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"The Application of Axiomatic Design and Lean Management Principles in the Scope of Production System Segmentation"

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Abstract

Systematic design and evaluation of segmented production system structures is subject of this paper. Recently emerged paradigms of Lean Management and Business Process Reengineering call for adaptation of production system's organizational structure to be more reactive to a volatile and diversified market behavior. One opportunity to optimize production system design is segmentation of the manufacturing enterprise into small, flexible and decentralized production units. The presented segmentation procedure utilizes an Axiomatic Design framework and supports Lean Management practices following strategic, organizational, and technological design aspects. A case study exemplifies the developed methodology to improve competitiveness of a manufacturing company.

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1 Introduction

In today's competitive environment companies are increasingly forced to respond to diverse market demands with the alignment of their organizational structure and their competitive strategies. The firm's need to respond to change with stable and long-term, yet flexible and responsive, process capabilities is greater than ever before. Up to the present, the production system and its internal structures are at the center of all entrepreneurial plans and doings to foster adaptation to actual market needs.

What do we understand as production system? The production system reflects the whole enterprise including all required functions, activities, processes, and resources to produce marketable performances.

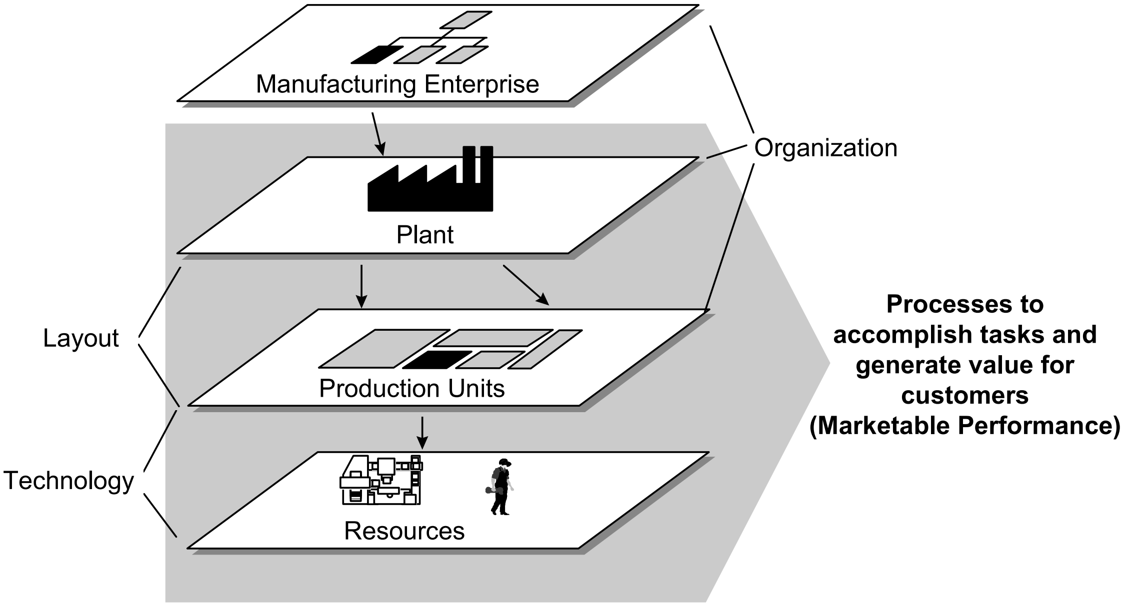

Figure 1: Focusing production system design.

A marketable performance is either a good (material product), a service (nonmaterial product), or a combination of both. Furthermore, the production system comprises all markets, customers, and suppliers as system entities. The term "process" generally describes a deliberately defined sequence of coherent actions in time and space. Objects of processing are materials and information. Processes serve three managerial tasks of the production system (Womack, Jones 1996):

1. Problem solving task: running from concept through detailed design and engineering of products and dedicated manufacturing systems to production launch.
2. Information management task: running from customer order taking through detailed scheduling to delivery.
3. Physical transformation task: proceeding from raw materials to a finished product in the hands of the customer.

The literature proliferates several "stand-alone" advances to the complex challenge of designing a flexible and responsive production system organization. However, neither theoretical development nor empirical studies through survey of industry practice is common. A systematic design procedure to structure the production system which is based on a scientific basis or a general analytical guideline has not been elaborated yet. This paper introduces a design procedure for production systems relative to generalizable principles. The procedure integrates the so called Segmentation approach with Lean Management principles and is guided by the Axiomatic Design procedure. The thorough explanation of the abstract framework of segmentation will be followed by a concrete application in industry.

2 Generic Design Aspects of Production Segments and Lean Management Practice

A segmented production system resembles a hybrid form of centralized and decentralized organizational structure. Segments are organizational sub-units of the production system with dedication to integrated processes. Fig. 2 illustrates how, contrary to a centralized organization, the process-oriented system design individually integrates certain collections of activities of the three managerial tasks to fulfill comprehensive processes.

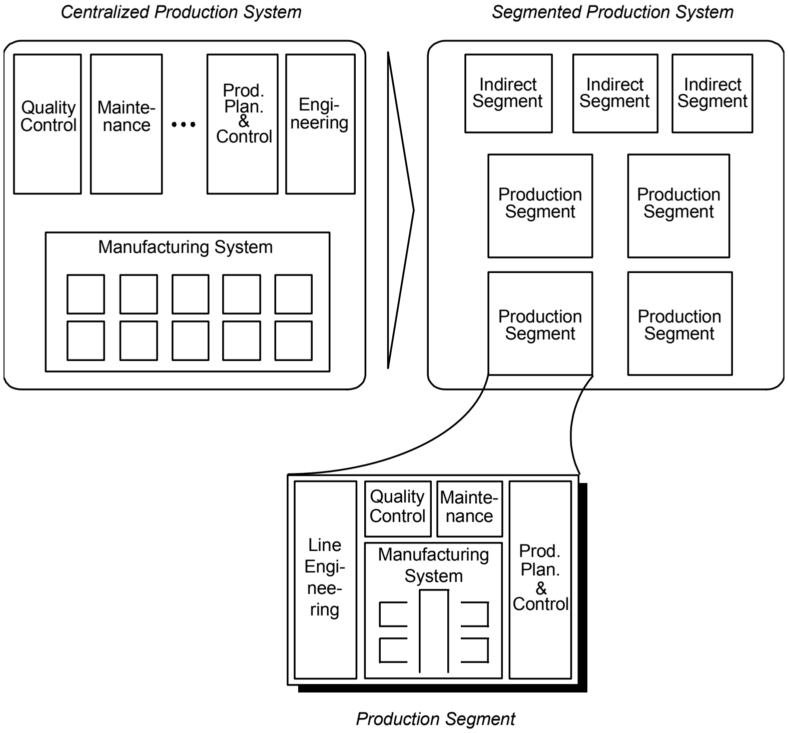

Figure 2: Segmentation decentralizes the production system organizationally and by physical layout.

