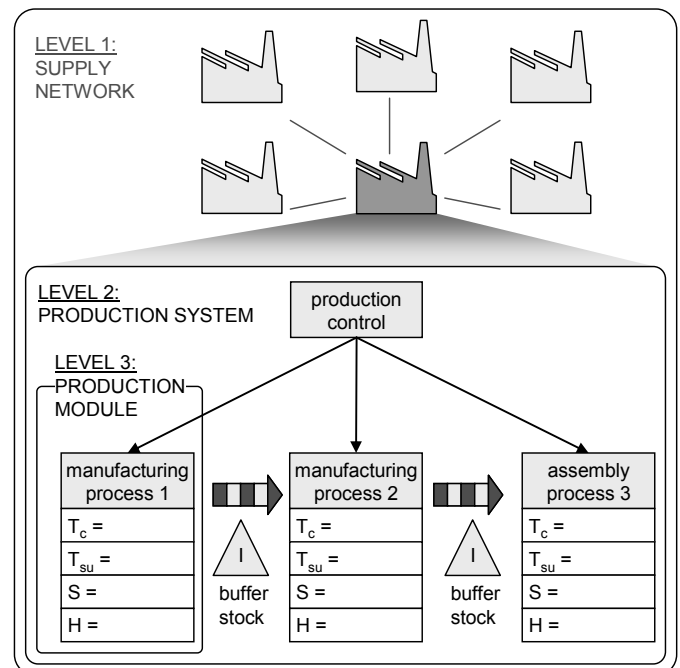


Figure 1 – System hierarchy

Common to this strategic approach and to nearly all concepts of production system design is that the design of producing units is oriented to product groups or product families [4], [5]. According to [4], the lifetime of such a design varies from 3 to 18 months. Afterwards, it is again subject to changes. Thus, the re-design process has to be very fast and efficient.

In order to accelerate the change management process in production system re-design, standards have to be defined that

can be applied independently from market and strategy specific dynamic requirements. Such a standard could be used as a “template” for the fast and efficient design of a system or system component’s.

This paper introduces a concept for the design of lean and agile production systems with the help of axiomatic designed production module templates. The objective of these generic templates is to help system designers to find and adapt a production module to their specific requirements in a very fast and efficient way.

2 AXIOMATIC SYSTEM DESIGN

Production systems are collections of people, equipment and procedures organized to accomplish the manufacturing operations of a company [6]. As system theory states, every system may be defined as an assemblage of subsystems [7]. Accordingly, a production system can be seen as an assemblage of production modules along the system’s value stream (Figure 1). The theory of Axiomatic Design is applicable to many different kinds of systems. According to the principles of Axiomatic Design [2], the design world consists of four domains: 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 [2]. According to [8], the physical domain is not needed for the design of manufacturing systems.

3 PRODUCTION MODULE TEMPLATES

A template can be defined as a form or pattern used as a guide to making something, as a model of an application that is customized by the system designer. It provides a separation of form or structure from content. Thus, it has to be a fixed system which functional requirements do not change as a function of time.

The design of supply networks and production systems depends on the definition the process sequence for the production of products or product families and thus is time variable. Therefore, neither level 1 nor level 2 in Figure 1 are suitable for the definition of system templates. In level 3, a production system’s value stream is split into single steps, the so called production modules. They represent single manufacturing or assembly processes serving only 1 or n different products. According to [9], a production module follows the flow principle, i.e. it does not contain any stoppages of material within its borderlines. It may be defined as a “black box”, with defined attributes and with assigned processes and resources (Figure 2). It has interfaces with the environment and can receive input and send output in form of material, information and energy [10].

