Axiomatic Design as a Tool to Develop a Global Production Strategy in Transportation Industry

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Abstract. Manufacturers of almost every industry sector face the challenge to develop and constantly adapt their production strategy according to a changing political and economic environment. A well aligned production strategy is the basis to satisfy customer demands, create competitive advantage and therefore expand the market share. In an increasingly globalized economy, global production strategies and the design of global value chains become more and more important to gain sustainable competitive advantage in global markets. This is, to a large extend, a management challenge that inheres a change in strategy in terms of network design, process technology and manufacturing, leadership, and training, and forecasting and planning. To master these challenges Axiomatic Design (AD) was used to derive concept design parameters based on the analysis of customer attributes (CAs). Coming from the definition of internal stakeholders of the production strategy, CAs were defined and matched with system and company internal constraints. The remaining CAs were grouped into a set of functional requirements and broken down to an implementable set of design guidelines for a global production strategy. The results show a global production strategy approach based on five independent pillars while the decomposition allows to point out important interdependencies and helps to schedule an implementation process of the strategy.

Keywords: Axiomatic Design, Global Production Strategy, Sustainable Manufacturing, Industry 4.0.

1 Introduction

Complex systems require special treatment and attention in every phase of their life cycle. Especially in the design phase crucial elements, stakeholders and limitations need to be identified to create a holistic view on the target. The tradeoff between market, product and process requirements is the starting point of the analysis of production systems. Based on these dimensions and the individual company profile a first impression on the complexity and diversity of a future global production strategy is created.

The motivation to create a suitable production strategy is five-dimensional. The first and leading element of the motivation is **profit maximization**. This can be seen as the overall company goal independent from the industry sector. Going into more detail, increasing, or at least retaining, **market share** is crucial in public transportation due to the constant pressure from competitors. Flexibility and adaptability in critical to fulfill the latest market requirements. For this reason, it is highly aimed to provide **individual customer solutions**. This implies the product design as well as the lead time from engineering to delivery. Through these individual solutions, **competitive advantage** can be created. Being close to the customer, physically in terms of production and virtually in terms of administration, is key. The fifth pillar therefore is the increase of **internal flexibility** by well trained staff that can be employed more flexible when demand changes. To master this multi-dimensional task, a proper production strategy needs to be worked out and aligned to internal and external requirements.

2 Theoretical Background

The design of an adequate production strategy including the applied tools, mechanisms, and strategic measures as well as an aligned global production network play a significant role for a successful production.

2.1 Production Strategy and Systems

Since the 1960's strategic management is treated as a separate discipline in business administration which has developed and continuously evolved over the past decades from being based on empiric values to scientific modelling and market-specific approaches [1]. Production strategy often is defined as the exploration and exploitation of production capabilities by structural and infrastructural decisions to achieve a unique strategic position in the market, which matches overall business objectives [2, 3, 4].

To define a production strategy, internal and external analysis need to be executed. The external analysis helps to determine the position of the company in the market. The internal analysis has the purpose to set strategic goals for the production. Additionally, companies face the challenge to act agile and flexible concerning a changing business environment and customer demands [5]. A traditional SWOT (Strengths, Weaknesses, Opportunities and Threats) Analysis is a common tool in this first phase of the strategy design process [6]. Opportunities and Threats represent the two dimensions for the external, Strengths and Weaknesses the perspectives of the internal analysis.

2.2 Manufacturing Industry for Public Transportation

The following information has been collected through interviews with managers and experts in the rail sector.
Movement on tracks is a widely accepted mode of transport which is globally established since decades. The energy consumption with respect to the transported volume is significantly lower compared to other modes of transport. The rail industry is dominated by several big players in the market which either produce most of the components in house or rely on suppliers to produce the rail setup.

The rail industry is majorly characterized by project business. Public tenders determine the award process and are mostly driven by local governmental interests. Local content requirements, customer specific solutions, and governmental budgets request highly flexible production structures of OEMs and their suppliers and therefore increase product complexity and variances. The production of this product portfolio is mostly synchronized in one production line for optimized utility which further increases complexity and the need for agile production structures.

Despite the ongoing trend of urbanization in cities and the continuous interconnection on a national and international level, forecasts in the rail industry are hardly possible. Investments in infrastructure can affect several types of local or long-distance transport. These factors impede the overall forecast. As the railroad sector usually is state-owned, advancement and development are depending on political developments.