Two segment types are distinguished (Wildemann 1994). Indirect segments exclusively comprise indirect functions (informational processes) and serve the production segments. Production segments always unify direct functions (operational/ manufacturing processes) and decentralized indirect functions. Goal of segmentation is the allocation of operational functions, control functions, decision making functions, and all required resources which should be unified to fulfill a defined process most effectively and efficiently (Eversheim et al. 1997, Warnecke 1992), as is illustrated in Fig. 3.

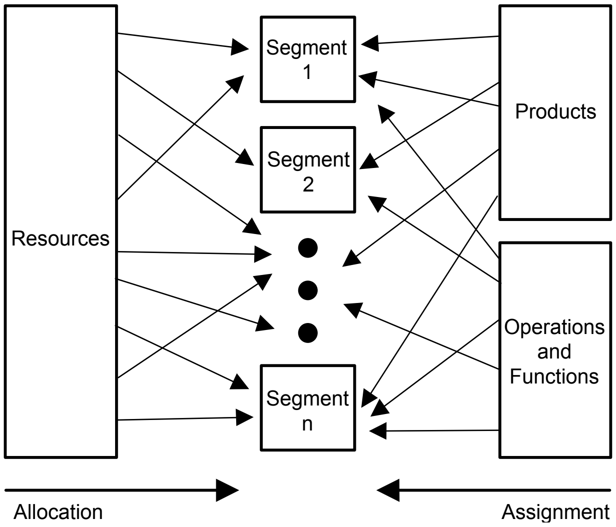

Figure 3: Formulation scenario in the scope of the segment design.

To manufacture and manage distinct classes of products, markets, customers, and combinations of those, operations and functions are aggregated to fulfill the assigned activities within the organizational unit of a segment. The design of segments synchronously optimizes three relevant system attributes: the logical boundaries of the segments, i.e. the procedure defines the integration of sub-processes, functions and operations into segments; the design of the segments' organizational and physical structure; and the linking relations between the segments (interfaces).

The concept of segmentation merges generic principles of lean production, strategic management and organization theory:

Value-Orientation

The classification of functions supporting the production system’s tasks provides a better understanding of business processes. *Value* of a performance is strictly determined by each single customer. *Value-added functions* contribute to the performance the customer desires and actually pays for. Some functions of the production system are *non-value-added* but an obligatory part of the business, as is illustrated in Table 1.

Table 1: The matrix classifies functions within the production system.

Functions	**Direct Functions** (Operational)	**Indirect Functions** (Informational)
Value-Added	Manufacturing Processing: - Fabrication - Assembly	- Product Design/Engineering - Marketing - Service - ...
Non-Value-Added	- Transport - Storage - Set-Up - …	- Capacity Planning - Accounting - Quality Assurance - ...

Process-Orientation: Decentralization of Direct and Indirect Functions

The lack of organizational integration of managerial tasks renders the control of the production system slow, bureaucratic, and hierarchical (Galbraith, Lawler 1993, Lentz 1996). Recently emerged paradigms of Lean Management (Cochran 1994, Shingo 1989) and Business Process Reengineering (Hammer, Champy 1993) call for the adaptation of the production system's structure to become more reactive to a volatile market behavior. The common approach of the process-oriented organization is the organizational allocation of functions that are interdependent to perform a desired output. The decentralization of functions into segments is to be designed so as to optimize the organization of the whole production system instead of single segments as isolated elements of it.

Integration of Marketing and Manufacturing Through Focused Design

In order to react quickly to changes in volume demand and product mix on the manufacturing system level, two requirements have to be satisfied. First, marketing and sales functions are integrated with manufacturing functions by organizational structure to ensure a close communication and fast reconciliation about a feasible manufacturing strategy. Second, the manufacturing system is designed to accommodate the required volume and product flexibility. Table 2 characterizes some generic manufacturing system types (Black 1991, Cochran, and Charles 1997). Lean Manufacturing Cells e.g. satisfy the system requirement of high volume flexibility.

Table 2: Characteristics of generic manufacturing system types.

Tendency	Volume Flexibility	General Product Flexibility	Product Life Cycle
Job Shop	*High*	*High*	*Short*
Flow Shop	*Medium*	*Medium*	*Medium*
Transfer Line	*Low*	*Low*	*Long*
Lean Manufacturing Cells	*High*	*Medium*	*Medium*
Multi-Functional Machine	*High*	*High*	*Short*
Flexible Manufacturing System (FMS)	*Medium*	*High*	*Medium*

According to actual market demands the competitive strategy defines requirements for the manufacturing system concerning costs, flexibility, delivery capability, and quality (Hayes, Wheelwright 1984, Skinner 1974). Segments concentrate their resources to a manageable group of products, technologies, unit rates, and markets.

Work Organization in Accountable Teams

Decentralization of functions enhances utilization of empowered teams. Wickens defines a team as a "group of individuals whose individual contributions are recognized and valued, and who are motivated to work in the same direction to achieve clear, understood, and stretching goals for which they are accountable" (Wickens 1993). The objective to diffuse market pressure and a continuous improvement culture throughout the production system is realized controlling production segments by performance measurement (for details compare Kaplan, Norton 1992). Entrepreneurial "freedom" of an accountable team is an incentive and responsibility at the same time for management of the segment as a small business within the whole business.

Segmentation in Two Dimensions

Segmentation follows two dimensions: "Vertical Segmentation" and "Horizontal Segmentation" (compare Fig. 4).

