A LEAN MANUFACTURING ROADMAP FOR AN AUTOMOTIVE BODY ASSEMBLY LINE WITHIN AXIOMATIC DESIGN FRAMEWORK

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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 redesigning a car body assembly line. Axiomatic Design theory provides a framework to simplify the whole problem. According to the AD principles, a hierarchical structure has been developed. The developed structure originated in lean manufacturing principles and existing conditions of an assembly line, revealed that elimination of all kinds of waste is a prerequisite for other functional requirements. Several main sources of waste were recognized in the assembly line and some practical solutions are suggested to alleviate these problems. In the initial survey, it became obvious that high work-in-progress is the major problem of this assembly line, which is the symptom of an unbalanced flow. Two cells have more problems than others and require to be modified first: the door cell and the underbody cell. Based on the hierarchy, these cells are redesigned. In addition to interior space of the cells, two automatic material handling systems - overhead chain conveyor- are employed respectively to facilitate handling operation of these cells. Main Line is another part of the assembly line, have to being modified by adding spot welding robots. The proposed plan is justified both technically and economically to the managers of the assembly line.

Key Words Axiomatic Design, Lean, Manufacturing, Automotive, Body, Assembly

چکیده. این مقاله به معرفی روش طراحی بدیهه‌گرا و مبانی آن می‌پردازد. با استفاده از این تئوری خط مونتاژ یک سیستم تولیدی مورد بررسی قرار می‌گیرد و مراحل باز طراحی آن ارائه می‌شود. مطالعات صورت گرفته در این تحقیق نشان می‌دهد که ساختار سلسله مراتبی روش طراحی بدیهه‌گرا بین حوزه‌های مختلف طراحی با حذف تکرارهای متداول موجود و به حداقل رساندن سعی و خطا، بهره‌وری فرایند طراحی بیشینه می‌گردد. پیاده‌سازی روش طراحی بدیهه‌گرا نشان می‌دهد که برای رسیدن به تولید ناب حذف اتلاف‌ها مقدم بر سایر فعالیت‌ها می‌باشد. با در نظر گرفتن نکات ذکر شده جهت کاهش زمان حین ساخت محصولات و بالا بردن بهره‌وری سیستم مونتاژ دو سلول ”مونتاژ دربها“ و ”مونتاژ کفی“ مورد بررسی قرار گرفت و بر اساس تئوری طراحی بدیهه گرا سیستم ساخت این دو سلول باز طراحی شدند که نتیجه حاصله و برنامه ارائه شده هم از نظر فنی و هم از نظر اقتصادی توجیه پذیر است.

1. INTRODUCTION

Several attempts have been accomplished in order to develop a design methodology, which is both flexible and special-purpose, but as Cross [1] cited in his book, we lack a successful simplifying paradigm of design thinking.

Several engineering design methodologies have emerged to capture design complications [2]. Modeling and analysis methodologies have been developed to clarify the system complexities and to provide some scientific tools in decision-making and to provide some scientific tools in decision-making [3].

As Nordlund and Tate have noted, "axiomatic design theory provides a valuable framework for guiding designers through the decision process to achieve positive results in terms of final design object" [4]. 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" [4]. 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 sentences:

First, traditional design methodologies of production systems have been challenged by continually increasing changes in business environments. The dynamics of markets necessitates that product development period is shortened as much as possible. Rapid development process will be a significant competitive advantage in the next decades. Cavallucci [5] 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". Advanced manufacturing technologies act as a competitive weapon in conquering world's ever-changing markets. The rapidly changing manufacturing environments require some new design principles, which have yet to be conceptualized [6]. It is believed that "the factory of the future will be a highly integrated information system combining advanced manufacturing technologies and innovative strategies, such as lean manufacturing, just-in-time, and total quality management" [7]. 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" [8]. AD may be an appropriate approach to encompass to the new challenges of manufacturing system design.

Second, manufacturing systems become more complicated and adaptation capability to the environmental conditions plays a crucial role in the survival of companies [9]. 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. In fact, by means of AD, we can interrelate the various levels of a manufacturing system such as production level, manufacturing level, and shop-floor level.

Third, the ongoing information revolution will influence the design process. Nowadays, design is not just a random creative issue of an experienced expert but it is the product of systematic reasoning that its bases can be captured and generalized [10]. "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" [11].

Fourth, the separation of what's and How's in the AD results in flexibility, which is a great advantage for AD 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.

2. AXIOMATIC DESIGN FUNDAMENTALS

"Axiomatic Design defines design as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through mapping between Functional Requirements (FRs) and Design Parameters (DPs)"[12]. The FRs represents the goals of the design or what we want to achieve. The DPs specify how FRs must be satisfied. There is four design domains: Customer Domain, Functional Domain, Physical Domain, and Process Domain. By mapping between domains, the design process initiates and a characteristic vector symbolizes the design [13]. FRs is defined in the functional domain in order to satisfy the needs, which are defined in the customer domain. Design parameters are the outcomes of mapping FRs in the physical domain.

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	Decentralized	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

At the first stage, customer needs and attributes are recognized and formulated as FRs and constraints [11]. There are looser bounds on constraints than FRs. Constraints must be regarded in the entire design process. "Constraints establish the bounds on the acceptable design solutions and differ from FRs in that they do not have to be independent" [11].

The main problem needs to be decomposed in order for alleviating its complexities. That is how the problem solving hierarchy composes. This decomposition operation is one of the most important advantages of AD approach that makes the design problem simple and easy to solve. Some researchers like Cochran believe that only the functional and physical domains require being decomposed in the manufacturing system design [6]. In this case, this may be due to difficulties of Process Variable definition. PVs could be defined easily when the main problem is a product development not a manufacturing system design.

Zigzagging between the domains produces the desired hierarchy, specifying the relevant subproblems in the next level of the hierarchy.

In order to mapping be satisfied between domains, two axioms must be followed [14]:

Axiom1: The Independence Axiom Maintain the independence of the FRs.

Axiom2: The Information Axiom Minimize the information content of the design.

Mathematically, the set of independent functional requirements can be considered as a vector FR with m components. In the same way, the design parameters may be treated as a vector DP with n components. Thus the design process in which the relationships of FRs and DPs are determined, may be expressed as:

$$\{FR\}=[A].\ \{DP\} \tag{1}$$

Where A is the design matrix. Each element of design matrix, Aij may be expressed as:

$$A_{ij}=\partial FR_i/\partial DP_j \tag{2}$$

Each line of above vector equation may be written as $FR_I=\sum A_{ij}\ DP_j$

If A varies with both FR_i and DP_j, the design is non-linear. In linear design, all A_{ij} are constant.

If the design matrix is diagonal, we have an uncoupled design. A design with triangular matrix is called a decoupled design.

