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CONCEPTUAL DESIGN OF LEAN PRODUCTION SYSTEMS THROUGH AN AXIOMATIC APPROACH

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ABSTRACT

In this paper, we are to present a practical application of Axiomatic Design (AD) methodology as a roadmap to lean production, in a car body assembly line. In addition to product development, AD has already been applied for manufacturing system design but we tend to expand its application to production system design, which besides manufacturing includes all activities required to satisfy customer needs. AD theory provides a framework to simplify the whole problem. According to the AD principles, a hierarchical structure for conceptualization of lean philosophy has been developed. This structure originates in lean manufacturing principles.

We argue that three essential bases of lean production are organizational capabilities, technological capabilities, and value stream analysis, represented as top DPs in the structure. These basic capabilities are interdependent and self-reinforcing. Among these DPs, organization capabilities would take priority over other others because implementation lean practices in a company require a lean organization. Therefore, DP2 'Developing required organizational capabilities for lean production' is decomposed to lower levels first. This is performed by means of zigzagging.

Having completed conceptually the production system design through AD, we have developed an operational procedure for implementation practices. The main stages of the procedure are 1) Develop a lean strategy. 2) Train the employees. 3) Eliminate non-essential infrastructural resources. 4) Performance measurement. 5) Establish a baseline. 6) Identify opportunities. 7) Prioritize opportunities. 8) Develop and implement the lean improvement plan. 9) Measure, monitor, and improve. 10) Hold the gains. 11) Strive for perfection. While the hierarchical structure act as a guideline, the procedure specifies the course of actions. both of them could be applied for other applications. We are trying to redesign this production system based on the conceptual model, represented as AD structure, as well as the operational procedure.

Keywords: Axiomatic Design, Lean Manufacturing, Production System Design

1 INTRODUCTION

"Axiomatic Design theory provides a valuable framework for guiding designers through the decision process to achieve positive results in terms of final design object" [Nordlund & Tate 1996]. Several companies have used the axiomatic design methodology successfully in order to develop new products, processes and even approaches. The ongoing trend toward AD is perceived obviously and "to date, companies in Asia, Europe and the US have successfully trained engineers in this method and begun integrating it into their product development effort" [Nordlund et al. 1996]. Through an axiomatic approach, the design problem is decomposed into a hierarchical structure in which the functional requirements and the design solutions are separated.

There are some reasons that will play key roles in the diffusion of AD in industry, which will be explained in the following:

First, traditional design methodologies of production systems have been challenged by continually increasing changes in business environments. Lean and agile manufacturing are two prevalent terms, characterizing the rapidly changing nature of manufacturing systems. Cavallucci [2000] have stated correctly that "in the face of competition, the ever more rapid emergence of new products, changing consumer fashions and globalization, companies are forced to call into question the efficiency of their design methods to keep their competitive edge and ensure their survival". The rapidly changing manufacturing environments require some new design principles, which have yet to be conceptualized [Cochran & Reynal 1996]. The changes influence various levels of manufacturing systems but "at firm and plant level, technological change can modify production techniques, product and process features and the way capital and labor is organized" [Alcorta 1998]. AD may be an appropriate approach to confront to the new challenges of production system design.

Second, manufacturing systems become more complicated and adaptation capability to the environmental conditions plays a crucial role in the survival of companies [Reynal & Cochran 1996]. The ability of AD in systematic propagation of functional requirements to the different facets of a system's design makes it a suitable approach in manufacturing system design.

Third, the ongoing information revolution will influence the design process. Nowadays, design is not just a random creative issues of an experienced expert but it is the product of systematic reasoning that its bases can be captured and generalized [Rowell 2001]."In the future, there will be a large demand on 'automated design procedures' in which a set of generalized principles or axioms will be applied or copied in different situations" [Lipson & Suh 2000].

Fourth, the separation of Whats and Hows in the AD results in flexibility, which is its great advantage versus other design methods. AD is flexible enough to come up with design decisions in a wide variety.

Consequently, it seems inevitable that manufacturing system design methodologies will be modified to become consistent with contemporary market characteristics and AD would serve as an effective tool toward today’s production benchmark, lean production.

Table 1: Comparisons of Lean Manufacturing with other Production Systems

Functions	Craft Production	Mass Production	Lean Manufacturing
Labor	Highly skilled craft workers	Narrowly & unskilled production workers	Multi-skilled production workers
Product	Customized products	High volume of homogeneous products	High volume with wide variety
Organization	Decentralised	Vertical integration - Ford; Decentralized divisions- Sloan	Team oriented
Production Volume	Low	High	High
Unit production cost	High	Low	Low
Machinery and Tools	Simple, flexible tools	Single-purpose machines	Flexible automated machines
Ultimate Goal	Customer specification	Good enough	Perfection
Flexibility	High	Low	High
Inventory turn	Less than 7	Less than 7	Over 10
Inspection	100%	Sampling	100% source
Scheduling	Customer order	Forecast-push	Customer order-pull
Manufacturing lead time	Long	Long	Short
Batch size	Small	Large with queue	Small-continuous flow
Layout	Process	Product	Product

2 LEAN MANUAFCTURING FUNDAMENTALS

Probably, the best way to describe lean manufacturing is to compare it with other existing production processes. In Table 1, lean manufacturing is compared with mass production and craft manufacturing systems.

Lean manufacturing features are the product of today's highly competitive markets that necessitate rapid response to customer needs. Schonberger [1982] argued that lean implementation demands adaptation ability, originating in cultural, regional, and technological characteristics. Since lean philosophy is based on a systematic approach, needed to be comprehensive enough to cover all system parameters, these characteristics must be analyzed carefully. The true benefit of lean implementation is to appear quickly the system drawbacks.

Industrial manufacturers strive to adopt lean philosophy but they find it difficult to achieve. It is important to keep in mind that transforming into a lean factory requires a systematic thinking. "Many observers of Toyota walk away with a piecemeal understanding of the systems, and they fail when endeavoring to implement a piece of the system taken out of the context" [Flinchbaugh 1998].

Successful implementation of TPS demands great struggle of the organization. Some indications of the success of a lean implementation are (Meier 2001):

1. Quick and obvious problem recognition
2. Creation a sense of urgency regarding system reliability
3. Consistent application of lean thinking in all areas

Taichi Ohno [1988] in his valuable book -Toyota Production System- cites seven types of waste:

1. Overproduction
2. Time on hand
3. Transportation
4. Waste on processing itself
5. Stock on hand-inventory
6. Movement
7. Making defective products

In lean implementation practices, we strive to reorganize the production system to eliminate the above causes of waste, emphasizing proactively on the main roots not the secondary effects.

3 THE SCOPE OF PRODUCTION SYSTEM DESIGN

From a socio-technical system standpoint, the components of a system (e.g. production system) are categorized as technology, personnel, the relevant external environments, and organization [Hendrick 1991]. The technological and personnel subsystems are interdependent, operate under joint causation, and require to be jointly designed for maximum efficiency. They are brought to transform inputs to outputs by the organization subsystem. The more effectively organization subsystem operates, the more efficient transformation process will be. Therefore, organization subsystem should be considered as an essential element in production system design.