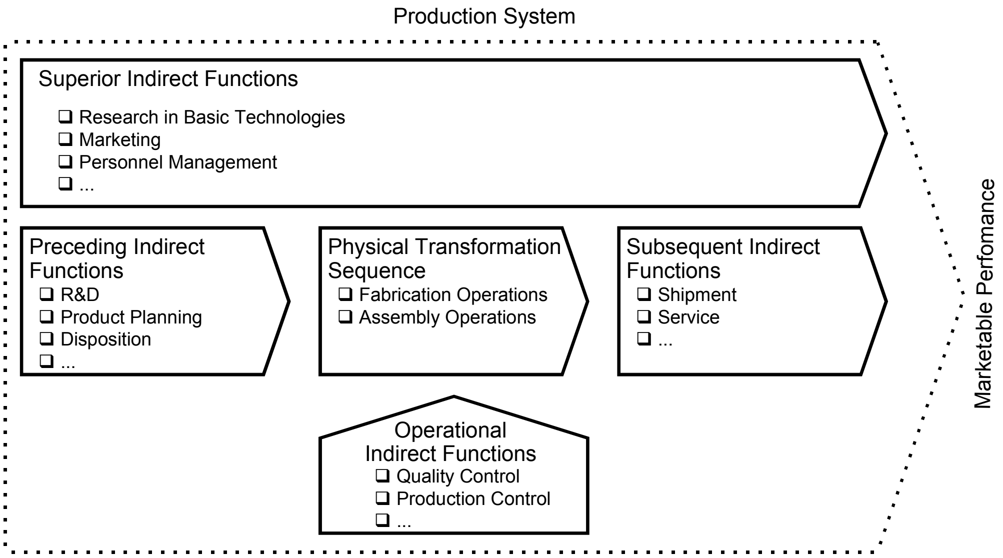

Figure 4: Classification of indirect functions relative to the physical transformation for organizational segment design.

Critical success factors for a product line have to be investigated and defined first, in order to elaborate the suitable production strategy for a segment ("Vertical Segmentation"). Each production segment serves a distinct Product-Market-Production-Combination (PMPC). Criteria for demarcation of PMPCs are:

- Customer Attributes:	Branch, Size, Type (Consumer/OEM), Geographical Location (Supply Chain, Distribution Channel), etc.
- Market Attributes:	Development (Competitive Situation, Share, Growth), Dynamics (Economical, Social, Political), Competitive Priority/Strategy (Cost, Quality, Delivery, Flexibility), etc.
- Product Attributes:	Demand Behavior (Volume, Frequency, Predictability, Takt Time), Technological Features (Product Structure, Geometry, Tolerances, Operational Manufacturing Sequence), Standardization (Product Family, Mix, Customization), Life-Cycle-Stage (Maturity, Stability), etc.

In case of a very expensive manufacturing resource, share of the resource between segments may be unavoidable. In this scenario the (centralized) resource constrains the design of respective production segments. A feasible segmentation procedure must be capable to indicate whether the design solution for segments is still "acceptable" or not.

Production segments always comprise several operations within the value chain to fulfill a customer order from receiving of incoming materials to shipment of finished goods . In case of a complete integration of material flow, all sub-processes of a product line's value chain are assigned to one segment. The determination of range of steps that are to be integrated in one segment is a crucial part of so called "Horizontal Segmentation".

The Role of Lean Management Principles

Lean Management philosophy offers several principles to optimize the effectiveness and efficiency of the manufacturing system but also of the entire production system (Shingo 1989). These principles resemble and sustain key design guidelines for the organizational and physical structure design of a segmented production system. Table 3 (Appendix A) indicates the relationship between the key principles of the Lean Production System with major design aspects of the segmentation approach (for details compare Shingo 1989, Cochran 1994).

3 Segmentation of Production Systems with Axiomatic Design

3.1 Proceeding in a Segmentation Project

The suggested procedure follows three consecutive phases (Fig. 5):

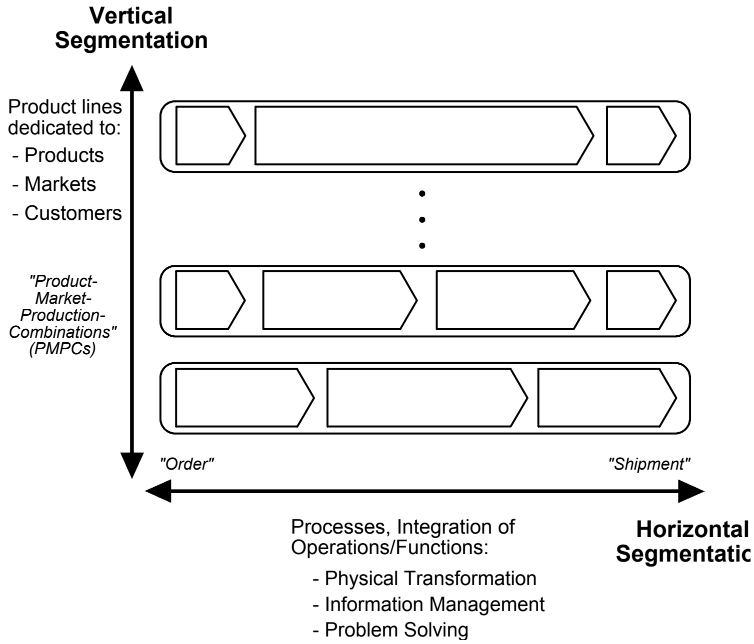

Figure 5: The vertical and the horizontal segmentation require iterative steps in the segmentation procedure.

The systemic view of a manufacturing enterprise is a prerequisite for identification of important design aspects. The analysis phase reveals characteristics of customers and markets the company competes in, as well as technological and organizational data concerning the offered product mix and product features, competitors, and existing or required managerial tasks and processes for the accomplishment of the marketable performances. The conceptualization phase comprises iterative steps of vertical and horizontal segmentation based on the data provided by the analysis. Axiomatic Design theory supports a robust conceptualization result. The designer is most likely not able to comprehend all marginal conditions of the complex system design on the highest design level; some restrictions may occur during the conceptualization and evaluation. Once the feasibility and economic evaluation have proven the design to be acceptable, the implementation of the final design solution is justified.

The research focuses on modification of Axiomatic Design theory to deploy the organizational and physical structure within production system segmentation.