Independence Axiom is dissatisfied with

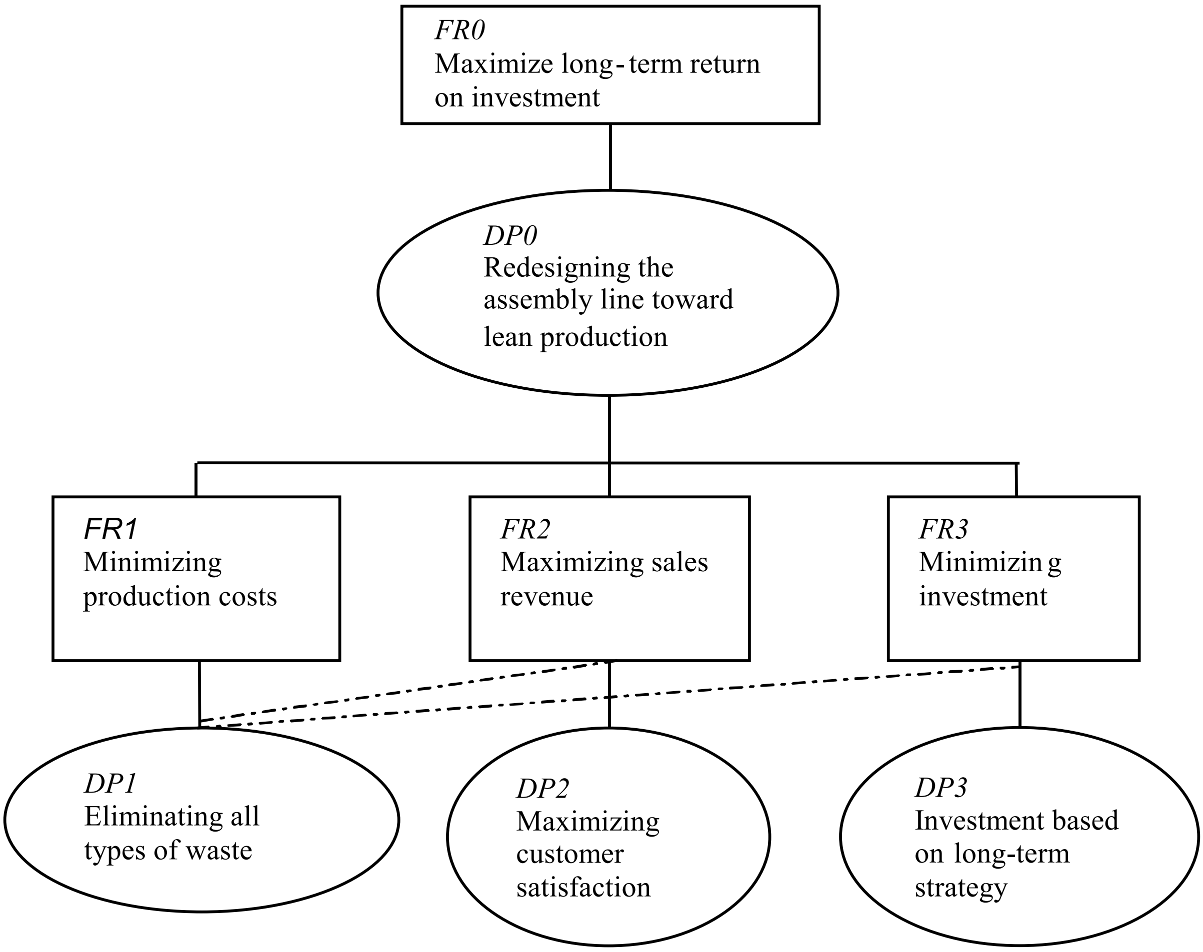

Figure 1. First Level of The Developed Structure.

coupled designs and in order to decouple such designs, some changes in the FRs and DPs are needed.

If the DPs of a decoupled design are ordered in a special manner, the Independence Axiom is satisfied.

3. LEAN MANUAFCTURING

Lean manufacturing, which is the analogue of Toyota Production System (TPS), is the world benchmark in manufacturing systems.

Adapting closely to the current competitive markets, "TPS is very robust, responding adaptively and effectively both to internal factors such as bad raw material or high product variability and to external factors such as demand fluctuations" [18]. "The TPS marked a running point in industrial organization as profound and far-reaching as the creation of the mass production model of the late nineteenth century" [16].

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.

Adopting lean philosophy, Japanese car manufacturers have strengthened their competitive capabilities. In comparison with average Western practice, average Japanese practice delivers [17]:

- ❖ Development lead times for a new car which

are 25% shorter;
- ❖ Half of the design man hours per model;
- ❖ Half of the assemblyman hours per car.

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 [15].

In this paper, we are to employ Axiomatic Design methodology in an automotive body assembly line to develop a systematic design structure by which a specific plan of actions toward lean production is produced.

4. CONCEPTUAL REDESIGN MODEL OF THE ASSEMBLY LINE BASED ON AD APPROACH

The case of this study is the second biggest automotive manufacturer in Iran and has been producing different kinds of car since 1968. The current products of this line have been in production from 1993. Therefore, this production system has gone beyond its transient state and functions in a steady state, that is, problems emerge in their authentic appearances.

The most important perceived drawbacks of this assembly line are:

1. High work-in-progress
2. Inefficient material flow
3. Low productivity level

By making use of AD approach, we analyze this discrete production system and propose a step-by-step plan toward lean manufacturing.

The highest-level functional requirement is chosen to be "Maximizing long-term return on investment." Its relevant design parameter is "Redesigning the assembly line toward lean production."

According to the first-level functional requirement, the structure is expanded to next level that is shown in Figure 1. The design matrix of the first level is as follow:

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \end{bmatrix} = \begin{bmatrix} X & O & O \\ X & X & O \\ X & O & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \end{bmatrix} \quad (3)$$

The design matrix is a decoupled one because both FR2 and FR3 are affected by DP1.

4-1- Relationship between FR1 and FR2 As seen in Figure 1, DP1 "Eliminating all types of waste" affects FR2 and FR3 so the design matrix is decoupled. In the following sections, we explain the causes of this relationship.

On the one hand, total supply of cars in Iran including import of foreign cars and internal production, cannot satisfy its growing market demands. Therefore, there is an unbalanced supply-demand relation and the producers of pre-sell their own products, that is, here FR2 means "increasing production volume".

On the other hand, increasing of production volume becomes practicable just after making the assembly line as efficient as possible. In other words, if we provide more facilities to augment production level, without removing inefficiencies, the manufacturing costs will augment and absorb any increase in sales revenue. "Eliminating all kinds of waste" can also result in ameliorated quality levels and less unit price, improving customer satisfaction. Therefore, DP1 "Eliminating all types of waste" is a predecessor for FR2.

4-2- Relationship between FR1 and FR3 As seen in Figure 1, there is another relationship between FR3 "Investment based on long-term strategy" and FR1 "Minimizing production costs."

On the road to achieving its objectives, a company requires to invest intelligently owing to capital scarcity. In this way there is a strict need for a company to minimize its demand for investment. Now a question emerges: how can we minimize the need for investment? The answer is: try to fully utilize existing facilities. Thus, DP1 "Eliminating all types of waste" is a prerequisite for FR3"Minimizing investment."

First level of structure reveals the importance of FR1 and as a logical conclusion; we must

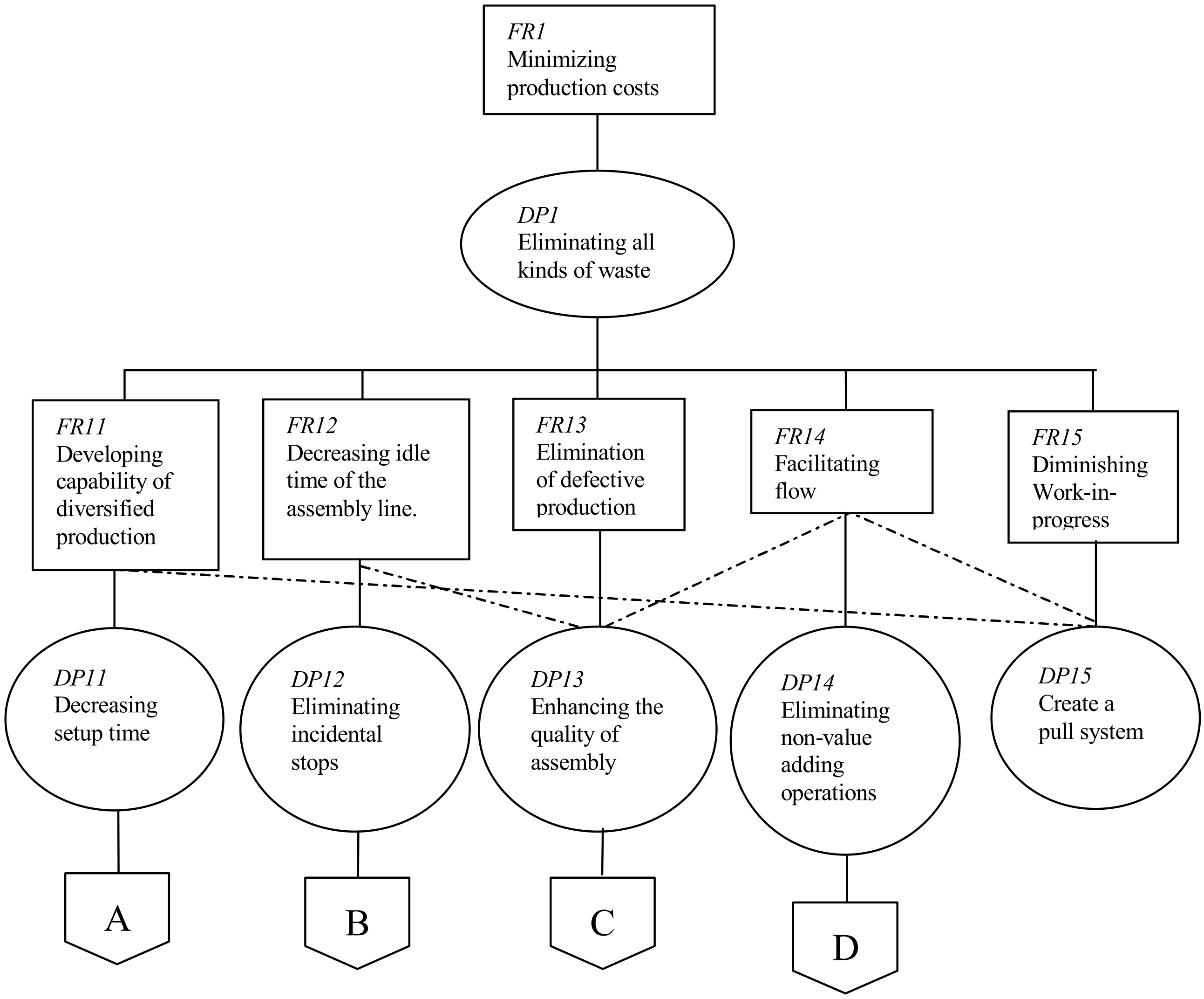

Figure 2. Second Level of the Developed Structure.

decompose it further to next levels.