We differentiate production system from manufacturing system. While manufacturing system embodies the elements involved in physical transformation of inputs to outputs, production system include all elements involved in satisfying customer requirements from customer needs definition to delivery. Therefore, manufacturing may be considered as a part of production system.

We can define the production function by means of $IDEF_0$[1] modeling technique whose components are depicted in Figure 1. The basic element of an $IDEF_0$ is called a function block. A function block symbolizes a transformation process by which inputs are converted to outputs. There are two other elements: mechanisms and controls. While the former is performing the transformation process, the latter direct and guide it.

The seven-aforementioned causes of waste, associated with the manufacturing function, are outcomes of malfunction in mechanisms and controls as well as poor input. Since organization subsystem functions to coordinate the transformation process, it may be derived that lack of a lean organization is the real cause of waste in a production system. That is why we conclude organizational capabilities are prerequisite for lean manufacturing.

[1] Integrated computer-aided manufacturing DEFinition

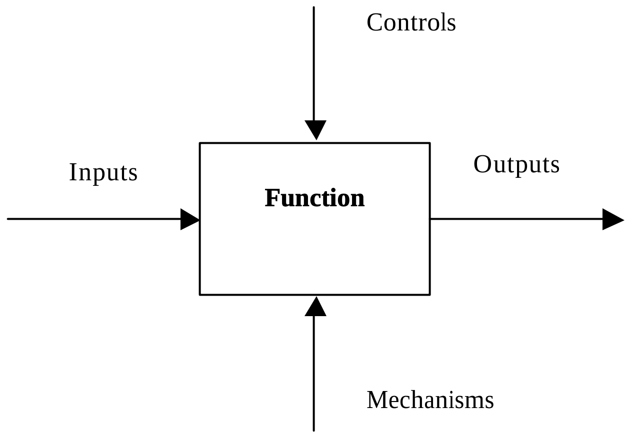

Figure 1: A Typical $IDEF_0$ Graph

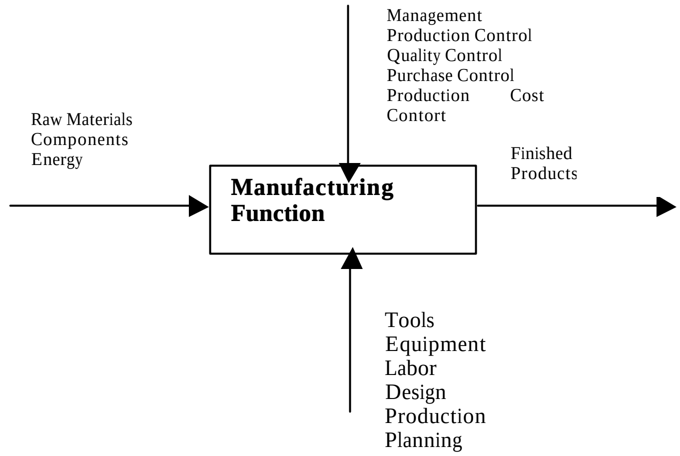

Figure 2: $IDEF_0$ Modeling of a Production System

4 PROBLEM DECOMPOSITION

Fujimoto (2001) categorizes the elements of lean production system in three classes: production characteristics, product development characteristics, and supplier characteristics. He states the Toyota system with the above characteristics has the following competitive capabilities:

1. Overcoming trade-offs between quality, productivity, and lead time
2. Flexibility in product mix, production volume, and model change
3. Organizational learning for productivity enhancement, quality improvement, and rapid, continuous problem solving on a company-wide scale.

In fact, it is more plausible to interpret the above competitive capabilities as the impetus of lean production system. In AD terms, various elements of lean production may be interpreted as reflections to customer wants, represented as functional requirements like flexibility, shorter lead time, high quality, and so on. These functional requirements are objectives of lean production design process and the core idea of lean thinking, elimination of all waste, satisfies them completely yet is a very comprehensive design parameter. There is a gap between theoretical foundation of lean production (reflected as FR-DP relationships) and implementation practices. Notwithstanding introducing Process Variables in AD methodology, more research needs to be conducted for application of Process Variables in lean production design.

Since production system design is a multidisciplinary function, it demands a systematic design process but we lack a thorough, practical methodology to link theoretical models with real world problems. In this section, we try to alleviate this problem by means of AD approach.

The highest-level functional requirement is chosen to be "Maximizing long-term profitability" Its relevant design parameter is "Designing the production system based on lean thinking"

According to the first-level functional requirements, the structure is expanded to next level that is shown in Figure 3. The design matrix is a decoupled one, because both FR1 and FR2 are affected by DP2.

DP2 and DP3 are general design parameters and require to be decomposed further. In Figure 4 and Figure 5, the second level of the hierarchy is depicted.