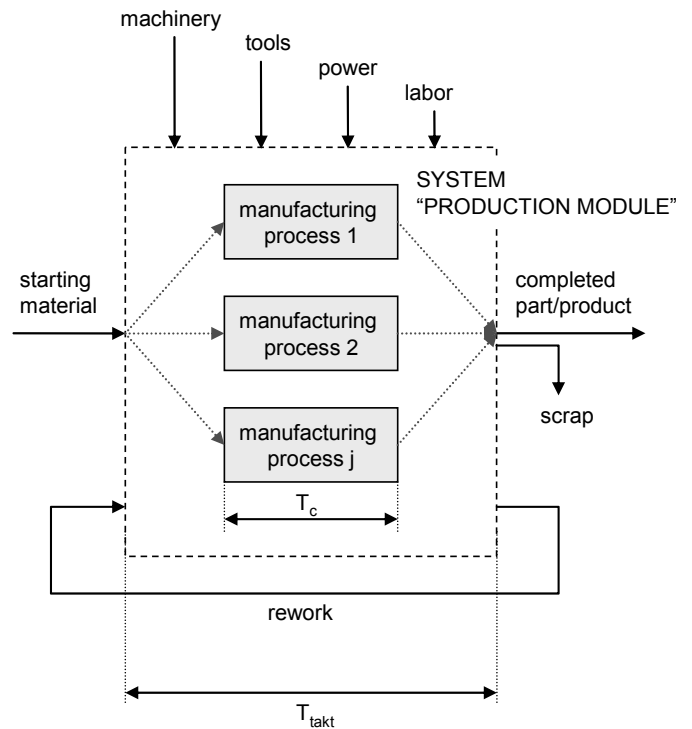


Figure 2: System definition of a production module

The definition of the CAs 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.

For the design of production module templates, two basic CAs can be identified: the **market and customer responsiveness** of the system in terms of agility, flexibility and times and the **total cost per output unit**, including fixed and variable costs.

3.1 MARKET AND CUSTOMER RESPONSIVENESS

To achieve a maximum market and customer responsiveness it is important to design the production module to be consistent with the pace at which the customer is demanding a part or product. This pace is often referred to as the “takt time” (a German word for cadence or pace) [6]. The takt time is the reciprocal of the demand rate, i.e. it is the time within which one part or product should be produced, based on the rate of sales, to meet customer requirements. It is calculated by dividing the customer demand rate per period, into the available working time per period [4].

For the production operation performed by the manufacturing or assembly process of a production module, the operation cycle time T_c is defined as the time that one work unit spends being processed or assembled. It is the time between when one work unit begins processing or assembly and when the next unit starts. It consists of the machining operation time T_o , the work part handling time T_h , and the tool handling time T_{th} per piece. As an equation, this can be expressed [6]:

$$T_c = T_o + T_h + T_{th} \quad (1)$$

In a customer driven production system, T_c ideally equals to the entire system's takt time. But this is not always feasible.

Accordingly, a customer driven production module must satisfy the following equation:

$$T_c = K \cdot T_{takt} \quad (2)$$

K is the factor that balances a production module's individual cycle time to the production system's takt time. Basically, three different cases for K may be differentiated:

1. $T_c = T_{takt} \Rightarrow K = 1$. In this desirable case, the cycle time of the production module is perfectly synchronized with the customer pace.
2. $T_c < T_{takt} \Rightarrow K = U$, where U = utilization of the production module by a specific product or product family. Utilization is defined as the proportion of time that the system is actually being used for performing the required operations compared with the time it is available [6]. This is usually the case for fast working processes (e.g. a stamping press) that can be used for different purposes (i.e. other product families).
3. $T_c > T_{takt} \Rightarrow K = \text{maximum integer of parallel (object principle: single-station system, with } K \text{ parallel stations) or sequentially synchronized and linked (process principle: sequential system with } K \text{ stations and fixed routing) machines or work stations needed to satisfy the customer demand rate.}$

As previously discussed, takt time is calculated by dividing the customer demand rate per period, into the available working time per period. The available processing time per year can be expressed in the following equation:

$$T_{avail} = A \cdot \left(S \cdot H - T_{ps} - \sum_{k=1}^m n_{bk} \cdot T_{su_k} \right) \quad (3)$$

where T_{avail} = available processing time per year of a manufacturing process (hrs), A = average availability of the manufacturing process, S = number of shifts per year (shifts/year), H = hr/shift, T_{ps} = time for planned standstills (agreed breaks, team meetings, workshops, planned maintenance, reconstruction) per year (hrs/year), T_{su_k} = average setup time to prepare one batch of product k (hrs), $n_{bk} = Q_k/Q_{bk}$ = annual number of batches of k , Q_k = (planned) average annual customer demand for product k (pcs), Q_{bk} = average batch quantity of product k (pcs) and m = average annual number of different product or part types produced.