5. DECOMPOSITION OF FR1

DP1 "Eliminating any kind of waste" is a very comprehensive design parameter and cannot be applied to the shop-floor level. Therefore, decomposition is inevitable to acquire a practicable hierarchy.

With a view to being lean, any activity that does not add value to the product would be categorized as waste or non-value adding activity. In Figure 2, by zigzagging, causes of waste for the system have identified.

The decoupled design matrix of the second level FRs and DPs is as follow:

$$\begin{bmatrix} FR11 \\ FR12 \\ FR13 \\ FR14 \\ FR15 \end{bmatrix} = \begin{bmatrix} X & O & O & O & X \\ O & X & X & O & O \\ O & O & X & O & O \\ O & O & X & X & X \\ O & O & O & O & X \end{bmatrix} \begin{bmatrix} DP11 \\ DP12 \\ DP13 \\ DP14 \\ DP15 \end{bmatrix} \quad (4)$$

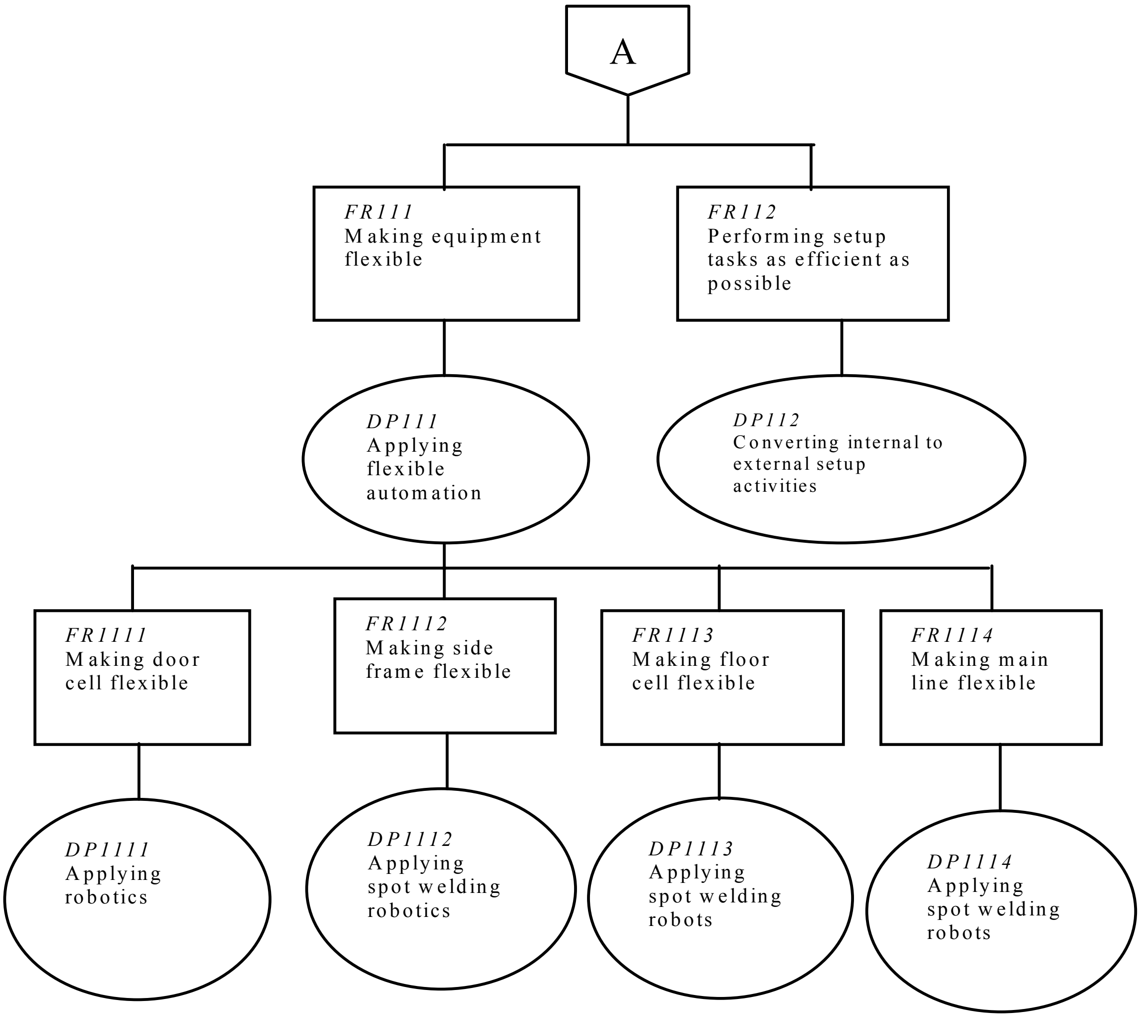

Figure 3. Third Level Decomposition of FR11.

Since every decoupled design is path dependent, it requires to be modified as follows

$$\begin{bmatrix} FR13 \\ FR15 \\ FR11 \\ FR12 \\ FR14 \end{bmatrix} = \begin{bmatrix} X & O & O & O & O \\ O & X & O & O & O \\ O & X & X & O & O \\ X & O & O & X & O \\ X & X & O & O & X \end{bmatrix} \begin{bmatrix} DP13 \\ DP15 \\ DP11 \\ DP12 \\ DP14 \end{bmatrix} \quad (5)$$

Now, the design matrix is triangular and we can deduce an order for the design process. In the following, a brief explanation of constituent functional requirements of FR1 is cited.

FR11 implies changeover wastes. The better organizational capabilities of a plant are, the easier changeover process will be. Rigid work structure, inflexible production method and equipment, and single-skilled workers all contribute to a solid production system with huge inertia that changes production with difficulty. The high inertia of the system results in high changeover cost. In other words, developing capability of diversified production plays an important role to decrease manufacturing cost. The decomposition of this functional requirement is shown in Figure 3.

Another factor affecting manufacturing cost is the operational readiness period. High investment in production facility necessitates full utilization of

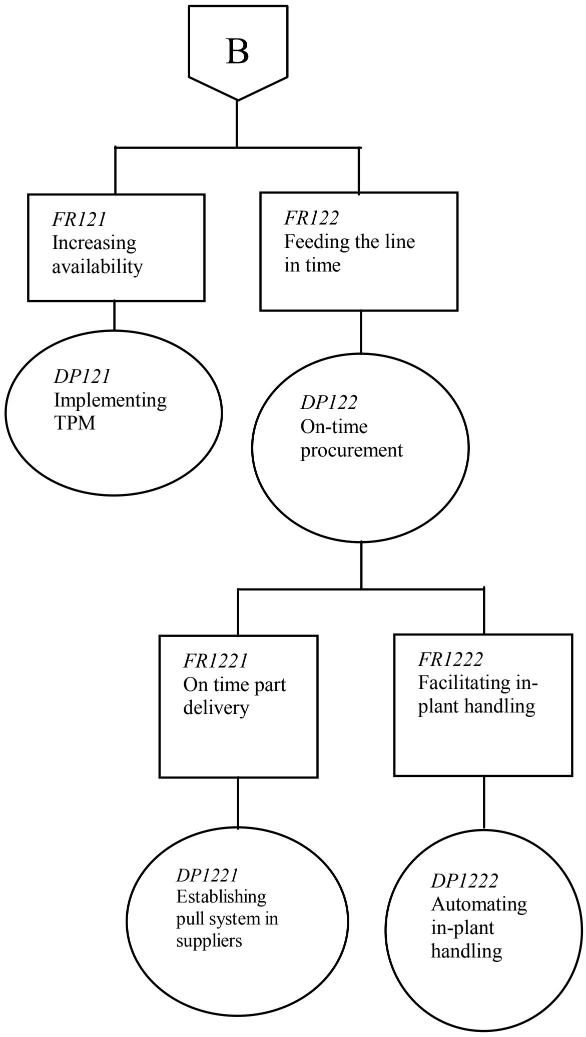

Figure 4. Third Level Deposition of FR12.

manufacturing equipment to compensate for extravagant capital expenditures. Any production disruption will result in production loss and overhead increase. Accordingly, FR12 "Decreasing idle time of the assembly line" is considered as a constituent part of FR1. On time procurement and implementing TPM[1] are design parameters that eventually satisfy FR12 (See Figure 4).

FR13 "Elimination of defective production" which is respectively a prerequisite for FR12 and FR14, assume greater importance. Assembly defects originate from four concurrent sources: deficient incoming parts, poor internal material handling, incomplete assembly operation, and defective manufactured parts in the press shop. In Figure 5, we depict its constituent elements. FR13 represents one of the crucial causes of waste: defective products. Making defective products is pure waste. Though in special circumstances, some of the defective parts may be reworked and the remainder would be scraped. It is better to prevent the occurrence of defects instead of finding and repairing defects. Defective production engages factory resources in non-value adding activities and in this way aggravate productivity.