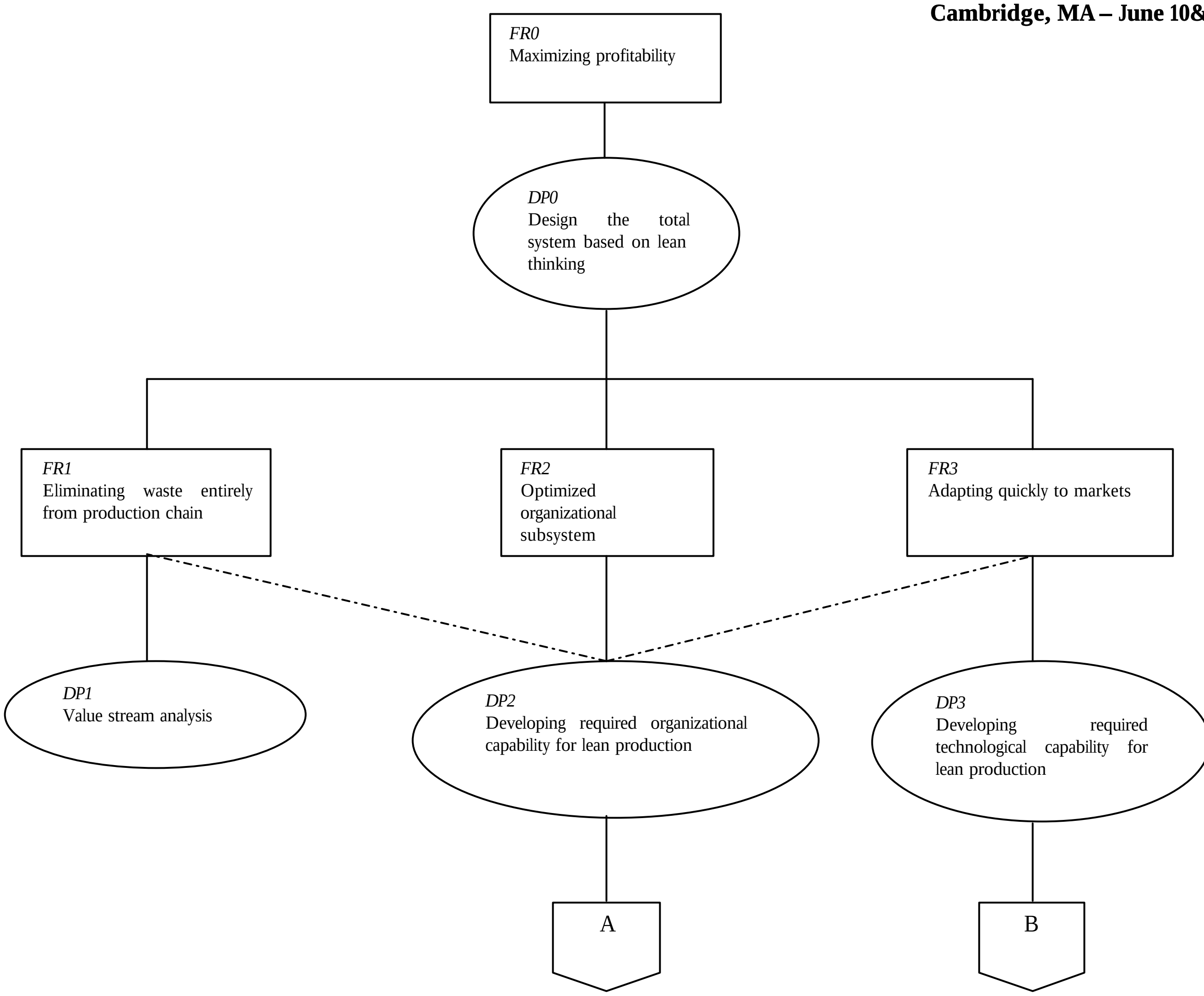

Figure 3: First Level of the Developed Structure

Implementation lean practices in a company require a lean organization. Instead of management of change, we require leadership of change in which people are allowed to identify and solve problems, affecting their work. Management only gives them the tools through training and facilitates personal involvement and commitment. In this managerial style, there is few issued instruction and management will not decide what to do, thus motivating employee to a high level. From lean management viewpoint, supervisors' responsibility is to provide the grounds for high quality and high productivity at the workplace.

Quick problem solving cycles is a general capability, which should be prevalent around the organization. Every non-value adding process is considered a problem in lean manufacturing. Here we confront two challenges: early problem identification and quick problem solving. Having been identified in the shortest period, problems require to be solved intelligently to improve productivity. The problem solving cycles may include revision of working standards led by shop floor supervisors, improvement proposals from individual workers and small group activities (Fujimoto 2001). The problem-solving loop is completed by follow-up. Other functional requirements like FR21, FR23, FR24, and FR25 are miscellaneous features of a lean organization.