3.2 Introduction to Axiomatic Design Theory

The approach of Axiomatic Design was advanced by Dr. Nam P. Suh in the mid-1970s with the goal to develop a scientific, generalized, codified, and systematic procedure for design. Axiomatic Design provides the designer with a theoretical foundation based on logical and rational thought processes and tools (Suh 1995). In order to systematize the thought process and to create demarcation lines between various design activities, four domains represent the foundation of Axiomatic Design procedure (Fig. 6).

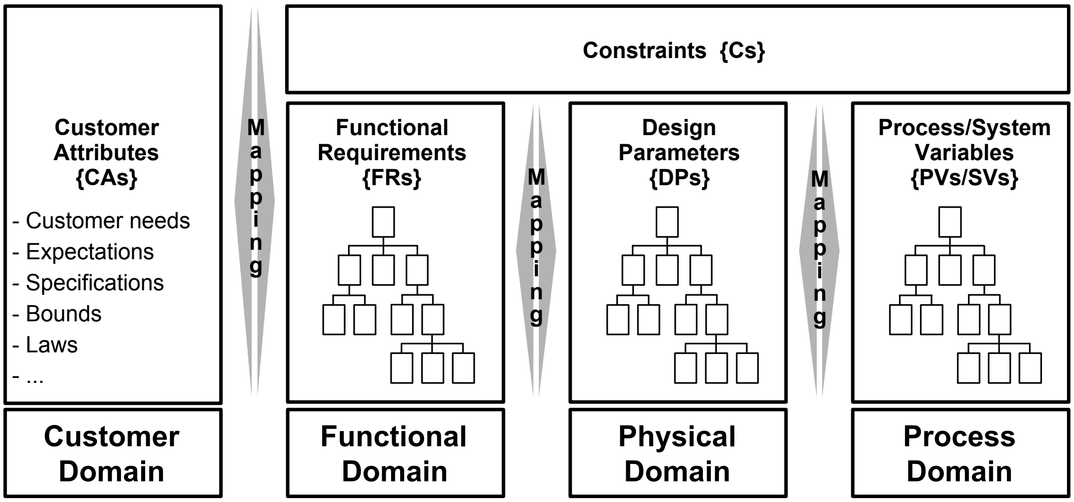

Figure 6: All design procedures can be represented in four domains. {X} are characteristic vectors of each domain (adapted from Suh 1990).

The domain on the left relative to the domain on the right represents "what we want to achieve", whereas the domain on the right represents the design solution of "how we propose to satisfy the requirements specified in the left domain". The customer domain is characterized by the customer 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 we want to satisfy the functional requirements. Finally, to realize the design solution specified by the design parameters, the system variables (SVs) are stated in the process domain.

The methodology provides a stringent procedure to deploy a system design in a “zigzagging” decomposition process between the domains from highest to lowest design level. Within mapping between the domains the designer is guided by two fundamental axioms to produce a robust design (Suh 1990):

Axiom 1: The Independence Axiom

=> "Maintain the independence of the functional requirements".

Axiom 2: The Information Axiom

=> "Minimize the information content of the design".

The axioms offer a basis for evaluating and selecting designs. In most design tasks, it is necessary to hierarchically decompose the problem. The FRs, DPs, and SVs can mathematically be described as vectors. The relationship between the design domains, of which each is represented by a vector, can be expressed as a matrix, respectively. This matrix is called the "Design Matrix" (DM) (compare case study). A design equation should be written for each transition between domains and at each decomposition level. Detailed information and elaborations on the scientific background of Axiomatic Design are provided by Suh (Suh 1990).

3.3 Using Axiomatic Design Theory in the Conceptualization Phase

The organizational design assigns certain operations and functions to the segments. The design of the physical structure allocates the required resources to the organizational unit for the support of the assigned tasks. The segments are designed to satisfy special objectives, hence, the goals of the design (FRs). The design goals of the production system are the abstracted processes of the system. Production segments and indirect segments are the highest level entities of the production system (compare Fig. 2). The organizational units satisfy the functional requirements and thus represent the design parameters (DPs). Suh’s physical domain (Suh 1990) is renamed to be the "Organizational Domain", since the organizational design is succeeded by the design of the physical structure. The mapping from the functional domain to the organizational domain is the first transition and establishes the organizational design structure. The second transition is the mapping between the organizational and the "Physical Domain" which substitutes Suh's process domain (Suh 1990). The system variables (SVs) reside in the physical domain and represent the structure of allocated capital resources. The customer attributes (CAs) represent the criteria for the demarcation of PMPCs. Appreciable criteria resulting out of the analysis phase must be translated to establish the highest level FRs during the first mapping (Fig. 7).

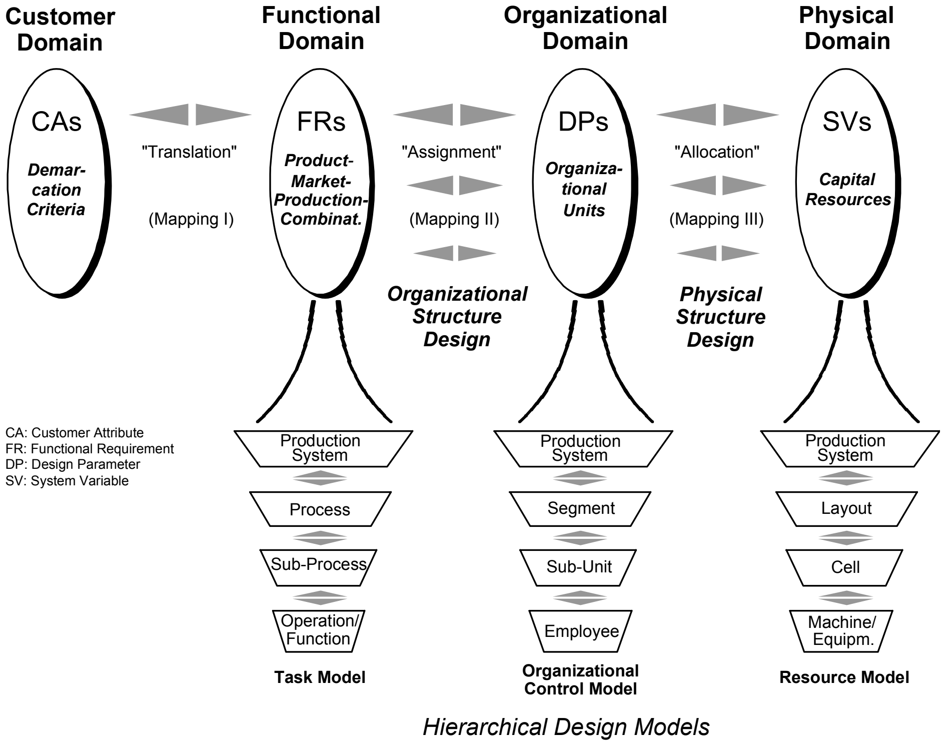

Figure 7: The design domains for a systematic segmentation of production systems.