The fourth accelerator force of inefficiency is the unbalanced flow, which is the result of poor process design. Three non-effective operations, handling, inspection, and storage, being shown in Figure 6, impose an unbalanced flow on the process. Since material handling has a direct effect on customer lead-time, it is very crucial

One of major causes of waste is overproduction due to traditional push flow. The most visible symptom of a push flow is work-in-progress leading to manufacturing cost increase. Pull system is the solution of this problem namely that we have to adopt a one-piece flow. Early production is as unpleasant as overproduction. In other words, each process must be completed exactly in time and has to proceed to the next process only when it is demanded. Downstream operations pull required parts, needed from upstream operations, at the required time. If each station produces only when it is needed, the production volume will be flexible and that is why the FR11 is affected by DP15 (See Figure 2).

6. DECOMPOSITION OF FR2

First level of decomposition expresses that FR1 takes priority over both FR2 and FR3. Now after focusing on FR1, we have to regard FR2 "Maximizing sales revenue". In order to maximize revenue, one company needs to expand its own market share with customer satisfaction. In today's extremely competitive markets, customer satisfaction is a survival factor of companies and

[1] Total Productive Maintenance

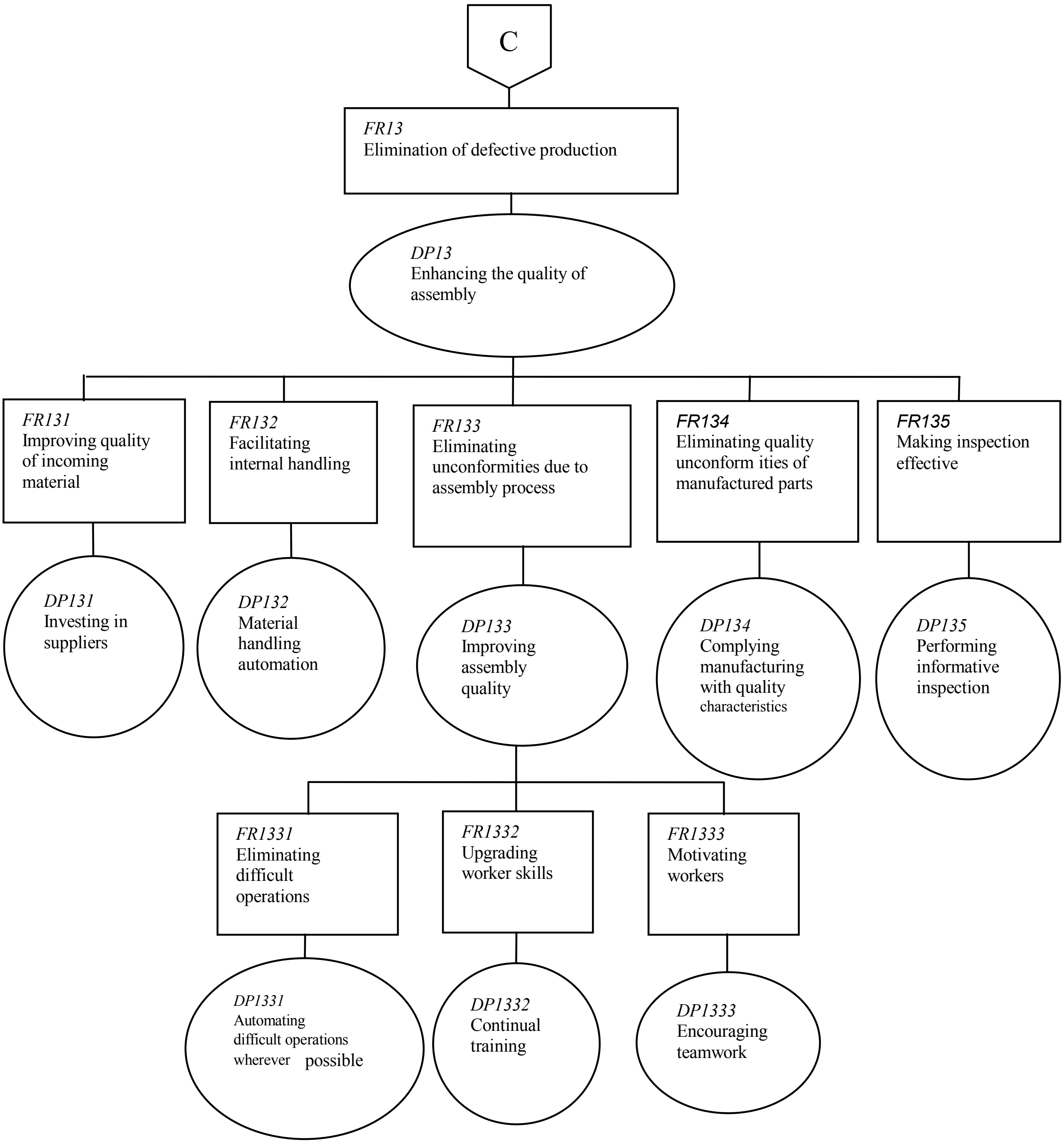

Figure 5. Third Level Decomposition of FR13.

has to be taken into account with high details. Therefore, "Maximizing Customer Satisfaction" represents how FR2 can be achieved and is considered as DP2. This DP is further decomposed based on the key attributes of manufacturing system performance that affect customer satisfaction: conformance quality (FR21), and meeting customer expected lead-time (FR22). The decomposition of FR2 is shown in Figure 7.

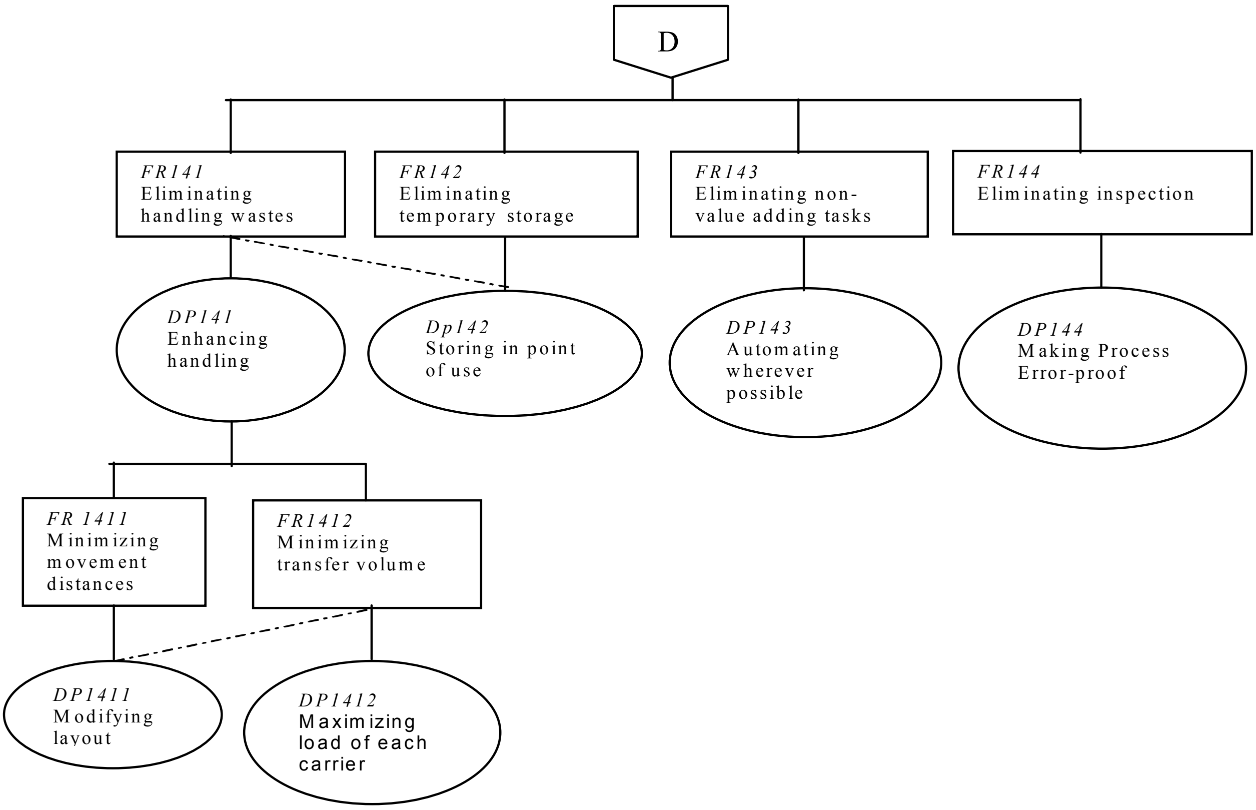

Figure 6. Third Level Decomposition of FR14.

7. PLAN OF ACTIONS TOWARD LEAN MANUFACTURING

Once we try to redesign a production system, we initiate a problem solving cycle to acquire higher efficiency, which includes setting objectives, problem formulation, alternative solution development, solution assessment, selection, and implementation. Intrinsic features of AD such as separation of design objectives with solutions, Independence Axiom, and its hierarchical structure all help facilitate design problem-solving cycles. Not only does AD formulate the design problem as various FRs but also does it contribute to appropriate solutions.