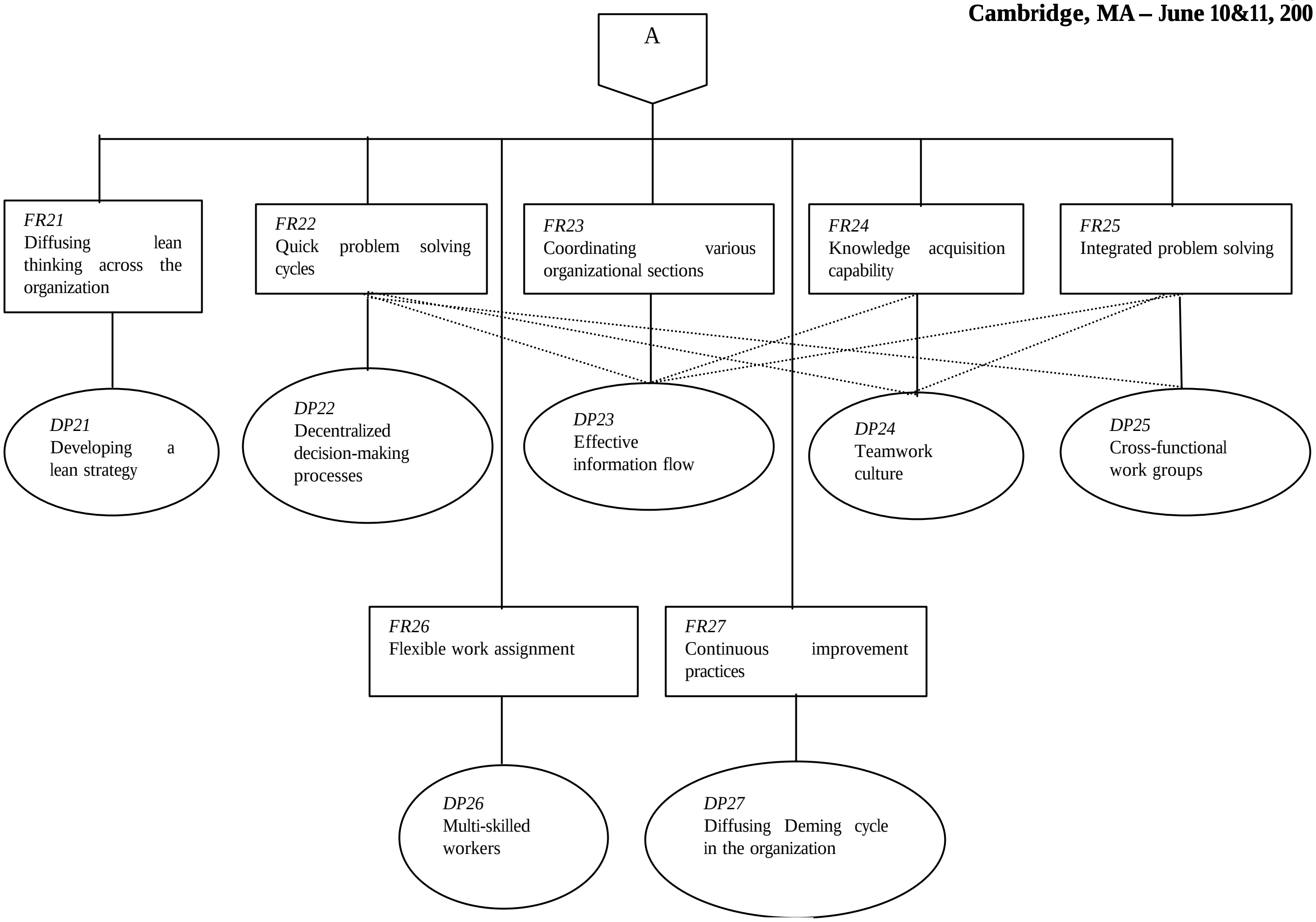

Figure 4: Decomposition of FR2

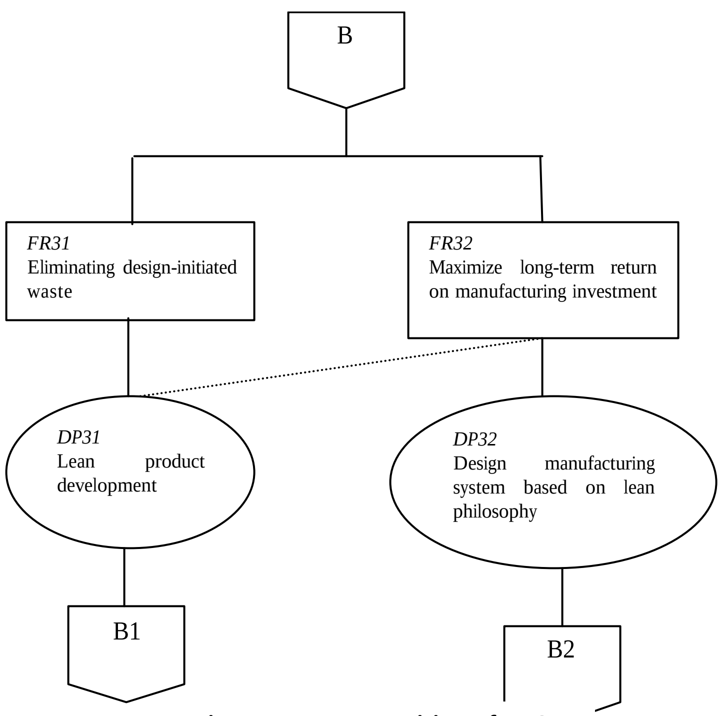

Figure 5: Decomposition of FR3

In Figure 6 and Figure 7, by zigzagging, FR31 and FR32 are decomposed, respectively.

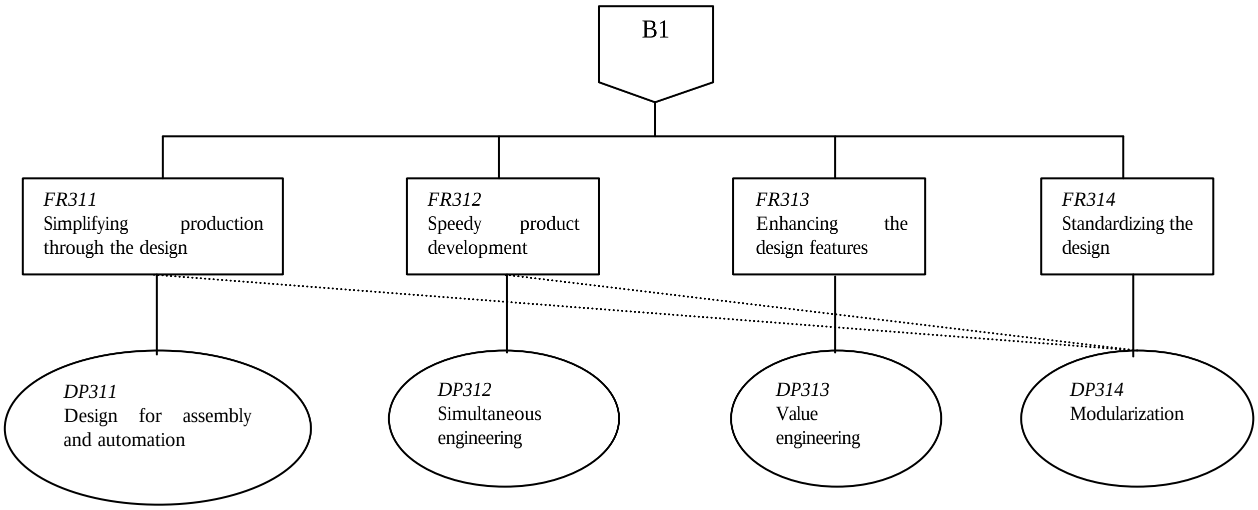

Figure 6: Decomposition of FR31 "Design-Initiated waste"

Simplifying product design itself (by cutting variation, increasing common parts and value engineering retracing the original plan), introduction and application of various design methodologies like Axiomatic Design and TRIZ[2], and extensive application of computer technology are among the attempts to alleviate existing inefficiencies in product development (e.g. trial and error approach). In product development, it is vital to solve as many problems as possible before prototyping owing to the following additional costs imposed by imperfect design.

Other functional requirements that require decomposition are depicted in figure 8, Figure 9, and Figure 10.

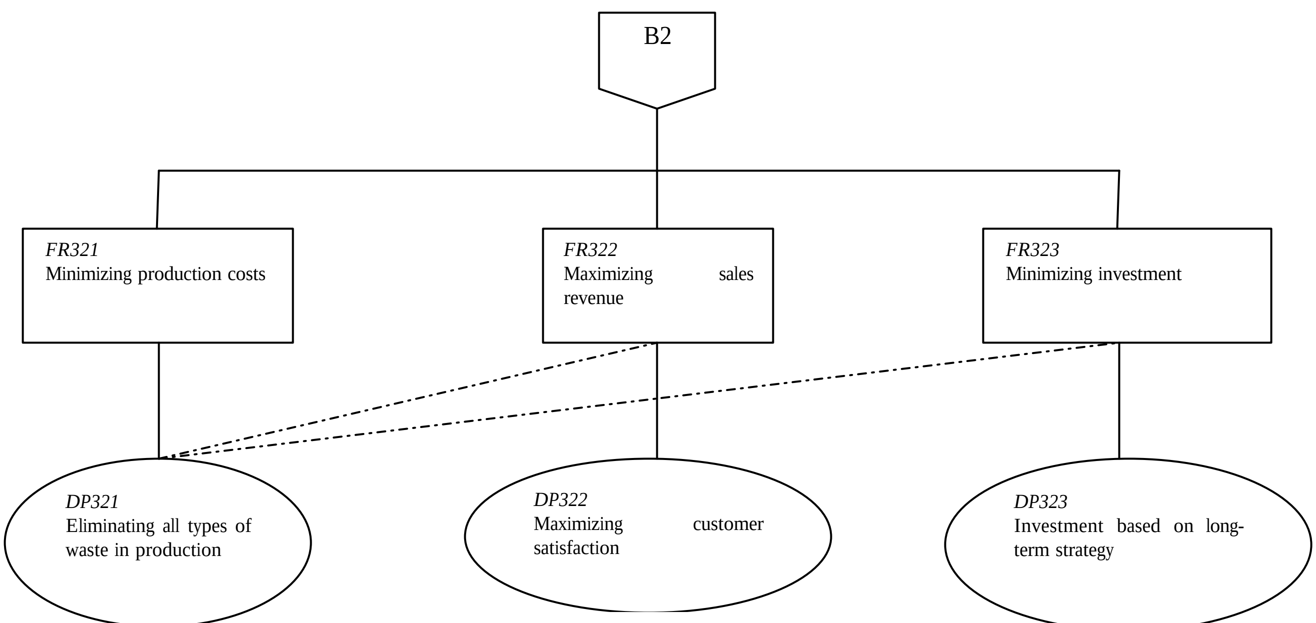

Figure 7: Decomposition of FR32 " Maximize long-term return on manufacturing investment