Availability is a measure of system reliability and is defined according to [6]:

$$A = \frac{MTBF - MTTR}{MTBF} \quad (4)$$

where $MTBF$ = mean time between failures (hr), and $MTTR$ = mean time to repair (hr). Unnecessary to explain that equipment tends to have a lower availability when it begins to age.

Thus, takt time for a production module can be expressed in the following equation:

$$T_{takt} = \frac{P_{ap} \cdot T_{avail}}{Q} = \frac{P_{ap} \cdot A}{Q} \cdot \left(S \cdot H - T_{ps} - \sum_{k=1}^m n_{bk} \cdot T_{su_k} \right) \quad (5)$$

with Q = annual average customer demand and P_{ap} = yield of good units produced by the system [6]:

$$P_{ap} = 1 - q + m \cdot q \quad (6)$$

where q = fraction defect rate of the parts produced in the production module and m = the probability that a defect will cause a module to jam. For $T_c > T_{takt}$ with $K > 1$ we suppose that all parallel machines or stations have the same m and q .

3.2 TOTAL COST PER OUTPUT UNIT

Besides maximum customer responsiveness, the second fundamental objective for the design of a production module is cost efficiency of operations. Decisions on automation machinery and equipment are usually based on the relative costs of alternatives. An important measure of performance of a production module is the cost per unit produced. This includes the cost of starting material to be processed, the cost of time in the module, and the cost of any tooling that is consumed. On the other hand, the cost per unit must take account of the output quality. Thus, the formula for unit cost calculation is as follows [6]:

$$C_{pc} = \frac{C_m + C_o \cdot T_p + C_t}{P_{ap}} \quad (7)$$

where C_{pc} = cost per good piece, C_m = cost of materials including the previously added value per piece, T_p = average production time per piece, C_t = cost of disposable tooling, P_{ap} = yield from Eq. (6) and C_o = the operating hourly cost of the production module, including the equivalent hourly cost of the module's one time expenditure C_{inv} (planning, investment, first setup), the hourly cost of power supply for the system C_{pow} , the total equivalent hourly maintenance cost for the system C_{ipm} , and the hourly labor cost of operating personnel C_{lab} .

For one specific product, T_p can be calculated [6]:

$$T_p = T_c + \frac{T_{su}}{Q_b} \quad (8)$$

3.3 HIGH LEVEL OF FRs AND DPs

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

The translation of the 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. As previously discussed, in production system design two basic CAs can be identified: the market and customer **responsiveness** of the system in terms of agility, flexibility and times and the total **cost per output unit**, including fixed and variable costs, both represented by Eq. (5) and Eq. (7).

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

- FR-1: Produce the required output within the defined due date
- FR-2: Realize lowest possible unit costs

The design parameters mapped by functional requirements are:

DP-1: The production module is designed to provide the output required by customers, by downstream operations or by subsequent supermarkets within the defined due date

DP-2 The production module is designed to realize the lowest possible total cost per unit

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

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \quad (9)$$

where X represents a non zero element, and 0 a zero element.

3.4 DECOMPOSING FRs AND DPs

Since the design solution can not be finalized or completed by the selected set of DP's at the highest level, the FRs need to be decomposed further. This decomposition is done in parallel with the zigzagging between the FRs and DP's [2], [11].

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 meeting a required production rate.

- 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

By doing the zigzagging between FRs and DP's, as done on the first level, the DP's for the second level corresponding to FR-2 were identified in order to maximize independence.

- DP-11 Determine the takt time according to Eq. (5)
- 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 [6]. In this case, the process-principle should be applied: depending on the total T_c , a single-station (for $K=1$) or multi-station (for $K>1$) automated or hybrid system with fixed routing and continuous flow should be chosen.
 - (b) *Batch model case*: $K=U$. Different parts or products are made by the system. Batching is necessary due to long setup or changeover times [6].
 - (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 [6].
 - (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 (single-station system, parallel stations for $K>1$) if lead times of the single process steps vary widely and cannot be balanced.

This is usually the case with a high complexity of the production program with very different variants.