The AD structure forms a thorough list of different factors as well as their relationships, which may be considered as a roadmap toward the ultimate goal, a lean assembly line. The lowest level of each branch is the starting point of implementation practices.

Redesigning this assembly line, just as any other similar manufacturing system, comprises several technological, managerial, and personnel problems, explained in section 7. Based on AD, we have developed a design hierarchy to tackle these problems, being summarized in Table 2.

In order to achieve FR1, five functional requirements of the second level, shown in Figure 2, must be satisfied. The design matrix of this level tells us that FR13 and FR15 are prior to other FRs. It is important to remember that FR11, FR12, FR14 are as significant as FR13 and FR15 but are satisfied at the next stage. In fact, there is no superiority between FRs at the same level. Existing waste in the assembly line originate from various factors, being reflected as the second level FRs. Among waste sources, we observe that WIP, crowded workstations with workers and semi finished parts, and unnecessary operation (e.g. transportation and storage) are more serious and do need an immediate attention. We will explain the detail of changes proposed for the assembly line in the following.

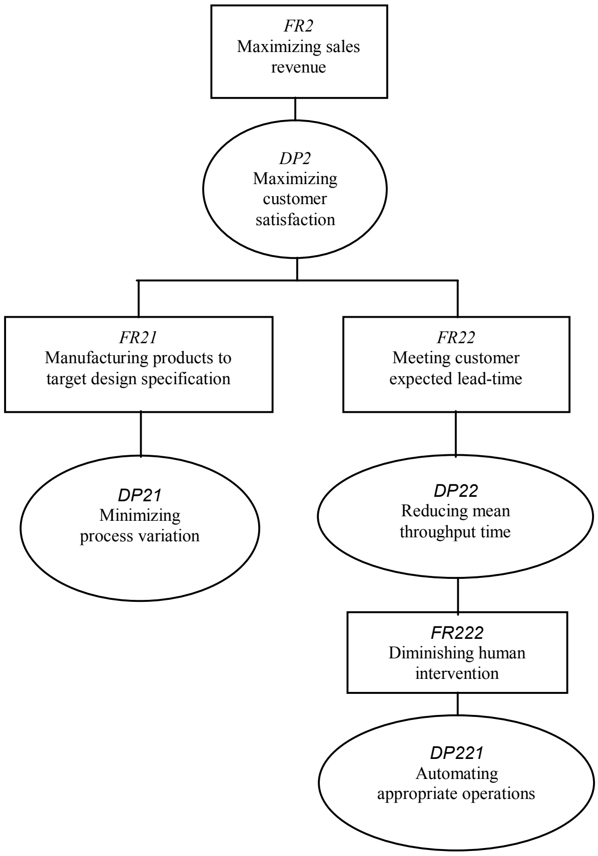

Figure 7. Decomposition of FR2.

8. RECOMMENDED DESIGN OF THE ASSEMBLY LINE

The assembly line has been producing two models of a car. The line layout is shown in Figure 8. As noted earlier, second level of the AD structure (See Figure 2) specifies that we should first focus on WIP reduction and defective production elimination. Direct observations of the assembly line as well as interview with the managers reveal that the door cell and the underbody cell comprise a big portion of WIP. Especially, massive accumulation of finished doors waiting for installation has a considerably negative effect on the assembly line's material handling.

According to the structure (See Figures 2,3,4,5,6), it is necessary to redesign some of the supporting activities of body assembly process like procurement or repair and maintenance, which is organizationally separate from body assembly unit, yet must be included in a systematic view of production activity. On the other hand, there were some internal factors that are directly related to intrinsic characteristics of assembly line such as tooling, material flow and the degree of automation. We have focused our analysis on internal factors because of project scope, which is confined to body assembly line. However, AD structure determines precisely the role of supporting activities in a lean manufacturing system and their relationship to internal factors.

8.1 Modification of Door Cell the existing layout of Door Cell is shown in Figure 9. Door Cell is not synchronous with the successor station and hence a large amount of work-in-progress accumulates around it.

This cell has two hemming presses that each one is allocated to lateral doors, respectively. Die change does not perform as quick as required to ensure a continuous flow, thus the managers have decided to produce in large batches to compensate organizational inefficiencies associated with die change. This causes mass of work-in-progress, which consumes some large floor around the cell and impedes the material flow. In addition, high work-in-progress imposes non-value adding operations such as transportation, delay, and storage on the assembly process.

Every ten finished doors (all of the same type e.g. front left door) are stored manually in one pallet around Door Cell. Focusing on AD structure, in regard to high WIP of doors, we observe that current hemming presses and manual door handling method are bottlenecks, imposing most of current waste on the process. Therefore, we recommend constructing a duplicate line (See Figure 10) to alleviate the existing waste and shorten the cycle time. FR14 and FR15 could be simply achieved by the modified changes. In figure 11, the recommended layout of power & free overhead conveyor is represented. As an important advantage, it is possible to store an optimum number of door pallets on the overhead conveyor to compensate production fluctuations.

The required space for releasing WIP provides the new line occupied space. It is noteworthy that the automatic handling system could be applied both for current and recommended designs.

In Table 3, we have outlined the relationships of

TABLE 2. AD Structure Developed for Redesigning Body Assembly Line.

Functional Requirement	Design Parameter
FR0 Maximize long-term return on investment	DP0 Redesigning the assembly line toward lean production!
FR1 Minimizing production cost FR11 Developing of diversified production FR111 Making equipment flexible FR1111 Making the door cell flexible FR1112 Making the side frame flexible FR1113 Making the floor cell flexible FR1114 Making the main line flexible FR112 Performing setup tasks as efficient as soon as possible	DP1 Eliminating all types of waste DP11 Decreasing setup time DP111 Applying flexible automation DP1111 Applying spot welding robots DP1112 Applying spot welding robots DP1113 Applying spot welding robots DP1114 Applying spot welding robots DP112 Converting internal to external setup activities
FR12 Decreasing idle time of the assembly line FR121 Increasing availability FR122 Feeding the line in the time FR1221 On time part delivery FR1222 Facilitating in plant handling	DP12 Eliminating incidental stops DP121 Implementing TPM DP122 ON-time procurement DP1221 Establishing pull system in suppliers DP1222 Automating in plant handling
FR13 Elimination of defective production FR131 Improving quality of incoming material FR132 Facilitating internal handling FR133 Eliminating unconformities due to assembly process FR1331 Eliminating difficult operations FR1332 Upgrading worker skills FR1333 Motivating workers FR134 Eliminating quality unconformities of manufactured parts FR135 Making inspection effective	DP13 Enhancing the quality of assembly DP131 Investing in suppliers DP132 Material handling automation DP133 Improving assembly quality DP1331 Automating difficult operations wherever possible DP1332 Continual training DP1333 Encouraging team work DP134 Complying manufacturing with quality characteristics DP135 Performing informative inspection
FR14 Facilitating flow FR141 Eliminating handling wastes FR1411 Minimizing movement distances FR1412 Minimizing transfer volume FR142 Eliminating inspection FR143 Eliminating non value adding tasks FR144 Eliminating temporary storage	DP14 Eliminating non value adding operations DP141 Enhancing handling DP1411 Modifying layout DP1412 Maximizing load of each carrier DP142 Making process Error-Proof DP143 Automating wherever possible DP144 Storing in the point of use
FR15 Diminishing work-in-progress	DP15 Create a pull system
FR2 Maximizing sales revenue FR21 Manufacturing products to target design specification FR22 Meeting customer expected lead time FR221 Diminishing human intervention	DP2 Maximizing customer satisfaction DP21 Minimizing process variation DP22 Reducing mean through put time DP221 Automating appropriate operations
FR3 Minimizing investment	DP3 Investment based on long-term strategy

our recommended modifications and the AD structure.

By these modifications, doors could be handled pallet by pallet, with extensively shorter waiting time, reducing work-in-progress considerably. In addition, a large amount of floor space around Door Cell would be released to be used for other purposes. Since there is a limited floor space, we urge to make use of the free overhead space.

Using overhead conveyors for doors handling has the following advantages:

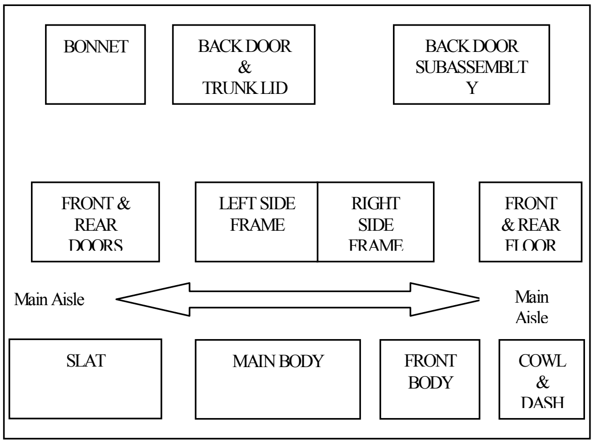

Figure 8. General Layout of the Body Assembly Line.