Additionally, requirements concerning safety are highly important in the industry as the transportation of passengers is risk critical. Further criteria are stability, resilience, robustness, and longevity as rail vehicles are commonly used up to 40 years.

2.3 AD for Global Production Strategies

The Axiomatic Design (AD) method is a top-down approach that belongs to systems theory and was invented by the scientist Nam P. Suh in the mid-seventies [7]. The purpose of AD was to find a method to control complex and interconnected systems [8].

The basis of AD are four domains in which aims, and requirements are specified. Within the customer domain (for production strategy: internal and external stakeholders) the aims of the customers (customer attributes - CAs) are defined [9]. The functional domain shows a deduction of the CAs and translates those attributes into functional requirements (FRs). FRs indicate the required function of the production strategy to satisfy a certain CA [10].

The physical domain consists of design parameters (DPs) and guidelines that provide a solution for the defined requirements. The process domain is the final domain within AD that converts design guidelines into measurable process variables (see Figure 1).

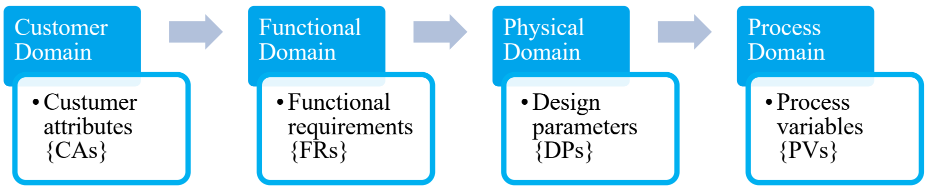

Fig. 1. The four domains in Axiomatic Design [11]

FRs and DPs are intended to build pairs. While FRs describe the requirement in an active way, the DPs represent the implementable result to fulfill the FRs. Within the matching process of FRs and DPs two axioms need to be considered [12].

> Axiom 1 - Independence axiom: FRs are independent from each other, meaning that requirements of the functional domain should be satisfied

by one design element of the physical domain [8]. The system is called ideal when there is no correlation between the elements [13].

Axiom 2 - Information axiom: The second axiom conveys that if there is more than one solution (DP) to a requirement, the one offering the least informative content should be preferred [8].

The requirements and design elements within the AD approach are becoming more detailed as the so-called decomposition of the top FRs is executed. A hierarchical tree structure evolves until an implementable level of design elements, the design guidelines, is reached [7]. DPs are mapped to FRs and with the "zigg-zagging" unspecified DPs are developed further to more detailed FRs [13]. The result of the decomposition process is the design matrix (DM) set up by the following Equation 1 [12].

Equation 1: $\{FR\} = [DM]*\{DP\}$

3 Concept Design for a Global Production Strategy

With the aid of the AD approach the concept design for a global production strategy is worked out. After the deduction of CAs and system constraints the leading FR's are derived. The presented concept design can be applied to other production strategy development initiatives with similar characteristics.

3.1 Deduction of Customer Attributes

Within a conducted workshop the stakeholders of a global production strategy were analyzed. The focus was on requirements towards strategy including the company vision and the business unit goals. These requirements represent the CAs of the AD approach. Additionally, system constraints were formulated that may interfere with strategy objectives and therefore might influence the design guidelines of the strategy.

It was agreed that, besides local governments, only internal stakeholders will be considered and can be subdivided into managing instances and affected departments. The requirements of OEM customers are represented by the sales department. The following list shows the stakeholders that are considered for further analysis (see Table 1).

Table 1: Stakeholders of a global production strategy

Managing instances	Affected departments
• Trustees / Owner	• Global and Local Sales
• Managing directors	• Procurement
• Business unit managers	• Operations
• Site managers	• Quality Management
Others	
• Local governments	

From these stakeholders CAs are be derived. An abstract of the most relevant attributes is displayed in Table 2.