Material Handling Devices (for all cases a, b and c): Ideally, material handling wouldn't be necessary at all. A production system without material handling is not feasible, but the objective is to reduce it to a minimum. In a first step, distances between the single value adding production steps have to be shortened. To avoid "coupling" between the single stations, products ideally pass the single production steps "at a clothesline" that determines the rhythm of production. Where this is not possible, other strategies have to be found. However, the handling of materials must be performed safely, efficiently, at low cost, according to the required rhythm or takt, accurately and without damages to the materials [6]. Ten generally applicable principles of material handling help with the design of the handling devices [12]: 1. plan material handling processes, 2. standardize material handling methods and equipment 3. minimize material handling work, 4. recognize human capabilities and limitations through ergonomic design of material handling activities, 5. size unit loads appropriately to fit the objectives of material flow and inventory, 6. utilize the available space in an effective and efficient way, 7. integrate material movement and storage activities in a coordinated system of the total supply chain, 8. automate material handling where feasible, and eliminate unsafe manual labor, 9. consider environmental impact and energy consumption in the selection of material handling devices, 10. analyze the entire life cycle cost of the material handling equipment and the resulting systems

- DP-13 Visual control and fast intervention strategy to increase the availability, use of TPM principles and methods
- DP-14 Reduction and workload optimized scheduling of planned standstills, use of TPM principles and methods
- DP-15 Setup reduction: Separate work elements in (1) internal elements that must be done during machine stoppage and reduce them to a minimum, and in (2) external elements that can be done in parallel to the running previous job. Provide setup tooling and methods to permit as much external elements as possible [6]. Provide standardized, modular and quick-acting fixtures.

The design equation is represented as a decoupled matrix:

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \\ FR14 \\ FR15 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \\ DP14 \\ DP15 \end{Bmatrix} \quad (10)$$

So far, FR-1 has been decomposed using Eq. (2) and (5). For FR-2 and its decomposition, Eq. (7) will help.

- FR-21 Achieve a high yield of acceptable work units
- FR-22 Minimize labor costs

FR-23 Minimize one time expenditures

The effective design parameters (DPs) are the following:

- 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

Eq. (11) shows again a decoupled design:

$$\begin{Bmatrix} FR21 \\ FR22 \\ FR23 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ X & 0 & X \end{bmatrix} \begin{Bmatrix} DP21 \\ DP22 \\ DP23 \end{Bmatrix} \quad (11)$$

3.5 NEXT LEVEL DECOMPOSITION

Decomposition of FR-21 refers mainly to P_{ap} and aims at the elimination or reduction of q and m .

- FR-211 Ensure defect free input material
- FR-212 Prevent making defects throughout the process
- FR-213 Do not advance defective parts to the next production module(s) and make sure, that defective parts do not create a station jam

The design parameters mapped by functional requirements are:

- DP-211 Initial quality check prior to process start
- DP-212 Use of standards and devices to prevent defects as well as Poka Yoke methods (e.g. contact, counting, motion-sequence)
- DP-213 Use of in-process and successive checks and devices to detect and eliminate defective parts, use of “decouplers” in inline multi-station systems to prevent the risk of station jams (see [2], pp. 311)

The matrix shows an uncoupled design:

$$\begin{Bmatrix} FR211 \\ FR212 \\ FR213 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP211 \\ DP212 \\ DP213 \end{Bmatrix} \quad (12)$$

The next decomposition of FR-22 aims at the reduction of labor costs. It establishes the connection to the field of ergonomics, workplace and work time organization and performance motivation through intelligent job design.

- FR-221 Eliminate or reduce non value adding activities
- FR-222 Enable worker to operate more than one machine or station
- FR-223 Plan resources to produce with different volumes

Effective DPs to implement FR-22x may be selected as:

- DP-221 Short distances between components, worker and task to eliminate wasted movement
- DP-222 Multi-functional worker (qualification, job rotation)

DP-223 Work time flexibility in combination with a direct and measurable relation between output and production hours of resources

Also this matrix shows an uncoupled design:

$$\begin{Bmatrix} FR221 \\ FR222 \\ FR223 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP221 \\ DP222 \\ DP223 \end{Bmatrix} \quad (13)$$

To minimize one-time expenditures with modular system components, F-23 has to be decomposed to provide some more help to the system designers:

- FR-231 Acquire only system components with a cycle time that fits to the required takt time
- FR-232 Ensure flexibility to accommodate capacity increments at lowest cost
- FR-233 Develop flexible tooling or prevent the need for different tools
- FR-234 Ensure flexibility to accommodate future products