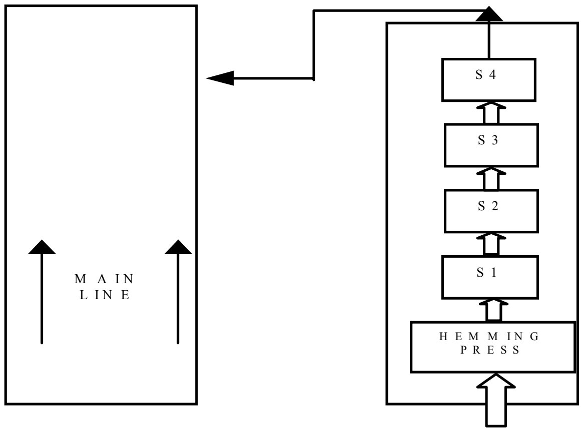

Figure 9. Existing Layout of Door Cell.

1. Elimination of in-floor handling and thus alleviating main aisle traffic
2. Overhead temporary storage instead of in-floor storage and thus space utilization improvement
3. Reduced WIP around Door Cell
4. Reduction of human intervention
5. Reduced handling costs
6. Safety improvement

8.2 Modification of Underbody Cell One main component of the body is underbody, composed of rear floor and front floor.

A detailed assessment of assembly process in this cell revealed the improvement potentials. The existing arrangement of the cell (see Figure 12) imposes some non-value adding operations on the assembly process like additional handling of semi-assembled parts between fixtures and delay of assembled floors to be transferred to the main line. Regarding the structure, it is revealed that we can apply automation to alleviate many existing problems. Most of functional requirements could be achieved by implementing proposed changes in Underbody Cell (See Table 4 for details).

In Underbody Cell, just like most of other cells, the main operation is spot welding that can be simply automated by robots. Spot welding robots are of greater efficiency because they operate more quickly and accurately than do the human operators. In addition, while human operators have difficulty to operate in certain positions, robots are able to easily reach different positions.

The most important benefits of robot application are:

1. Cycle time reduction
2. Making cell more comfortable for workers by eliminating repetitive tasks
3. Direct labor reduction
4. Reduction of process variation
5. Improvement of production flexibility

Since automatic feeding mechanisms for underbody parts increase the operation complexity and would be costly, we decide to isolate manual part loadings and fixations with complementary welding operations. For this purpose, fixture 1 & 2 of the rear floor section and fixture1 of the front floor are devoted to part loading and fixation welding and in the last fixture, robots will complete the assembly. The modified arrangement of Underbody is shown in Figure 13.

In-cell material handling is considered as another potential improvement opportunity. Semi automatic handling of parts between fixture 1, fixture 2, and fixture 3 in Rear Floor section as well as fixture1 and fixture 2 in Front Floor (See Figure 12) are non-value adding and could be eliminated. The automatic transfer mechanism between fixtures, called ATM, is our proposed low-cost solution for this waste (See Figure 13).

The comparison of existing standard time (ST)

TABLE 3. The Relationship of The Recommended Modifications and The Developed Structure at Door Cell.

Current Problems and Existing Improvement Opportunities	Associated Functional Requirements	Solution
Inefficiencies associated with door handling	FR132	Automatic finished doors handling
Increasing handling productivity	FR1411 & FR1412	Layout modification of Door Cell- overhead handling instead of floor handling
Lack of equipment flexibility	FR1111	To be analyzed application of sealer robots
Unnecessary temporary storage	FR144	Allocating some space on the main line for storage of only one pallet
Other existing non-value adding operations especially inside Door Cell	FR143	To be analyzed application of automation technologies
Lack of changeover capability	FR1111 & FR112	To be analyzed application of robots as well as Shigeo's setup reduction techniques
High work-in-progress	FR15	Control on door handling by main line workers
Human intervention	FR222	To be analyzed application of automation technologies

of operations with recommended design for rear and floor cells are listed in Table 5 and Table 6, respectively. Elimination of non-value adding operations could reduce cycle time of Underbody Cell from 141.6 to 103.2 seconds.

All in-cell transformation both in rear and front floor will be automated. This makes possible the one-piece flow concept, which is the ultimate objective of pull systems. Instead of separate handling of rear and front floor to the main line, we propose to join these parts together in the second fixture of the front floor before transformation to reduce the handling volume to one half.

8.3 Handling of Finished Underbodies to Main Body Line The current handling method of the underbody has the following disadvantages:

1. Increasing traffic of the main aisle
2. Requirements to WIP storage space
3. Manual loading and unloading of each carrier and its associated waste

These disadvantages clarify the inefficiency of current handling method. We have designed an overhead conveyor to alleviate some of current problems. In Figure 14, the arrangement of this system is depicted.

As it has noted before, our modifications, including application of robots, automatic in-cell handling system between fixtures, and an overhead conveyor for whole floor transportation to Main Line are based on the developed structure and the current arrangement of Underbody Cell.

8.4 Modification of Main Body Line In Main Body and Slat, all subassemblies such as underbody, side frames, roof panel, front body and so on are joined together, forming the whole body.

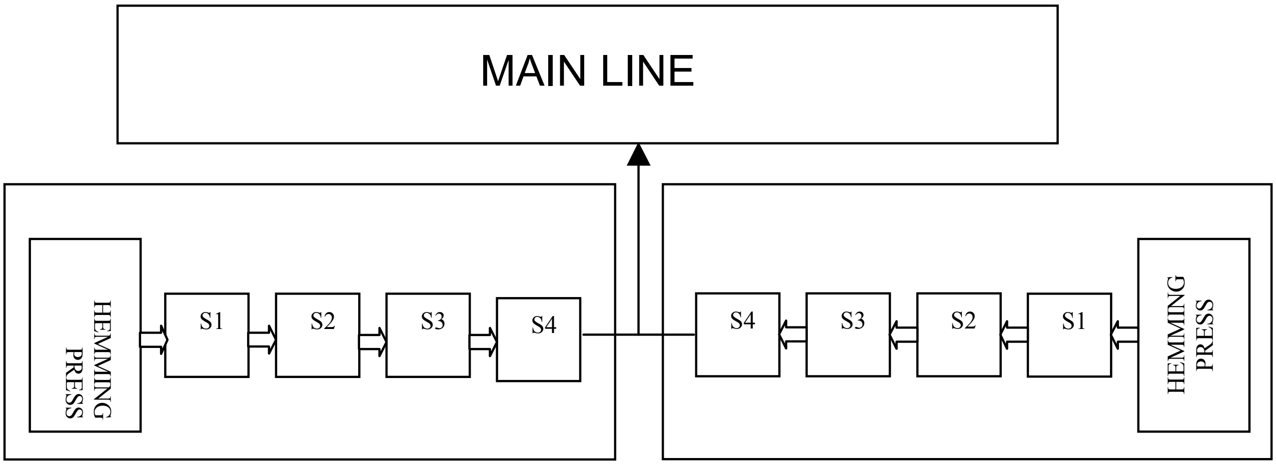

Figure 10. Recommended Layout of Door Cell.

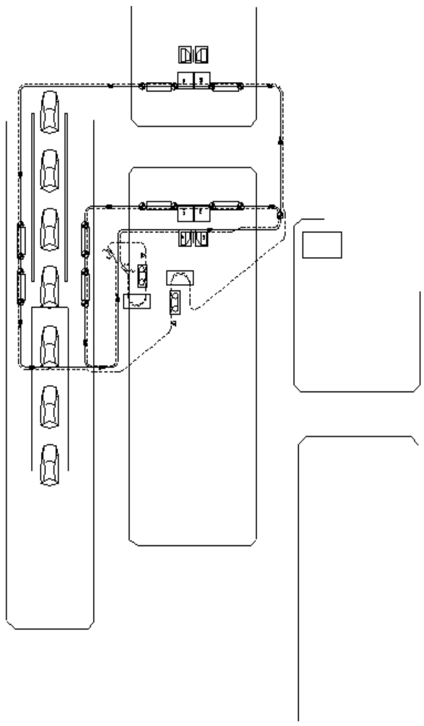

Figure 11. Recommended Layout of Transportation System for Door Cell.