The definition of design domains was accompanied by the development of three hierarchical design models for the decomposition of a segmented production system. The "Organizational Control Model" defines the segment as the highest and the employee as the lowest level organizational control entity within the system. The "Task Model" reflects the decomposition of processes. The process as the highest level FR integrates all activities, i.e. direct and indirect functions, of the three managerial tasks that are required to accomplish the marketable performance of a demarcated PMPC. A process can be hierarchically decomposed in subordinate sub-processes, and the sub-process in operations/ functions. For example, an order transactions process for product X may be decomposed in the sub-processes such as order administration, engineering, production planning, receiving, forefabrication, production control, assembly, and shipping. Furthermore, the forefabrication sub-process may be decomposed in the operations milling, drilling, grinding, welding, and so forth. The "Resource Model" reflects the physical structure of the segments and the production system in the physical domain. The general layout of a segment's manufacturing system or office depicts the highest level physical entity for the design of a segmented production system. The cell and the machine/ equipment represent the lower levels of the physical structure.

How can the modified Axiomatic Design procedure support the conceptualization phase? It is apparent that the design axioms do not provide the required knowledge of a subject to determine design solutions. The strengths of Axiomatic Design are the structuring of the design procedure, the possibility to evaluate and compare alternative design solutions, and the documentation of the design history. The Independence Axiom is useful to indicate functional interdependencies of organizational units or resources. The Information Axiom is apt to evaluate the quality of alternative design solutions by comparing their Information Contents. The "Information Content" measures the probability of the design solution to satisfy the design problem. Ideally, a robust design is uncoupled, the number of FRs, DPs, and SVs is equal and the information content is zero (for detail compare Suh 1990).

4 Application within a Case Study

The observed company offers high performance Vibration Isolation Systems and Optical Tables to academic, industrial, and governmental research facilities worldwide. Purchase orders of the company are basically composed of a specified table top, a support isolation system (leg stand),

and supplementary accessories. For each product classification various variations in seizes and technical features (damping metrics and characteristics) are offered as standard products. Additionally, customized special orders are also processed. Thorough analysis of plant layout, product features, and physical transformation task (Fig. 8) was succeeded by analysis of market situation, competitors, and information management and problem solving tasks.

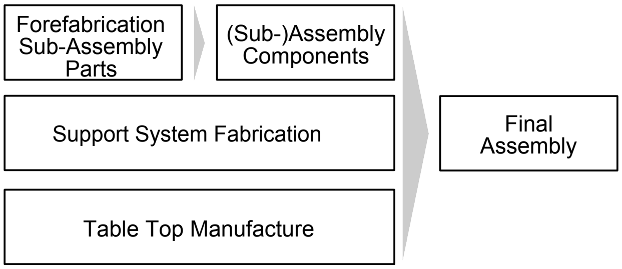

Figure 8: The transformation tasks of the observed company.

The analysis of sales metrics elucidated characteristic market demand behaviors of products with respect to the demarcation criteria "demand volume" and "demand frequency". The analysis of sales distribution decomposed by product sizes revealed that specific sizes of the standard product series are sold with a high frequency, whereas others are seldom purchased. Based on the analysis of the competitors "the delivery speed" was elaborated to be the competitive priority for the highly frequently sold products with standard sizes. The implementation of a defined stock of forefabricated items close to the Final Assembly represented a solution to substantially reduce the order lead time of these "runner" Support Systems.

Conceptualization begins with the statement of the design constraints. At the observed company design was mainly constrained by a partially fixed layout, existing human and capital resources, outsourcing of a painting process (Support Systems), and qualification level in the direct sector.

In the course of investigations for a vertical segmentation the following relevant customer attributes (CA) were established and translated to functional requirements (FR):

Table 4: Definition of high level processes.

$$\left\{\begin{array}{l}\text{CA1: Conversion Flow}\\ \text{CA2: Standardization}\\ \text{CA3: Demand Volume}\\ \text{CA4: Demand Frequency}\\ \text{CA5: Predictability}\\ \text{CA6: Competitive Priority}\end{array}\right\} \rightarrow \left\{\begin{array}{l}\text{FR1: Production of Table Tops}\\ \text{FR2: Production of Support Systems}\\ \text{FR3: Production of Non - Standard Products}\\ \text{FR4: Production of Standard Products (Low Frequency)}\\ \text{FR5: Production of Standard Products (High Frequency)}\end{array}\right\}$$

The assignment of these high level processes to production segments requires the preceding exploration of opportunities to integrate direct and indirect functions into decentralized units. The Independence Axiom (Axiom 1) was utilized to expose interdependencies between functions of the high level processes. Concerning the integration of direct functions the analysis indicated that for the Table Tops (TT) and the Support Systems (SS) most of the manufacturing processes are supported by different sub-units of the existing production system:

Table 5: Design Equation for direct functions of the high level processes.