Table 2: Abstract from CAs derived from stakeholder analysis

No.	Stakeholder	Customer Attribute
CA_1	Trustees // Owner	Long-term competitive advantage
CA_2	Business unit managers	Maximize profit over all sites
CA_3	Business unit managers	Use capacities of all sites
CA_5	Site managers	Maximize profit at own site
CA_6	Site managers	Use capacities of own site
CA_8	Trustees / Owner Managing directors	Increase or retain market share
CA_{10}	Procurement	Transparency of long-term demands
CA_{13}	Global and Local Sales	Fulfill local content requirements
CA_{16}	Quality Management	Produce at local quality requirements
CA_{17}	Workers Council	Safe jobs and employment
CA_{18}	Operations	Generate high productivity
CA_{20}	Operations	Be able to react to demand volatilities

Coming from the overall objective the following superior FR for the development of a global production strategy is defined:

FR0 Create organizational and functional framework to maximize profit

To meet this requirement the corresponding solution approach on the physical design domain DP0 is dedicated:

DP0 Global Production Strategy

3.2 Determination of Top-Level Functional Requirements

The overall goal to maximize profit (first level of FR and DP pairs) can be deducted within a systematic and structured decomposition process (see Table 3). In addition to the previously defined CAs also the first level of FRs and DPs was aligned within the interviews with strategically important stakeholders of the production strategy (see Table 1 and 2).

Table 3: Decomposition FR_0 - Level 1

FR_1	*Create an efficient production network*	DP_1	*Production Network Strategy*
FR_2	*Produce requested quality at minimum cost*	DP_2	*Operations and Manufacturing Strategy*
FR_3	*Ensure high education of employees on every level*	DP_3	*Know-How and Training Strategy*
FR_4	*Ensure accurate forecasting and planning on different hierarchy levels for production*	DP_4	*Forecasting and Planning Strategy*
FR_5	*Push innovation, digitalization, and automation in production*	DP_5	*Process Technology Strategy*

The result is the categorization into the five pillars of the production strategy. Each pillar can be seen as an individual strategy to serve the previously defined FR-DP_0 requirement.

These five categories build the foundation of the production strategy. The pillars Production Network, Operations and Manufacturing, Know How and Training, Forecasting and Planning, and Process Technology are independent, and their design-matrix shows an uncoupled structure (see Equation 2) which was confirmed during the interview and workshop sessions held with the stakeholders.

Equation 2: $$\begin{pmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \\ FR5 \end{pmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} * \begin{pmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \\ DP5 \end{pmatrix}$$ *"uncoupled"*

3.3 Decomposition of Functional Requirements

For demonstration reasons the first pillar is decomposed in the following section. The analysis of the first pillar (FR1) shows that three partial requirements can be derived (see Table 4).

Table 4: Decomposition FR_1 - Level 2

FR_{11}	*Generate a clear understanding of the production landscape*	DP_{11}	*Criteria and categorization of production sites*
FR_{12}	*Decrease production cost*	DP_{12}	*Grouped and connected production sites for a network*
FR_{13}	*Decrease logistics cost*	DP_{13}	*Standard allocation process for customer orders*

The DM for this section of the decomposition shows a decoupled design as for increased efficiency (DP_{12}) and the optimal choice of a production site (DP_{13}) the production site set-up needs to be analyzed and assessed (DP_{11}). Additionally, the efficiency effects within a designed production network have a heavy impact on logistics cost, which is explained in lower levels of detail in the following paragraphs (see Equation 3).

Equation 3: $$\begin{pmatrix} FR11 \\ FR12 \\ FR13 \end{pmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & X & X \end{bmatrix} * \begin{pmatrix} DP11 \\ DP12 \\ DP13 \end{pmatrix}$$ *"decoupled"*

Both pairs (FR-DP_{12} and FR-DP_{13}) require a further decomposition which is not shown in the following section of this paper. The procedure of the decomposition is exemplarily shown for the pair FR-DP_{11}). The following figure (Fig. 2.) shows an abstract of the tree chart to visualize dependencies and levels of detail within the decomposition starting from FR/DP_{11}.