In most stations, spot welding is the main process, which could be simply performed by robots. There are yet some part feedings in Main Line, hindering application of robots. However, just like underbody cell, it is possible to separate manual part fixations from complementary welding processes to apply spot welding robots. Furthermore, some part positioning processes may

TABLE 4. The Relationship of the Recommended Modifications and the Developed Structure at Underbody Cell

Current Problems and Existing Improvement Opportunities	Associated Functional Requirements	Solution
Inefficiencies associated with underbody handling	FR132	Overhead conveyor for underbody handling
Increasing handling productivity	FR141	Layout modification of underbody cell-transportation of complete underbody instead of separate rear & front floors
Lack of equipment flexibility	FR1113	Spot welding robots
Unnecessary temporary storage	FR144	One-piece flow for the completed underbody to the main line
Other existing non-value adding operations especially inside Underbody Cell	FR143	Automatic in-cell handling (between fixtures)
Lack of changeover capability	FR112	To be analyzed application of Shigeo's setup reduction techniques
High work-in-progress	FR15	Control on underbody handling by main line operators
Human intervention	FR222	Spot welding robots- automatic material handling
Tedious and boring operation	FR1331	Spot welding robots

be automated with low cost solution, paving the way for robotic spot welding. All stations in Main Body are analyzed and redesigned in which 14 spot welding robots are recommended to be installed (See Figure 15 and Figure 16 for modifications).

Handlings between stations could be automated to improve productivity. Another impetus for applying robots is that robotic stations cannot operate with manual handling operations because of safety considerations. The relationships between FRs and solutions are represented in Table 7.

9. MODIFICATION OF OTHER CELLS

In addition to Door Cell, Underbody Cell, and Main Line, there are other workstations, assembling the other components of body. We have analyzed them to find ways of improvement especially application of automation. However, we cannot employ automation to increase these cells productivity because of:

1. Small, numerous parts in Dash & Cowl Cell
2. Deviating routes to Main Line, impeding material handling automation
3. Obstructing facility for automatic handling of Bonnets and Back Door
4. Low cost and simple manual handling especially for Back Door

10. ECONOMIC ANALYSIS OF THE PROPOSED PLAN

Since managers tend to be cautious about their capital. Investment in advanced manufacturing

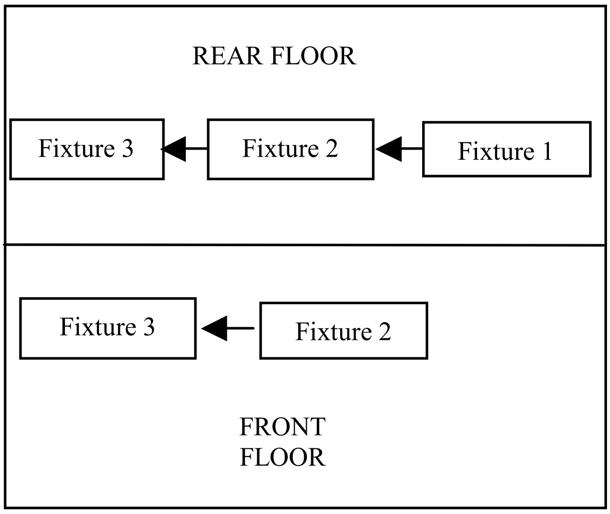

Figure 12. Existing Layout of Underbody.

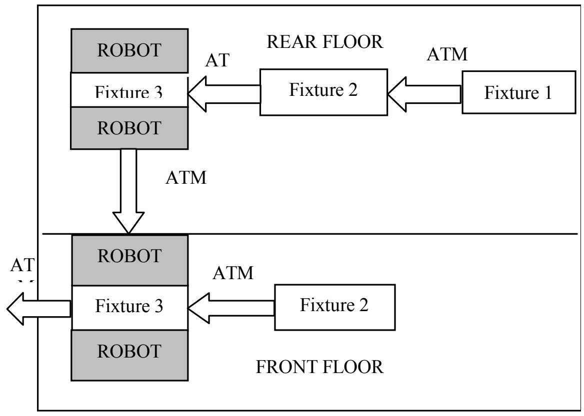

Figure 13. Recommended Layout of Underbody Cell.

technologies like robotics requires being justified both technically and economically to managers. Decomposition process in AD provides a framework for technical justification of recommended plans because it is accomplished in accordance with constraints and higher functional requirements. In fact, every proposed modification that can satisfies one or more FRs as well as constraints would be considered a technically feasible solution. But the chain of changes as a whole must give rise to acceptable benefits to compensate for excessive investment costs. In Table 8 and Table 9, we outline the benefits and costs of the project.

If one tends to summarize the benefits of the proposed plan, the followings may be listed:

1. Reduction of work-in-progress
2. Diminishing cycle time of Underbody Cell
3. Increasing flexibility owing to robots.
4. Diminishing volume of transportation to 50% by joining front and rear body at Underbody Cell instead of Main Line.
5. Reduction of consumed floor space owing to automatic handling both in Door Cell and Underbody Cell.
6. Diminishing traffic across Main Aisle of line owing to employing overhead space.
7. Improvement of quality through automating assembly processes.

Total investment of the proposed plans amounts to 4847038 US $, including feasibility studies, preliminary training, purchase of equipment and peripheral tools, delivery, engineering consulting, installation, production stop, civil works, and assembly line preparation.

According to the project's costs and revenues summarized in Table 8 and Table 9, the cash flow profile is presented in Table 10. This table is the base for calculating common economic indexes (see 11). A brief description of these methods is mentioned in the following.

The NPW[2] method compares all of a project's estimated expenditures to all of its estimated revenues and other benefits at a reference

Time called the 'present'. For a particular interest rate, if the present values of the revenues and other benefits exceed the present value of the expenses, the project is acceptable. Rate of Return is the interest rate at which the present worth of the cash flow is equal to 0. The payback period method determines the length of time required to recover the initial investment at a zero rate of interest. The smaller payback period is, the more attractive investment

[2] Net Present Worth

TABLE 5. Comparisons of Standard Time between Existing and Recommended Design at Rear Floor.

Description	Station Code	Worker	Existing Design	Recommended Design (estimated)
First Operation of Rear Floor	S_1	A	112.2	77
First Operation of Rear Floor	S_1	B	74.4	74.4
First Operation of Rear Floor	S_1	C	135	103.2
Second Operation of Rear Floor	S_2	A	141.6	70.6
Second Operation of Rear Floor	S_2	B	141.6	70.6
Second Operation of Rear Floor	S_2	C	69.6	69.6
Third Operation of Rear Floor	S_3	A	117.6	90 (by robot)
Third Operation of Rear Floor	S_3	B	116.4	90 (by robot)

TABLE 6. Comparisons of Standard Time between Existing and Recommended Design at Front Floor.

Description	Station Code	Worker	Existing Design	Recommended Design (estimated)
First Operation of Rear Floor	S_4	A	181.8	90
-	S_4	B	-	90
Second Operation of Rear Floor	S_5	A	161.4	90 (by robot)
-	S_5	B	-	90 (by robot)

is. Benefit to Cost ratio (B/C) is another technique for economic assessment. A project is deemed to be acceptable if $B/C \geq 1$, that is, if the project's benefits equal or exceed its costs. NEUA[3] is the net uniform series, being equivalent to different cash flow items. More details on various economic evaluation methods can be found in Thuesen [18] and Grant [19].

As seen in Table 11, the economic indexes are within acceptable limits and thus this plan is economically justified. For example, payback period is about three years that is suitable.

[3] Net Equivalent Uniform Annual

11. CONCLUSION

We have applied AD method to tackle a multi-aspect production problem, redesigning an automotive assembly line toward a lean system. One of the most important advantages of AD, its approach to develop a hierarchical design structure, helped us to alleviate the complexity associated with the whole problem. The developed structure revealed that elimination of all kinds of waste is a prerequisite for other actions. Several main sources of waste were recognized in the assembly line and some practical solutions are suggested to alleviate them.

The most important perceived drawbacks in this

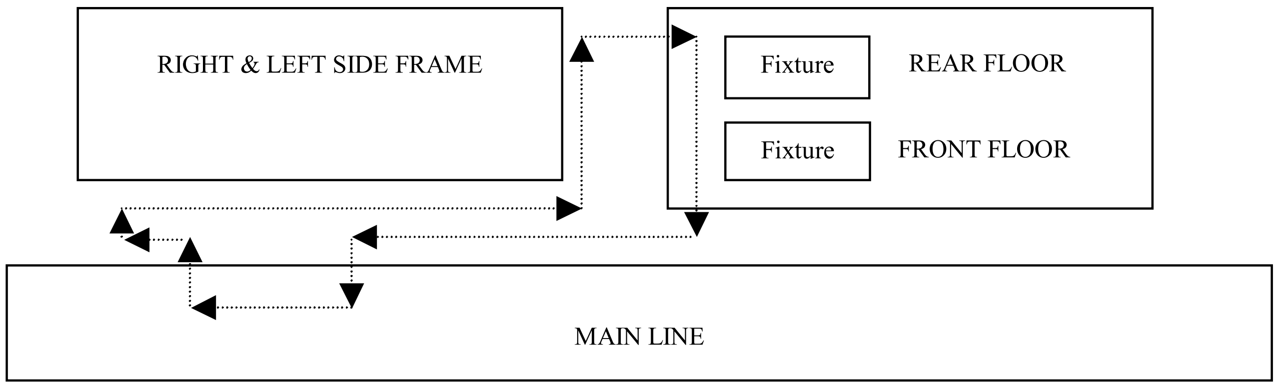

Figure 14. Recommended Layout of Transportation System for Underbody Cell.