The effective design parameters for these are:

- DP-231 Modular system components focused on customer demand pace and value-added work
- DP-232 Capacity extension by reproducible design of system components
- DP-233 Flexible tooling design; standardization of tasks to reduce the number of different tools
- DP-234 Movable machines and reconfigurable stations to enable new system design

Eq. (14) shows a decoupled design:

$$\begin{Bmatrix} FR231 \\ FR232 \\ FR233 \\ FR234 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP231 \\ DP232 \\ DP233 \\ DP234 \end{Bmatrix} \quad (14)$$

4 CASE STUDIES

4.1 SINGLE MODEL CASE

The first example shows the practical application of the presented approach in automotive supplier industry. The company produces sub-assembly groups for electronic devices with yearly volumes of millions of units.

The sub-assembly group SAG-3 had been redesigned for a new series of products and has to be produced in 7 variants (SAG-3.1 to SAG-3.7) with an average daily output of 6.550 pieces. Every component consists of one base plate, three distance holders and one insert part. Variants are determined just by the variation of the components, with no changes to the assembly process. A new or optimized production module for the assembly of SAG-3 has to be designed with a special focus to cost efficiency and reusability of the concept, because the customer guarantees the volumes for just one year, afterwards the production of the sub-assembly family SAG-3-x could possibly be re-integrated into the

customer’s own production lines. However, the current production of the “old” SAG-3-x product family has a productivity of 400 units per hour in two shifts in a hybrid assembly system with one worker per shift loading and unloading. The objectives: $Q = 1,440,000$ pcs/year, $P_{ap} = 0.999995$ (5 ppm – parts per million), $S = 220$ days, $H = 8$ hrs, $T_{ps} = 1.5$ h/week = 66 hrs/year, $A = 0.95$ (95%), $T_{su} = 0$ (!)

Thus, T_{takt} is calculated according to Eq. (5):

$$T_{takt} = \frac{0.999995 \cdot 0.95 \cdot (220d \cdot 8h/d - 66h - 0) \cdot 3600s/h}{1,440,000unit} = 4s/unit$$

With a takt time of 4 seconds (DP-11) and constantly high production volumes with no significant variations within the selected product family, FR-12 can be satisfied by choosing the single model case (a) within DP-12: a hybrid or automated system designed according to the process-principle. The necessary assembly operations are quite simple and easy to automate, with a total (value adding) assembly time of 12 seconds without loading and unloading. Using Eq. (2) for T_{ass} , K_{ass} can be determined: $K_{ass} = 3$. Thus, at least three sequential process steps within the assembly system are needed. According to the principles of material handling, distances between the single process steps are shortened and the products are moved from one to the next station with no “pick-and-drop” operation necessary.

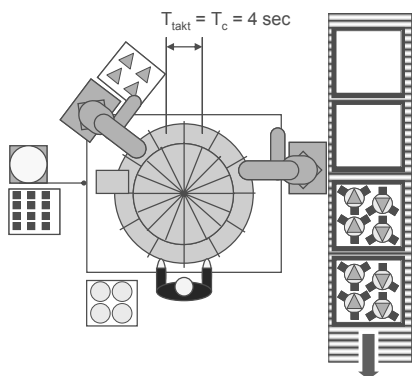


Figure 3: The redesigned assembly workstation concept

Unloading is easy to automate. However, automation of the loading operation for the base plate requires some effort with the risk of mistakes. Thus, this loading operation should possibly be subject to manual material handling. An accurate MTM analysis showed that this operation could be performed manually within the required takt time. Thus, a single shift operation with just one worker is feasible. Productivity is increased by about 100% from 400 units per hour to more than 800 units per hour.

The introduction of TPM (total productive maintenance) will make sure, that unplanned and planned standstills are reduced to a minimum (DP-13 and DP-14). To achieve the target of $T_{su}=0$, standardized devices for the parts transport and fixture within the system are used (DP-15). A rigid quality control (DP-211) of incoming materials ensures a defect free input material for the production module. The design of the process steps according to Poka Yoke principles helps to prevent defects during the assembly process (DP-212). A 100% quality control is required by the customer. With a given takt time of just 4 seconds, this check must be performed by an automated station at the end of the

process just before unloading the parts into a transport container. Defective parts must be immediately removed. Only good parts are passed on (DP-213).