$$\left\{\begin{array}{ll}\text{FR1:} & \text{Shearing (TT)}\\ \text{FR2:} & \text{Shearing (SS)}\\ \text{FR3:} & \text{Wooden Core Fab. (TT)}\\ \text{FR4:} & \text{Frame Welding (TT)}\\ \text{FR5:} & \text{Corrugation (TT)}\\ \text{FR6:} & \text{Bonding (TT)}\\ \text{FR7:} & \text{Drilling and Tapping (TT)}\\ \text{FR8:} & \text{Drilling and Tapping (SS)}\\ \text{FR9:} & \text{Grinding (TT)}\\ \text{FR10:} & \text{Grinding (SS)}\\ \text{FR11:} & \text{Sawing (TT)}\\ \text{FR12:} & \text{Sawing (SS)}\\ \text{FR13:} & \text{Welding (SS)}\\ \text{FR14:} & \text{Painting (TT)}\\ \text{FR15:} & \text{Painting (SS)}\end{array}\right\} = \begin{bmatrix} X&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\ X&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&X&0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&X&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&X&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&X&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&X&X&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&X&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&X&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&X&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&X&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&X&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&X&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&X&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&X \end{bmatrix} \bullet \left\{\begin{array}{ll}\text{DP1,2:} & \text{Shearing}\\ \text{DP3:} & \text{Carpentry}\\ \text{DP4:} & \text{Frame Welding}\\ \text{DP5:} & \text{Corrugation}\\ \text{DP6:} & \text{Bonding}\\ \text{DP7:} & \text{Drilling (old)}\\ \text{DP8:} & \text{Drilling (new)}\\ \text{DP9:} & \text{Machining Cells}\\ \text{DP10:} & \text{Grinding}\\ \text{DP11:} & \text{Machining Cells}\\ \text{DP12:} & \text{Saw II}\\ \text{DP13:} & \text{Saw I}\\ \text{DP14:} & \text{Welding Cell}\\ \text{DP15:} & \text{Painting \& Lam.}\\ \text{DP16:} & \text{Outside Painter}\end{array}\right\}$$

The design matrix indicates coupling of functional requirements. Only the shearing machine (DP1) is a shared resource for the shearing operations (FR1, FR2) of Table Tops and Support Systems. All other functional requirements of the conversion flows are independently satisfied (Axiom 1). Considering the constraint of zero capital investment, the assignment of the Table Top manufacture and the Support System Fabrication in separate organizational units was sensible. Share of resources is minimal and the individual conversion flow in separate lines is a valid criterion for the vertical segmentation.

Due to fixed layout focus of optimization was the design of the organizational structure of segments. The relatively small size of the company makes the centralization of most indirect functions compulsory. However, two major potentials for improvement were deduced in the as-is-analysis: first, further decentralization of operational indirect functions, i.e. in specific production control and quality assurance functions; and secondly, distinction and refinement of value streams to harness different competitive priorities within product lines. Former, inefficient scheduling of complete transformation sequences based on reverse back-scheduling of required manufacturing processes was partially substituted by Kanban control systems for standard items. Kanban systems decentralize production control functions by nature (Shingo 1989). Table 6 illustrates the decentralization of production control (PC) functions to operators of the respective working areas. The form of the equation represents an incomplete design, since production control is centralized (DP3).

Table 6: Design Equation for production control functions of the high level processes.

$$\left\{\begin{array}{l}
\text{FR1: Fine Scheduling of TTs and SSs (Low Freq.) Fabrication} \\
\text{FR2: PC Replenishment Forefab. - Welding} \\
\text{FR3: PC Welding - Outside Painting} \\
\text{FR4: PC Outside Painting - Assy and Test} \\
\text{FR5: PC Assy and Test - Final Assy and Shipping} \\
\text{FR6: PC Replenishment SS Comp. (High Freq.)} \\
\text{FR7: PC SS Comp. (High Freq.) Machining - Welding} \\
\text{FR8: PC Forefab. Components - Sub - Assembly} \\
\text{FR9: PC Sub - Assembly - Final Assembly}
\end{array}\right\} =
\begin{bmatrix}
X & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & X & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & X & 0 & 0 & 0 & 0 \\
0 & 0 & X & 0 & 0 & 0 & 0 \\
0 & 0 & X & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & X & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & X & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & X & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & X
\end{bmatrix} \bullet
\left\{\begin{array}{l}
\text{DP1: Production Manager} \\
\text{DP2: Welding Operator} \\
\text{DP3: Production Controller} \\
\text{DP4: Final Assembly Operator} \\
\text{DP5: Machining Cell Operator} \\
\text{DP6: Forefab. Sub - Assy Operator} \\
\text{DP7: Sub - Assembly Operator}
\end{array}\right\}$$

Outside painting and shipping processes require central coordination and central paper administration for the complete collection of simultaneously processed purchase orders. As a result, the coupled processes represented by FR3, FR4, and FR5 remained centralized and are performed by the production controller (DP3). These FRs were restated to decouple the design (compare Table 7). All other FRs are independently satisfied by the new design. Analogously, inspection functions traditionally performed by a centralized quality inspector were partially decentralized to the operators. The decentralization documented in Tabel 7 reduces non-value-added waiting time and motivates the operators to be self-responsible for achieved work results. The design is completely uncoupled.

Table 7: Design Equation for indirect functions of the high level processes.

$$\begin{Bmatrix} \text{FR1: Centralized Inspection Processes} \\ \text{FR2: Test of Support Systems} \\ \text{FR3: QC of Processed Parts of the Machining Area} \\ \text{FR4: Inspection of Assembled Components} \\ \text{FR5: QC of Processed Parts in all Other Working Areas} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \bullet \begin{Bmatrix} \text{DP1: Inspector} \\ \text{DP2: Welding Operator} \\ \text{DP3: Machining Operator} \\ \text{DP4: Assembly Supervisor} \\ \text{DP5: Respective Operator} \end{Bmatrix}$$

The transformation task of the observed company was vertically segmented in five major processes (PMPCs: FR1 to FR5, Table 4) with respect to relevant demarcation criteria. The material flow integration determines which operations of the transformation task are assigned to which production segment (horizontal segmentation). Vertical segmentation indicated the independence of the manufacturing processes for the Support Systems and Table Tops. To fulfill a purchase order, these two value streams necessitate coordination to merge their outputs at the right time for Final Assembly and Shipping. Organization of work teams around these value streams is sensible, since the performances of these teams result in completely different products. Approximately half of the operators work in the areas for the Table Top Manufacture. Considering the constraints and the goal of a balanced size (span of control) of segments, the segmentation scenario resulted in the design of two production segments (Fig. 9).