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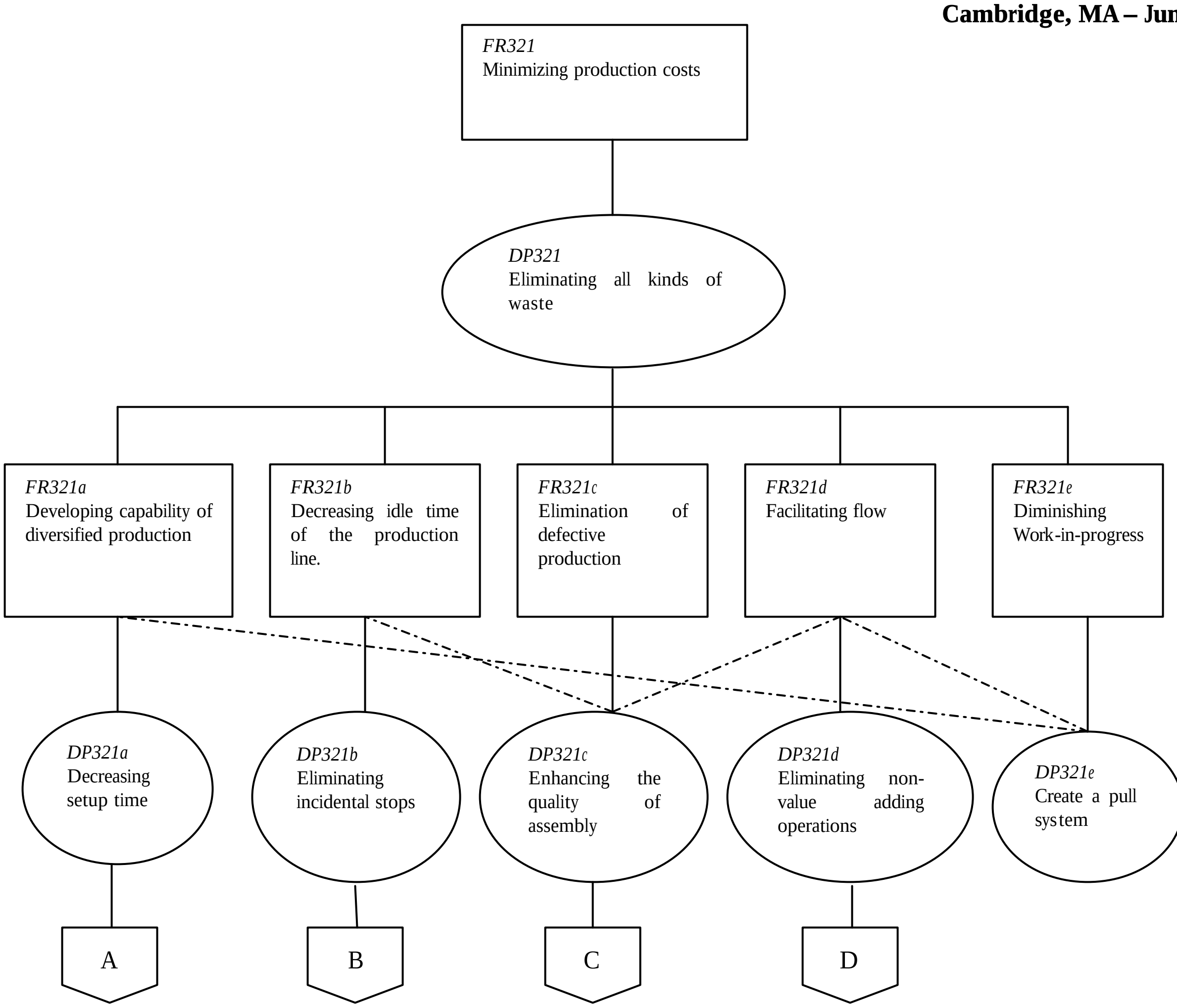

Figure 8: Decomposition of FR321 "Minimizing production costs"