FR-22 refers to the reduction of labor costs. Still the system is designed with one worker doing loading operations. Keeping this manual operation, the container with the base plates must be placed close to the worker, with an autonomous refilling system (e.g. a “milk runner” who refills the feed track when moving away the finished goods container), so that operations can be performed in an efficient way (DP-221). To enhance work life quality by keeping monotony as low as possible and to guarantee interchangeability of workers a regular and consequent job rotation is introduced (DP-222). For short term adaptability, flexible work time must be introduced. In this case, this is done within the entire production system: supermarket pull systems guarantee certain volume adaptability; work time flexibility makes sure that peaks are manageable (DP-222).

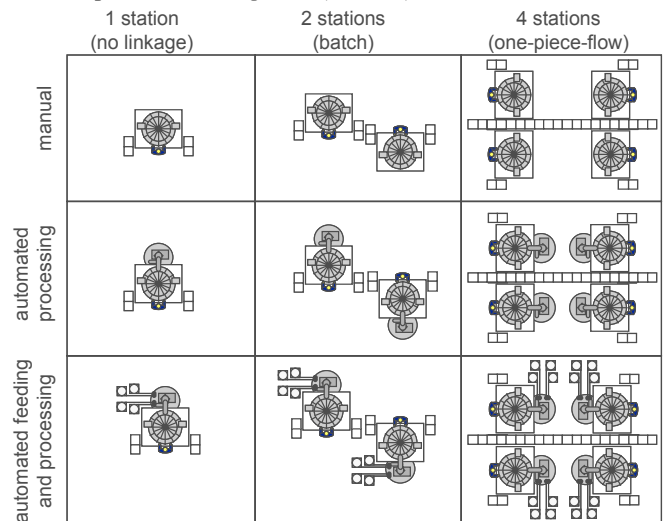


Figure 4: Modular hybrid assembly system [13]

FR-23 aims at the minimization of one-time-expenditures. The company produces a wide variety of assembly groups with very similar characteristics. Thus, a modular (DP-231) assembly system has been introduced that can be flexibly combined (DP-232) to adapt to changing variant and volume requirements (Figure 4, taken from [13]). Tools and handling devices are designed to be used for different purposes (DP-233). The assembly workstations are moveable and can be flexibly combined (DP-234). Figure 3 shows the chosen concept. However, the conception of a specific parts feeder, selector and orientor system for the handling of the base plate is still interesting and could help to eliminate manual feeding operation.

4.2 MIXED MODEL CASE

In this example, it is presented how the production module template approach has been used to solve a design problem of a producer of shower cabins. The main reason for the company to change the existing production system was due to a new market and product offensive that was expected to bring an increase in sales of about 30% to 40% within the next 3 years. The major

concerns of the managers about the existing plant were four fold: long order-to-delivery times, high WIP levels, limited space and low productivity. The assembly area was the first to undergo redesign in this company in order to create a better production system. In a first step, the author executed a process and information analysis for all the high volume parts in order to create information and production flows within the assembly area. All the steps in order to create an assembled shower cabin were recorded. The old system was designed to produce seven basic product types with variants in seven separate assembly lines with sequentially arranged, manual assembly stations. The huge variety of product variants caused a highly fluctuating spread of the cycle times at the single stations in the assembly lines and thus created a lot of waste due to waiting times and increased handling efforts.

In a first step, a product analysis was performed and three product families (PFA, PFB and PFC) were created according to the logical manufacturing sequence and similarities of the products. This case study just deals with one of these product families, called PFA.

Then the objectives for the future state of PFA were defined: $Q = 183,000$ pcs, $P_{ap} = 0.997$ (99.7%), $S = 220$ days, $H = 8$ hrs, $T_{ps} = 40$ hrs, $A = 1$ (100%), $T_{su} = 0$ (!)