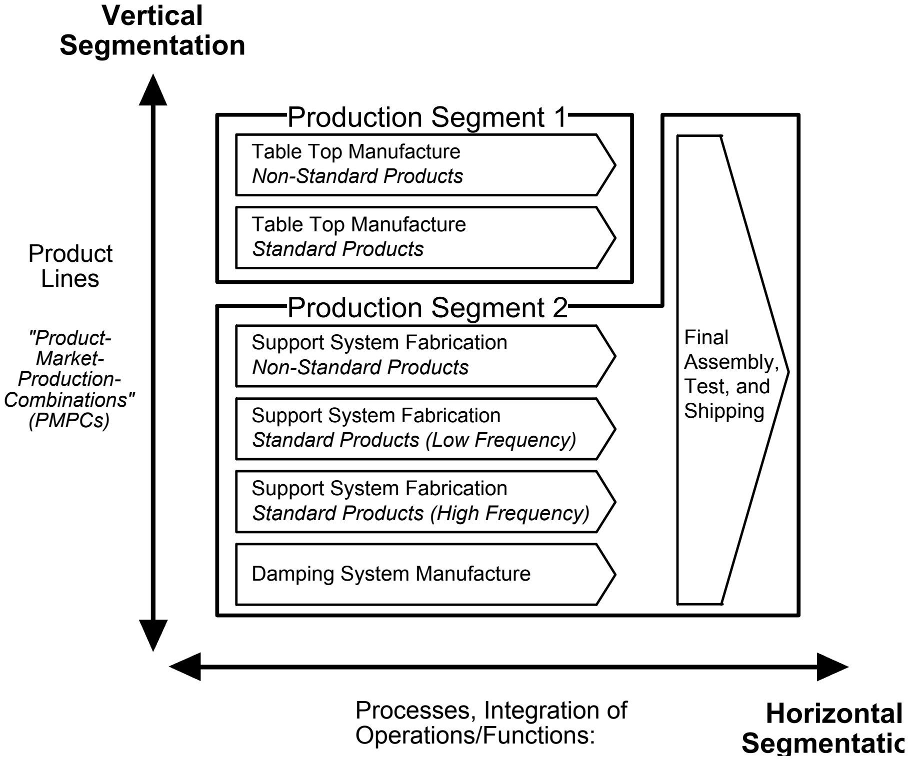

Figure 9: The design solution of the production system segmentation at the observed company.

Production segments and each sub-unit are responsible for quality of their performances, fine scheduling of operations, and improvement of their processes. The highest level design parameters are the Production Segment 1 (DP1), Production Segment 2 (DP2) and one Indirect Segment (DP3). The Indirect Segment comprises all indirect functions that were not decentralized into the production segments. The selected highest level design parameters require the refinement of the highest level functional requirements previously stated in Table 4, as the following equation indicates.

Table 8: Coupled design of high level processes and organizational units.

$$\left\{\begin{array}{l}\text{FR1: Production of Table Tops}\\ \text{FR2: Production of Support Systems}\\ \text{FR3: Production of Non-Standard Products}\\ \text{FR4: Production of Standard Products (Low Frequency)}\\ \text{FR5: Production of Standard Products (High Frequency)}\end{array}\right\} = \begin{bmatrix} X & 0 & X \\ 0 & X & X \\ X & X & X \\ 0 & X & X \\ 0 & X & X \end{bmatrix} \bullet \left\{\begin{array}{l}\text{DP1: Production Segment 1}\\ \text{DP2: Production Segment 2}\\ \text{DP3: Indirect Segment}\end{array}\right\}$$

Table 8 represents an incomplete design. Processes represented by FR3, FR4, and FR5 are coupled with the ones of FR1 and FR2. Production Segment 1 manufactures Table Tops, but also Non-Standard Products. Production Segment 2 manufactures all Standard and Non-Standard Support Systems. The Indirect Segment serves the processes of both production segments. The equation of Table 9 developed a refined set of high level FRs, which established a clear relationship between the segments and the processes they own.

Table 9: Final design equation for the conceptualized scenario at the observed company.

$$\left\{\begin{array}{l} \text{FR1: Integrated Process for Table Top Manufacture} \\ \text{FR2: Integrated Process for Support System Manufacture} \\ \text{FR3: Information Management and Problem Solving} \end{array}\right\} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \bullet \left\{\begin{array}{l} \text{DP1: Production Segment 1} \\ \text{DP2: Production Segment 2} \\ \text{DP3: Indirect Segment} \end{array}\right\}$$

The design is an uncoupled design. FRs are independently satisfied by DPs on the highest design level. The hierarchical decomposition with a design tree documented the assignment of sub-processes and functions/ operations to the organizational sub-units and employees. Integration of direct and indirect functions of processes FR1 and FR2 into organizational units determined the segment boundaries. Axiomatic Design procedure supported and verified design decisions. The design was completely decomposed for the transition between the functional and the organizational domain. Table 10 (Appendix B) exemplifies the thorough hierarchical decomposition of the highest level design for FR2 presented in the design equation of Table 9.

The elaborated scenario describes possibilities of functional decentralization and refinements in the process organization. The scenario proved to be technically and economically feasible. The implementation of the new production system reduced order lead time of the high running Standard Products more than 50 %. Reduced complexity in production control in combination with the implementation of differentiated production strategies lead to a presumed increase of sales volume of 5-10%. Improvement was solely sustained by reorganization in compliance with the constraint of zero capital investment.

Although the procedure is based on a rational thought process, experience in the field of production system design is required to deploy a robust design. However, the benefit of the developed procedure proved to be the support of Lean Management principles as design guidelines in combination with Axiomatic Design as a systematic design decomposition tool.

5 Summary and Concluding Remarks

This paper introduces a design framework for systematic segmentation of production systems supported by Axiomatic Design procedure. Often manufacturing enterprises begin the design process with the system structure as an assumption or restriction. Axiomatic Design procedure forces the designer to first clarify what the true objectives and constraints of the system design are. Based on the requirements placed on the production system by markets, customers, and products the suggested procedure deploys the organizational and physical structure of integrated subsystems. The design procedure mandates a step-by-step establishment of design objectives and elements with the hierarchical decomposition of the design structure across demarcated design domains. Generalized design axioms support a robust production system design in compliance with the sound application of lean management principles. A thorough analysis of business processes, markets, customers, products and competitors provides a strong knowledge base for the design synthesis which is succeeded by an economic evaluation and feasibility study for verification purposes. As such, the methodology stresses the importance of considering multiple design aspects and a structured thought process in the design synthesis. An actual factory design problem was used to illustrate the benefit of applying Axiomatic Design and Segmentation to reduce complexity by decoupling system design.

Future work will focus on integrating monetary aspects of system design in conceptualization phase the design procedure rather than conducting “ex-post” economic evaluation. Further work is suggested to elaborate on requirements such as the segment’s structural flexibility, as well as the adaptability and share of manufacturing resources to accommodate increasing multiplicity and volatility of market demands with a proper system design. Moreover, further research is recommended in the logical design and decomposition of the linking elements between system entities to control the production system according to the goals of the organization.