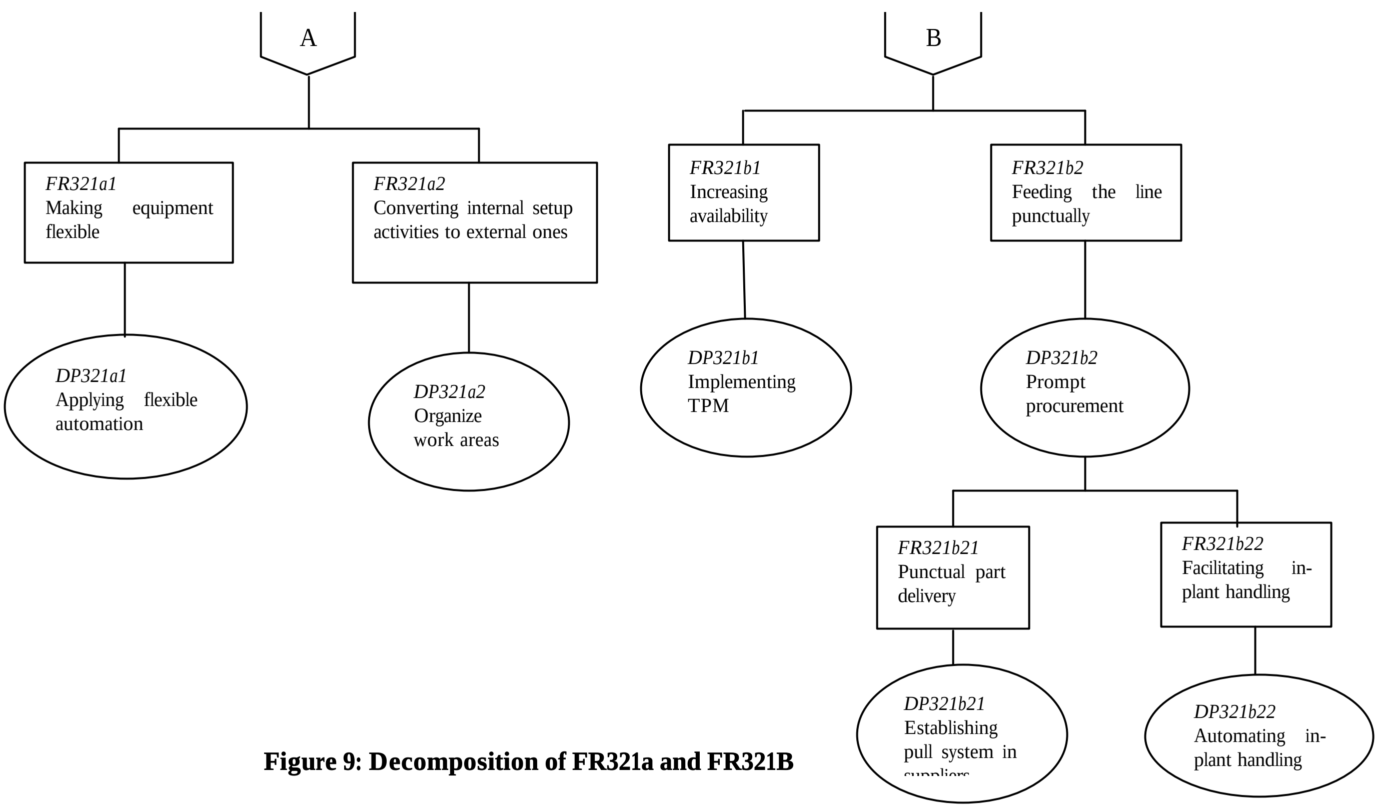

Figure 9: Decomposition of FR321a and FR321B

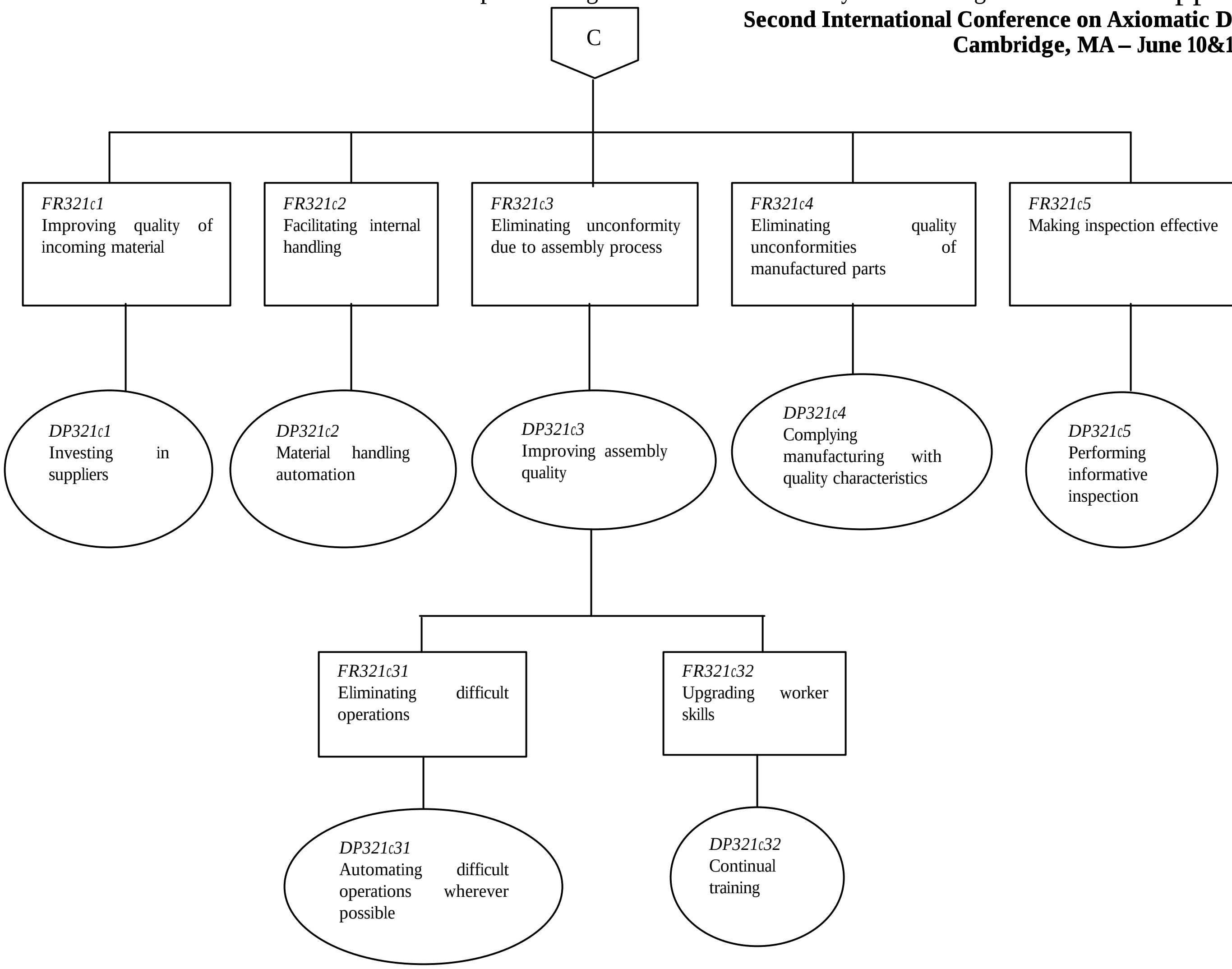

Figure 10: Decomposition of FR321C "Elimination of defective production"

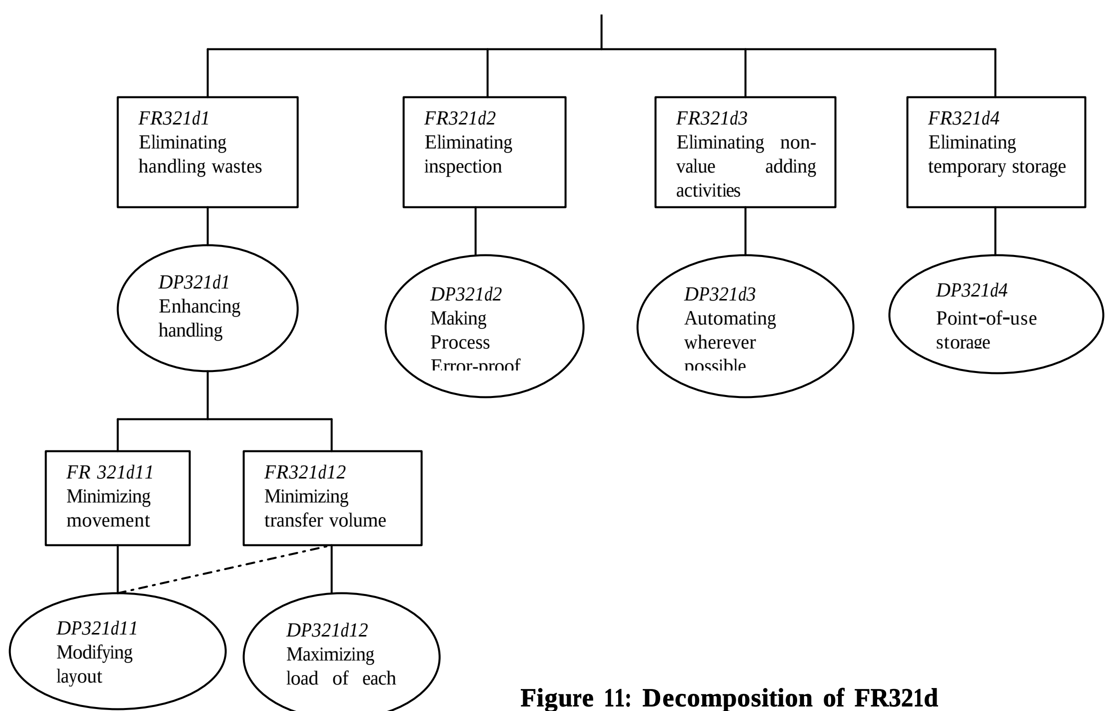

Figure 11: Decomposition of FR321d "Facilitating flow"