Thus, T_{takt} is calculated according to Eq. (5):

$$T_{takt} = \frac{0.997 \cdot 1 \cdot (220d \cdot 8h/d - 40h - 0) \cdot 3,600s/h}{183,000unit} = 33.7s/unit$$

Starting from a required takt time of 33.7 seconds per unit (DP-11), the future state map was developed following the seven basic rules of [4]. In a first step, several production modules were defined as “black boxes” in the future state map and then designed according to the design principles for production module templates presented in chapter 3. In the following, practical application of the template will be demonstrated by the example of the production module “final assembly”. The product family PFA is characterized by a huge variety of derivatives. Differences in product dimensions and in the types of fixings do not permit automation of the final assembly processes. Furthermore, stepwise assembly in sequentially arranged assembly stations is not recommendable, because the single steps cannot be well balanced due to different process times. Thus, an object-oriented design of the assembly process was chosen: a “single-station manual cell” according to the mixed model case (c.2) in DP-12.

With the help of MTM (methods of time measurement), the standard assembly time was determined (PFA average: $T_c = 312$ seconds). With Eq. (2), the K-factor can be determined: with $K > 1$, $K = 10$ (maximum integer of 9.25). Thus, ten parallel working single-station manual assembly cells will be necessary. FR-13 is satisfied by the introduction of a visual warning signal at every single assembly cell, the line manager will immediately try to solve the problem. However, a TPM (total productive maintenance) strategy will make sure, that unplanned and planned standstills are reduced to a minimum (DP-13 and DP-14).

To avoid setup times (target: $T_{su} = 0$), the assembly cell has to be designed to fit for every product type. Eventual devices for the fixture of components should flexibly adapt to different dimensions without need for individual setup (DP-15). To enhance the yield of good parts produced (P_{ap}), the next level

FRs of FR-21 have to be satisfied. The establishment of a rigid quality control (DP-211) of incoming materials ensures a defect free input material for the production module. The design of the process steps according to Poka-Yoke principles helps to prevent defects (DP-212). Finally, every worker makes a quality check at the end of the process. Defective parts must be immediately signed and removed. Only good parts are forwarded. A barcode sticker with the responsible worker’s identification number ensures direct re-traceability of eventual defects (DP-213).

FR-22 refers to the reduction of labor costs. Where human workforce cannot be replaced by automated systems, workplaces have to be organized in order to eliminate unnecessary operations, like excessive transporting of parts, walking to another location to get the necessary tools, stockpiling intermediate products, changing hands to pick up parts, etc. According to [13], FR-221 can be satisfied by the systematic elimination of non value adding moving and handling operations. Ideally, all necessary components and tools are placed around the worker, so that operations can be performed without any excessive movements or handling (DP-221).

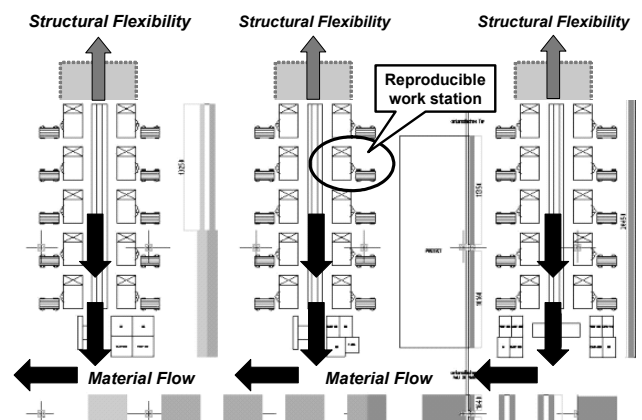


Figure 5: Flexibility through reproducible work stations

Within PFA, every workplace has to process the same variant complexity. This requires an appropriate qualification of the workforce. Interchangeability of workers between the three segments of different product families is created by regular and consequent job rotation (DP-222). FR-223 aims at a volume flexibility of resources. For short term adaptability, flexible work time must be introduced. Longer periods of over or under capacity can be managed by activating or deactivating capacity increments with a predictable output rate. In an object-oriented design, every single workplace has a defined productivity. Thus, capacity can be adapted in steps of 10% ($K=10$; see Figure 5).

To minimize one-time expenditures (FR-23), modular system components should be used (DP-231). The company decided to introduce a standard set of components (norm profiles, fixings and pneumatic components) to be used companywide for the realization of assembly systems. However, creating always different cells with standard components would still not be the best way to minimize the one-time expenditures. Efficiencies of scale may be obtained by the flexible extension of capacity with reproducible cell concepts (DP-232). A large number of variants raise the risk of increasing tooling cost. A flexible tooling design

helps to reduce tooling cost and prevents increases in labor cost due to extra handling of different tools. In this practical case, tools are needed for screwing and sealing. Standardization of screws and sealing rubber helped to reduce the number of tools to a minimum (DP-233). The flexibility to accommodate future products (FR-234) is ensured by the cell's design concept: the standardized components (see also DP-231) can be easily adapted to changing requirements (DP-234).