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Appendices

Appendix A

Principles of the Lean Production System	**Aspects of the Segmentation Approach**																						
	Organizational Design	Decentralization of Preceding Indirect Functions	Decentralization of Operational Indirect Functions	Decentralization of Subsequent Indirect Functions	Decentralization of Superior Indirect Functions	Decentralization of Directive Authority	Integrating Marketing and Manufacturing Functions	Work Organization in Accountable Teams	Self-Organization	Customer-Supplier-Relationship	Decentralization of Problem Solving Competence	Integrated Information Systems	Demarcation of Markets, Customers, and Products	Process Orientation	Cost or Profit Responsibility	*Physical Layout Design*	Decentralization of Direct Functions	Orientation to Products	Integration of Material Flow	Several Steps of the Logistic Chain	Alignment of Mfg System to Distinct Prod. Strategy	Transparency / Visibility	Allocation of all Required Resources
Pull System																							
Kanban			○				○		○	●		●		○			○		○	○	○	●	
Order-Based-Production		○			○		●		○		○	○	●	○							○		○
Takt Time		○	○		○		●		○			●	●	○			○				○		
One Piece Flow							○			○			●		○		●	●	○		○	●	○
Small Lot Production																							
Mixed Model Production		○			○		●		○			○	○								○		○
Lead Time Reduction		○	●	○	○	○		○	○	○	○	○	○	○			○	○	○	○	○	○	○
Leveling		○			○		○		○			○	○								○		
Synchronization		○	○	○	○			○				○		●			○	○	○	○	○		○
Standard Operations							○							○	○		○	○	○			○	○
Easy Machine Handling							○	○															○
Elimination of Muda																							
Layout by Flow Principle			○											○			○	●	○	○		○	○
Multi-Machine Handling			○						○	○		○		○			○	○	○	○		●	○
Multi-Process Handling			○						○	○		○		○			○	○	○	○		●	○
Operator Loops			○						○	○		○		○			○	○	○	○		●	
U-Shaped Layout														○			○	○	○	○		●	
Motion Improvement														○					○			○	●
Stopping the Line			○			○		○	○	○	●	○		○	○							○	
Autonomation			○						○	○	●	○										○	
Integrated Quality Assurance																							
Operation (including Inspection)			●						○	○		○		●	○				○	○		○	
Visual Control			●					○	○	○			○	○	○							●	
Poka Yoke			○						○	○		○			○							○	
Multi-Functional Worker		○	●	○				○	○		●			○	○		○		○	○		○	
Improvement Circles					○			○	○		●		○	○	○							○	
Kaizen					○			●	●		●		○	○	○							○	
Target Costing																							
Market => Selling Price							●	○	○	●	○		●	○	●								
Process Cost Reduction		○	●	○	○	○	○	○	○	○	○	○	○	●	●		○	○	○	○	○	○	○

Key: ☐ : No Direct Relation ○ : (Mutually) Supportive Relation ● : Congruence

Table 3: Key principles of the Lean Production System serve as design rules for the design of the production segments.

Appendix B

FR2	**Integrated Process for Support System Manufacture**	**DP2**	**Production Segment 2**
FR21	Support System Fabrication	DP21	Shearing, Machining and Welding Cell
FR211	Forefabrication of Components	DP211	Shearing and Machining
FR2111	Shearing	DP2111	Shared Shearing Machine Operator
FR2112	Belt Sanding	DP2112	Machining Operator (Cell1)
FR2113	Press Shearing	DP2112	Machining Operator (Cell1)
FR2114	Sawing and Deburr	DP2113	Drilling Machine Operator (Cell1/2)
FR2115	Drilling, Countersink, and Tapping	DP2113	Drilling Machine Operator (Cell1/2)
FR2116	Knob Fabrication	DP2114	Lathe Operator (Cell 2)
FR2117	Prod. Control Standard Comp. (High Frequency)	DP2115	Respective Machining Operator
FR212	Welding of Legstand Components	DP212	Welding Cell
FR2121	Leg Welding and Stud Welding	DP2121	Welder
FR2122	Brace Welding	DP2121	Welder
FR2123	Leak Test	DP2121	Welder
FR2124	Legpair Welding	DP2122	Shared Welder
FR2125	Grinding and Cleaning	DP2122	Shared Welder
FR2126	Prod. Control Replenishment Forefabrication - Welding	DP2123	Respective Welder
FR22	Damping System Manufacture	DP22	Machining and Assembly
FR221	Forefabrication Sub-Assembly Parts	DP221	Forefabrication Assembly
FR2211	Production Control Forefab. Components - Sub-Assembly	DP2211	Forefabrication Assembly Operator
FR222	Sub-Assembly Components	DP222	Assembly
FR2221	Individual Airmount and Control Panel Assembly	DP2221	Cell 3
FR22211	Production Control Cell 3 - Final Assmbly Cell	DP22211	Cell 3 Operator
FR2222	Leveling Valve Assembly	DP2222	Cell 4
FR22221	Production Control Cell 4 - Final Assmbly Cell	DP22221	Cell 4 Operator
FR2223	Benchmate Assembly	DP2223	Cell 5
FR22231	Production Control Cell 5 - Final Assmbly Cell	DP22231	Cell 5 Operator
FR2224	Airmount Assembly	DP2224	Cell 6
FR22241	Production Control Cell 6 - Final Assmbly Cell	DP22241	Cell 6 Operator
FR23	Final Assembly	DP23	Final Assembly Cell
FR231	Prod. Contr. Replenishment SS Comp. (High Frequency)	DP231	Final Assembly Operator
FR24	Shipping Preparation and Transactions	DP24	Boxmaking & Shipping
FR25	Segment Management	DP25	Production Management
FR251	Fine Scheduling of Operations within Support System Mfe	DP251	Production Segment 2 Manager
FR252	General Segment Administration and Supervision	DP251	Production Segment 2 Manager
FR253	Supervision and QC of Assembly	DP252	Assembly Supervisor
FR254	Supervision and Administration of Shipping/Receiving	DP253	Shipping/Receiving Supervisor

Table 10: An excerpt of the hierarchical design decomposition of the segmented production system.

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