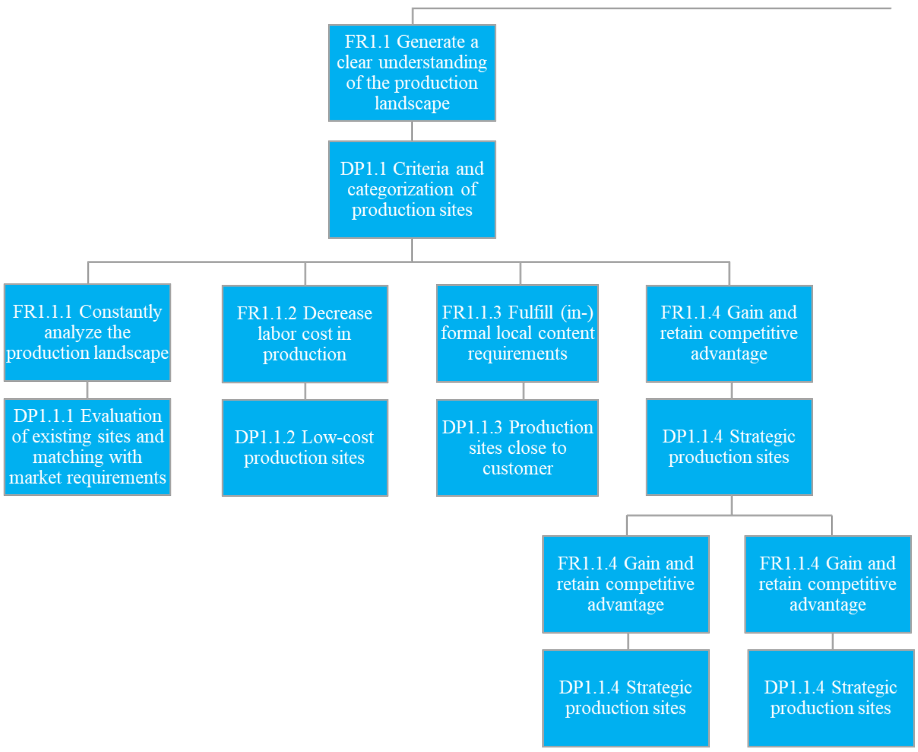

Fig. 2. Exemplary Decomposition of FR_{11}

All three second level subcategories can be split up further into the next level of partial requirements. The constant screening and evaluation of existing sites is essential to react to a changing market environment (FR/DP_{111}). In order to remain competitive and decrease labor cost, it is recommendable to install low-cost production sites (FR/DP_{112}). Local content requirements and short delivery lead times can be generated by production sites close to important customers (FR/DP_{113}). An additional leverage is possibility of geographical proximity is to create stronger business relationships. To gain und to retain sustainable competitive advantage the establishment of strategic production sites is advisable (FR/DP_{114}).

Again, the DM shows a decoupled design as for the configuration of low-cost, geographically close, and strategic production sites the evaluation of all sites in necessary (see Equation 4).

Equation 4: $$\begin{pmatrix} FR111 \\ FR112 \\ FR113 \\ FR114 \end{pmatrix} = \begin{bmatrix} X & O & O & O \\ X & X & O & O \\ X & O & X & O \\ X & O & O & X \end{bmatrix} * \begin{pmatrix} DP111 \\ DP112 \\ DP113 \\ DP114 \end{pmatrix}$$ *"decoupled"*

Strategic production sites have two different purposes in the described framework. This is detailed further in the next decomposition step. Strategic production sites come in two different shapes. One aim can be to dispel competitors from strategically important markets (FR/DP_{1141}). The other is to shorten development and engineering times ("time-to-market") by the establishment of technology factories with focus on R&D activities and product development (FR/DP_{1142}). The DM for this section is uncoupled.

4 Application Use Case: Global Production Strategy Design in Transportation Industry Sector

The final level of DPs in each pillar of the production strategy is considered the set of design guidelines that need to attain the desired effects and finally satisfy the previously defined CAs. In the following section all design guidelines are summarized and grouped in work packages.

4.1 Design Guidelines

Production Network Strategy
The Production Network Strategy consists of three different work packages. At first the **production site classification** is executed by the evaluation of the existing production landscape and the categorization of existing production sites towards their purpose (low-cost, closeness to customer, strategic, lead factory).
The next step is the **set-up of a production network**. It needs to be decided whether the entire production landscape or only several sites are linked within in a network. Regular and automated data exchange is installed between the sites of the production network and a superior instance to manage and control the network is established. Additionally, continuous reviews of the network and the remaining sites are performed to adapt the production according to changing internal and external influences.

The third package is about a **standard allocation process**. Once defined, it should ease the allocation of production orders (especially within the network) in terms of time and cost and should consider all relevant stakeholders.

Operations and Manufacturing Strategy
The Operations and Manufacturing Strategy is subdivided into three work packages that basically cover the fields of **lean management process tools** with the implementation of global and local process experts as well as the integration and documentation of standard production processes. Additionally, **best practice approaches** need to be pushed by global and local experts and incentives need to be set at sites to pursue group goals not site goals.