Figure 6: The new single-station manual assembly cell

The result of the systematic use of the production module templates: the new designed single-station manual assembly cell (Figure 6). Some of the results created by redesigning the assembly area are the following:

1. Assembly time of PFA units decreased by 45 % already 4 months after the roll-out of the new concept
2. Perfect fit to customer demand: work in progress inventories reduced by more than 60 %
3. Space reduction by more than 30%
4. Higher RFT-rate (right first time rate) of final products (before: $P_{ap} = 0.993$; after: $P_{ap} > 0.997$)
5. 100% re-traceability of product defects
6. Maximum volume flexibility: optimal adaptation to required volumes, daily variations in planned average volume of $\pm 40\%$ are feasible
7. High variant flexibility: biggest lot size of one type of product is 5 pieces.
8. Motivated workforce through higher responsibility and better identification with the product

Calculating the total cost per unit according to Eq. (7) with a payback period for the investments of 3 years, a cost reduction of € 1.75 per unit produced could be obtained for product family A. Thus, just for PFA an annual cost reduction of about 320,000 € could be achieved. In total, yearly manufacturing cost was reduced by nearly one million €.

5 CONCLUSIONS

The theory of Axiomatic Design demonstrates to be an effective tool for the conceptual modeling of production systems, serving as a guideline in the design process.

One of the most important advantages of Axiomatic Design is its hierarchical structure, which helps to handle design complexity. In this paper, an approach was presented that uses Axiomatic Design for the conceptualization of a general applicable template for production module design. Several successful implementations demonstrated the validity of the presented method.

6 REFERENCES

- [1] Brown, S., 2000, *Manufacturing the Future*, Pearson Education Limited
- [2] Suh, N.P., 2001, *Axiomatic Design: Advances and Applications*, Oxford University Press
- [3] Spath, D., Matt, D., Riedmiller, S., Selinger, G., 1999, Productivity oriented Process Planning and Control for Production, *Manufacturing Systems*, Vol. 29 – n°. 2, 1999, pp. 179-183
- [4] Rother, M., Shook, J., 1998, Learning to See. Value Stream Mapping to Create Value and Eliminate Muda, *The Lean Enterprise Institute*
- [5] Cochran, D. S., Eversheim, W., Kubin, G., Sesterhenn, M. L., 2000, The Application of Axiomatic Design and Lean Management Principles in the Scope of Production System Segmentation, *The International Journal of Production Research*, Vol. 38, No. 6, 1377-1396.
- [6] Groover, M.P., 2001, *Automation, Production Systems and Computer Integrated Manufacturing*, Prentice Hall, Inc.
- [7] Züst, R., Schregenberger, J. W., 2003, *Systems Engineering – a Methodology for Designing Sustainable Solutions in the Fields of Engineering and Management*, Verlag Eco-Performance (in German)
- [8] Reynal V. A., Cochran D. S., 1996, Understanding Lean Manufacturing According to Axiomatic Design Principles, *The Lean Aircraft Initiative*, Report Series, #RP96-07-28.
- [9] Matt, D.T., 2005, Design of self-contained, adaptable factory modules, *Proceedings of the 1st International Conference on Changeable, Agile, Reconfigurable and Virtual Production - CARV 2005*, Munich.
- [10] Houshmand, M., Jamshidnezhad, B., 2002, Conceptual Design of Lean Production Systems through an Axiomatic Approach, *Proceedings of ICAD2002 Second International Conference on Axiomatic Design*, Cambridge, MA.
- [11] Cochran D. S., Reynal V. A., 1996, Axiomatic Design of Manufacturing Systems, *The Lean Aircraft Initiative*, Report Series, #RP96-05-14.
- [12] CICMHE, 1997, *The Ten Principles of Material Handling*, College Industry Council on Material Handling Education, *Material Handling Institute*, Charlotte, North Carolina.
- [13] Lotter, B., Hartel, M., Menges, R., 1998, Manuelle Montage wirtschaftlich gestalten, *Expert Verlag (in German)*