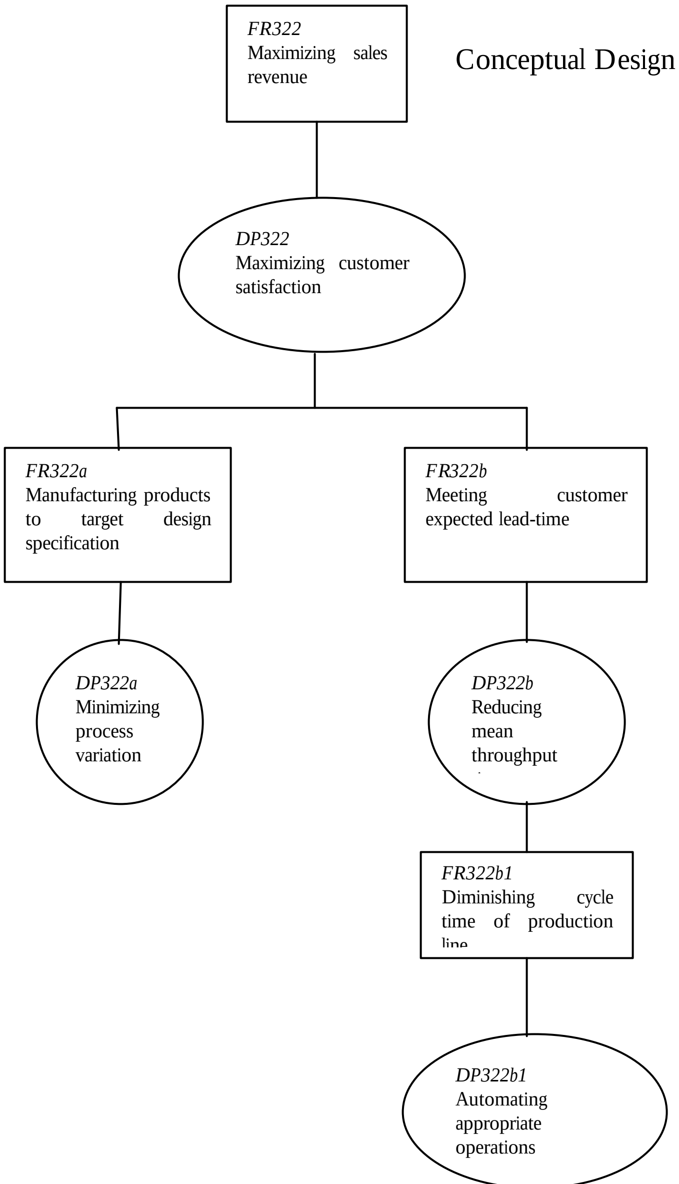

Figure 12: Decomposition of FR322 "Maximizing sales revenue"

5 OPERATIONAL PROCEDURE FOR IMPLEMENTATION

As noted earlier, lean production implementation demands a systematic approach. We can not simply imitate TPS." The principle of increasing profit through eliminating waste must be embraced by management first, so that when the line needs to shut down to determine the root cause of problem, thereby eliminating that waste a second time, management will support the decision" [Shingo 1989] .

The developed structure elucidates the objective of design process as FRs and their solutions as DPs however, it is not a descriptive model by which the exact solution is determined in detail. In fact, it serves as a conceptual model of design process that outlines the scope of decision-making but we lack for an operational procedure to lead us to the true solutions. The theoretical concepts involved in the structure impede to achieve practical alternatives.

In Figure 13 the operational procedure is proposed. We explain different stages of the proposed procedure in the following.

Develop a lean strategy. This stage contains situation analysis and objective formulation. The former calls for an analysis of the current state of operation of the manufacturing organization as well as market research. Through market research, the future prospects of potentially attractive markets are identified. In fact, we apply situation analysis to provide a correct answer to the key question 'where are we now?'. The next logical question is 'where should we be?'. The answer contains definition of the required performance of the system, identification of conflicting objectives and interests, and recognition of all constraints. The collection of situation analysis and objective formulation is presented as strategic planning package. As cited before, adopting a lean strategy is inevitable for better competitive capabilities. Therefore, it is necessary to consider lean philosophy in company's strategic planning.

Train the employees. Since the human resource is the most valuable capital of any company, training is very essential. "An integral - but often overlooked - element of Toyota's success using the TPS has been the institutionalization of a system designed to capture intellectual capital and use it to improve responses to customer needs, new product development and launch, and process innovation."(Vaghefi et.al 2001). Having been provided by suitable training, management, labor, and suppliers could all share responsibility in TPS implementation. Human resource management practices include cross-skill training for flexible production, on-the-job training, job rotation, and lean toolkit training.

Eliminate non-essential infrastructural resources. Though with different definitions, words 'structural' and 'infrastructural' are proposed by a number of authors for manufacturing resources. In one definition, infrastructural resources are "the set of structures, controls, procedures, systems and communication combined with attitudes, experience and skills of the people involved with the manufacturing system and structural resources as the technology, equipment and facilities of the manufacturing system"(Correa 1994). Albeit characteristics of human resources are included as part of the infrastructural resources, we prefer to consider them as structural resources. Since non-essential infrastructural resources such as controls, procedures, relationships, and information couplings may cause some kind of waste in the overall system, it is necessary to eliminate unnecessary ones.

Performance measurement. When we intend to convert a system to a lean one, we should gain an insight into the real problems. This becomes possible only when a complete performance measurement is conducted. There are some popular measures, e.g. sale to inventory ratio, which may act as benchmark to clarify the big picture of system.

Establish a baseline. In this stage, we tend to determine quantitative targets, serving as assessment criteria of implementation practices.

Identify opportunities. The developed structure is a useful guideline to identify lean implementation opportunities. As noted earlier, every non-value adding operation is considered a problem in lean manufacturing and should be dealt with.

Prioritize opportunities. Design matrixes of various levels may clarify the importance of functional requirements in some extents. However, financial constraints play an important role in prioritization of opportunities.

Develop & implement the improvement plan. Employee involvement is very critical in this stage. Employees would exercise lean thinking by internally driven plans.

Measure, monitor, & improve. Once an improvement plan is conducted, it is possible to compare the intended objectives with the achieved results. This makes possible reviewing primary plans.