Know-How and Training Strategy
For the Know-How and Training Strategy two different dimensions need to be covered. The first one is to **enable management** employees to communicate globally and create a mutual understanding of the production processes and objectives. Additionally, know-how losses due to employee fluctuation need to be prevented. The second dimension is about the **production know-how** of manufacturing employees and the development of a training program. Furthermore, the employee training needs a proper location and set-up to be efficient.

Forecasting and Planning Strategy
The Forecasting and Planning Strategy is a two-dimensional workspace covering **regular exchanges** with sales and the set-up of a comprehensive production execution and planning. The continuous **tracking of capacities and capabilities** over all sites as well as the planning of future production activities starting from this general overview is core of this work package.

Process Technology Strategy
The Process Technology Strategy again is a two-dimensional workspace. At first the **basis for automation and innovation** needs to be created by comprehensive and structured master data care and the capturing of all essential production data. These are translated into a reporting system where first control relevant indicators are defined and then transferred into a KPI reporting. With an established KPI reporting, the basis for site comparisons is given and a benchmarking system can be implemented.

Production optimization takes place in three separate dimensions. The first one is the immediate instance responsible for trouble shooting of urgent requests. The second dimension is the standardization of processes and components, and the third dimension covers the product and process optimization.

4.2 Timeline

A big advantage of the AD method is the possibility to derive the timeline directly from the strategic content. The previously defined independence of the five pillars technically indicates, that the implementation of all five pillars can start simultaneously. By applying this approach to the use case, it becomes clear that (in this specific case) certain design elements need to be established prior to others. Within a strategic pillar the DMs clearly determine the order of work packages for a successful implementation.

Therefore, it is recommended to start with the first and second pillar of the production strategy. It is important to note that due to the independence axiom the work packages must be processed in the given order to avoid negative correlations.

5 Discussion and Conclusion

The developed model of a five-pillar global production strategy is a comprehensive and holistic approach that supports medium-sized companies with global production and a high ratio of manual production processes to formulate their individual production strategy. With little assumed fundamentals the developed work packages allow the user to build a company strategy from top management goals. Besides the consideration of the global production network and the integration of production sites to increase efficiency, also site internal topics are touched. The emphasis on standardized processes and clearly defined responsibilities is the heart of the operations and manufacturing. New to this approach is the emphasis on the people's education and development which is essential for highly manual manufacturing. The enabling of workforce on every company level to act in an international context as well as executing defined production processes with highest precision is key to successful operations. Forecasting and planning is essential to provide a comprehensive view in the global production strategy. Process technology in the sense of digitalization, automation, and innovation technically is not new to the theory of production strategies. However, multiple (especially medium-sized) companies struggle with the integration of innovative activities into the live production. This gap is closed by the two-dimensional design of this production strategy pillar, data base and competitive advantage. Bringing those together is a challenge for every company that tries to implement international structures and additionally requires a change in the mindset of people.

To use the methodology of axiomatic design within the production strategy development has several advantages. Besides the delivered top-down approach the approach forces the relevant stakeholders to consider all production related topics and interfaces and additionally implement the company strategy and mission. Furthermore, axiomatic design supports the strategy design workshops by a systematic guidance for workshops and interviews and provides a structure during the process. This additionally applies to the implementation phase after the strategy development as the sequencing of tasks or work packages is provided through the correct application of axiom 1 and the DM.

Even though the developed concept for a global production strategy considers different aspects and dimensions, the model still lacks the coverage of a few relevant topics. This is mainly driven by the fact that the model is developed for small and medium sized companies with no or only rough strategic elements in the production environment. It therefore focuses on laying a foundation for other strategic add-ons. It is considered most important to first create a proper basis and ensure the strategic readiness of the company before focusing on higher level design elements of the strategy. For this reason, concepts for agile manufacturing and implementation approaches for mobile production solutions are not considered in the developed model. Additionally, there is little focus on automation in production. Automation in production in only touched in the last pillar bringing in a future oriented perspective but this is not worked out in detail. Furthermore, the described and required organizational and processual changes require a high level of sensitivity with respect to a proper change management. Comprehensive communication about the desired changes and the managerial idea behind those changes is highly important for a successful implementation, as people are the main driver and therefore the most critical blockers of change.

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