Hold the gains. By standardization, we can maintain the desired results. This will reduce repetitive activities.

Strive for perfection. When we achieve some improvements in the production system, we should seize on new opportunities of waste elimination because lean thinking is a continuous process.

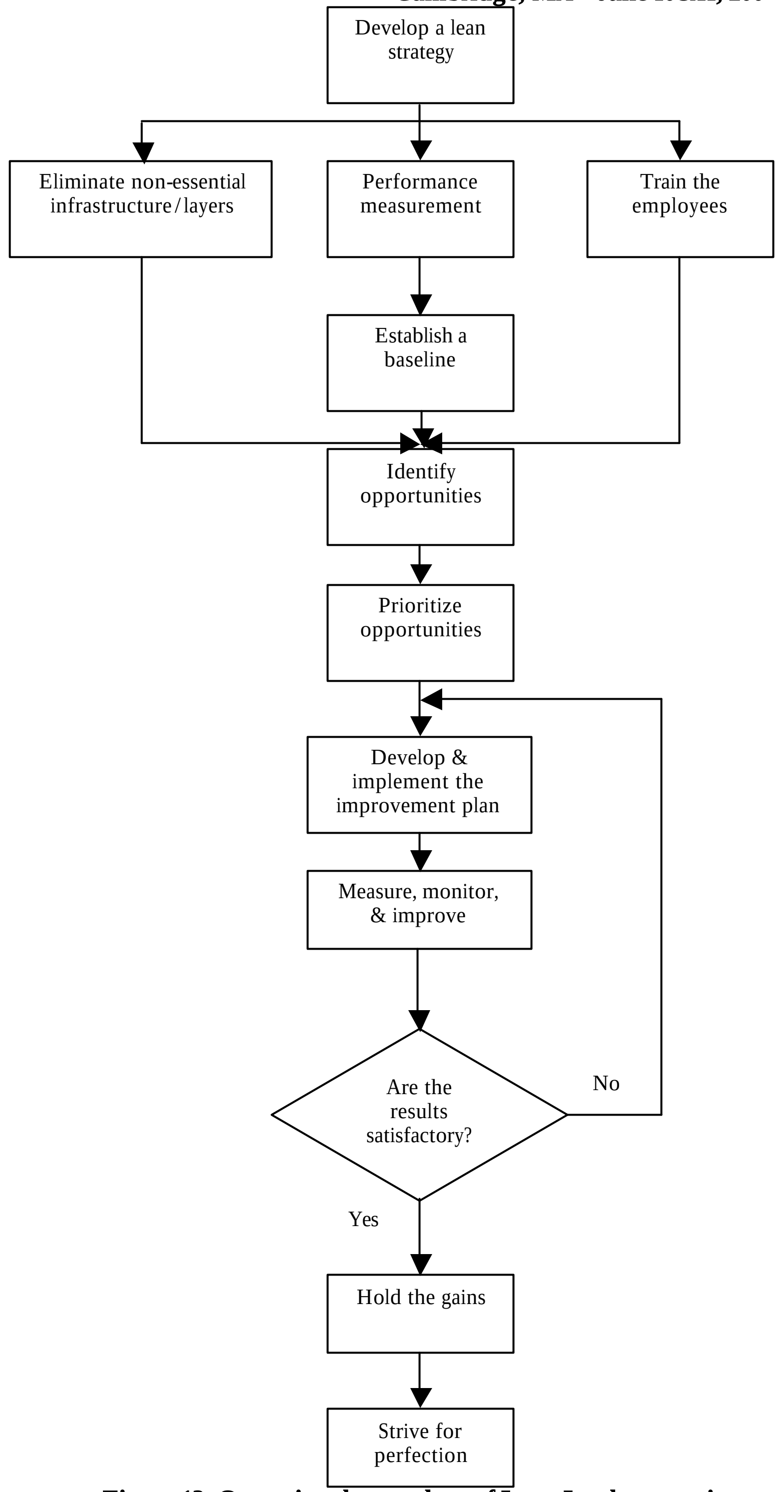

Figure 13: Operational procedure of Lean Implementation

6 CASE STUDY

The proposed procedure are being implemented in a car manufacturer company. In the first stage a strategic planning was conducted in which long-range, medium-range and short-range objectives and their associated policies are determined to reach world-class manufacturing standards.

At the second stage, a thorough performance measurement was conducted which is shown in Table 2

Table 2: Performance Indexes of the Factory

Year Index	Unit	1995	1996	1997	1998	1999
Unit cost	$	3997.5	3652.5	4377.5	5298.8	6823.8
Value added	M$	32.6	50.1	61.3	52.2	68.1
Operational profit	M$	19.2	37.9	29.7	40.6	54.9
Sale	quantity	13841	21416	32453	43755	42106
Employee	Person	2346	2899	3289	3497	3674
Salary	$	476.3	562.5	783.8	1285	1485
Unit revenue	$	6032.5	5717.5	6023.8	6220	8027.5
Material cost per unit sold	$	4417.5	3365	4027.5	5056.25	6026.3
Operational profit to revenue	-	.25	.31	.17	.15	.16
Profit before tax to revenue	$	1181.3	1282.5	1167.5	815	1285
Net profit to revenue	-	.17	.18	.15	.07	.12
Revenue per employee	$	35591.3	42237.5	59441.3	77827.5	91995
Asset	M$	201.5	200.8	370.8	400.6	554.9
Fixed asset	M$	30.4	71.6	100.1	110.1	159
Current asset to fixed asset	-	6.6	2.8	3.7	3.6	3.5
Sale per employee	$	737.5	923.4	1233.4	1564	1432.6
Quality level	-	29.9	20.6	20.7	57.6	50.3

Financial ratios demonstrated extravagant production costs, declaring different kind of waste imposed by non-value adding processes as well as low productivity.

We are recognizing lean opportunities in the system. The resistance to change is the most important obstruction in implementation practices. Management have fear to perform modification in the current system.

7 CONCLUSION

AD theory demonstrates to be an effective tool for conceptual modeling of systems, serving as a guideline in the design process. One of the most important advantages of AD is its hierarchical structure, which alleviate design complexity.

We have applied AD to model the lean production system design. Basic requirements of a lean production are categorized in three classes: organizational capabilities, technological capabilities, and value stream analysis. These basic functional requirements are decomposed to lower layeas. Organizational capabilities have greater importance because they provide grounds for other functional requirements. The developed structure is necessary for guiding designers through the design process.

In spite of AD advantages, more research should be conducted for its application in production system design. Interpretation of Process variables in production sysytems is difficult and that is why we haven't applied them in our proposed model. There is a gap between concepts reflected as FR-DP relationships and implementation practices. We have proposed an operational procedure to bridge the theoritical foundation of lean production modeled by AD approach and implementation plan of actions.

The proposed model is being implemented in a car body assembly line. Resistance of change is the main challenging obstruction. It is completely expectable because lean thinking is a new production philosophy, demanding strong organizational and technological bases.

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