TABLE 7. The Relationship of the Recommended Modifications and the Developed Structure at Main Body Line.

Current Problems and Existing Improvement Opportunities	Associated Functional Requirements	Solution
Inefficiencies associated with main body handling	FR132	Handling automation between stations
Lack of equipment flexibility	FR1114	Spot welding robots
Difficult and tedious operation	FR1331	Spot welding robots
Lack of changeover capability	FR112	To be analyzed application of Shigeo's setup reduction techniques
Human intervention	FR222	Spot welding robots
Other existing non-value adding operations	FR143	Spot welding robots

production system are:

1. High work-in-progress
2. Inefficient material flow
3. Low productivity level

Based on the developed structure, we first focus on the methods of cost reduction because it is the prerequisite of other functional requirements. According to the structure, it is necessary to redesign some of the supporting activities of body assembly process like procurement or repair and maintenance, which is organizationally separate from body assembly unit, yet must be included in a systematic view of production activity.

Two cells have more problems and require to be modified first: door and underbody. Based on the hierarchy, these cells are redesigned. In addition to interior space of the cell, two automatic material handling systems - overhead chain conveyor - are employed respectively to facilitate handling operation of these cells. Main Body Line is another important part of the assembly line, being analyzed to find ways of improvement. 14 spot welding robots could be applied there, by which a chain of facilitated, continuous flow would be created.

The proposed plan has the following advantages:

1. Reduction of work-in-progress

TABLE 8. Annual Benefits of Recommended Modifications.

Description	Estimated Quantity (US $)
Maintenance	20000
Training	5000
Depreciation	112250
Operation management	12500
Total	**149750**

TABLE 9. Annual Extra Costs of Recommended Modifications.

Description	Estimated Quantity (US $)
Production increase	5840625
WIP reduction	35000
Saving in material handling costs	18750
Saving in labor costs	61000
Saving in floor space	125000
Total	**6080375**

TABLE 10. Project Cash Flow Profile.

Year	Cash Flow Item
0.	-4847037
1.	1070075
2.	2286125
3.	3502250
4.	4718250
5.	5934375
6.	5934375
7.	5934375
8.	5934375
9.	5934375
10.	5934375

TABLE 11. Economic Indexes of the Proposed Plan.

Measure	Unit	Calculation
NPW	Million dollars	11.45
NEUA	Million dollars	2.58
ROR[1]	-	57%
PP[1]	Year	3.15
B/C	-	2.98

2. Diminishing cycle time of the underbody cell from 141.6 seconds to 103 seconds
3. Increasing flexibility owing to employing robots
4. Diminishing volume of transportation to 50% by joining front and rear body at this cell instead of main line.
5. Reduction of consumed floor space owing to automatic handling
6. Diminishing traffic in the main aisle of line owing to employing overhead space.

Since the structure is based on lean principles, it is thorough and flexible enough to be applied in similar researches with minor amendments. Our experience elucidates that AD approach is very useful in complex production system design problems, yet there is a gap between abstract concepts represented in AD structure and exact applicable solutions. Although Process Variables are introduced to bridge this gap, their definition and interpretation is somehow

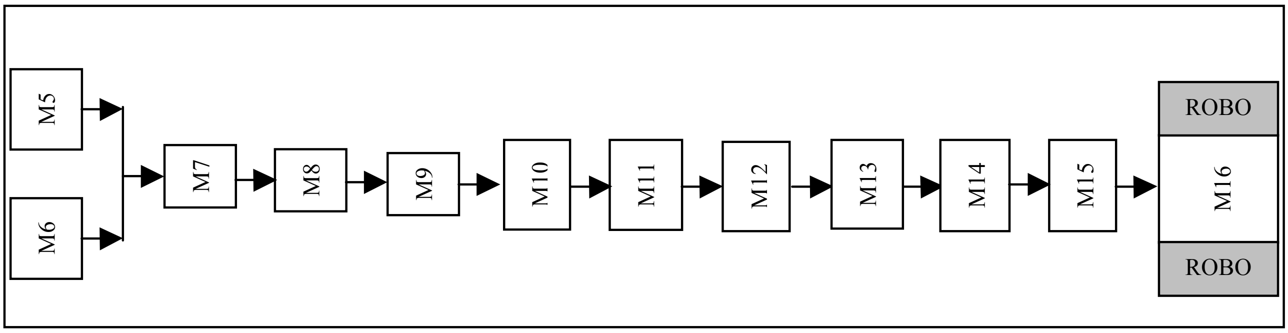

Figure 15. Existing Layout of Main Line.

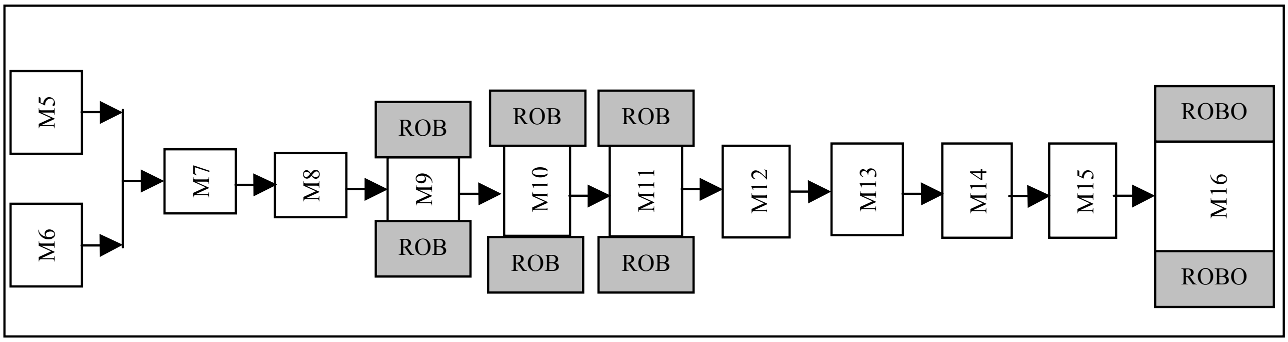

Figure 16. Recommended Layout of Main Line.

difficult.

12. ACKNWLEDGMENTS

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13. REFERENCES

1. Cross, N., Dorst, K. and Roozenburg, N., (Eds.) “Research in Design Thinking, Delft University Press, Delft, Netherlands, (1992).
2. Killander, A. J. "Why Design Methodologies are Difficult to Implement", ***International Journal of Technology Management***, Vol. 21, Nos. 3/4, (2001), 271-276.
3. Narayanan, S., Bodner, D. A., Sreekanth, U., Govindaraj, T., McGinnis, L. F., and Mitchell, C. M., "Research in Object-Oriented Manufacturing Simulations: an Assessment of the State of the Art", to Appear in ***IIE Transactions***, (2001).
4. Nordlund, M., Tate D., and Suh, N. P. "Growth of Axiomatic Design through Industrial Practice", ***3rd CIRP Workshop on Design and the Implementation of Intelligent Manufacturing Systems***, Tokyo, Japan, (June 19-21, 1996), 77-84.
5. Cavallucci, D. and Lutz, P., "Intuitive Design Method (IDM), A New Approach on Design Methods Integration" ***First International Conference on Axiomatic Design, Proceeding of ICAD***, Cambridge, MA, (June. 2000), 21-23.
6. Cochran, D. and Reynal, V. A., "Axiomatic Design of Manufacturing Design", The Lean Aircraft Initiative, Report Series, (November. 1996), #RP96-05-14.
7. Coates, J. F., "Manufacturing in the 21st Century", ***International Journal of Manufacturing Technology and Management***, Vol. 1, No. 1, (2000), 42-59.

8. Alcorta, Ludovico. "Flexible Automation and Location of Production in Developing Countries", The United Nations University, INTECH, Discussion Paper Series #9805, (1998).
9. Reynal, V. A, and Cochran, D., "Understanding Lean Manufacturing According to Axiomatic Design Principles", The Lean Aircraft Initiative, Report Series, #RP96-07-28, (1996).
10. Rowell, A. A., "Critical Thinking", An Interview with Dr. Nam P. Suh, MCAD Vision, www.MCADCafe.com. (2001).
11. Suh, N. P., "Engineering Design", CRC Press LLC, (1999).
12. Almstrom, P., "Systematic Design and Analysis of Manufacturing Systems – Industrial Experiences", ***Proceedings of the 14th International Conference on CAD/CAM, Robotics and Factories of the Future***, Coimbatore, (December 1-3, 1998).
13. Lipson, H. and Suh, N.P., "Towards a Universal Knowledge Database for Design Automation", ***Proceeding of ICAD2000, First International Conference on Axiomatic Design***, Cambridge, MA, (June, 2000), 21-23.
14. Suh, N. P., "The Principles of Design", Oxford Press, New York, (1990).
15. Flinchbaugh, J., "Using Integrated Management Systems to Design a Lean Factory", ***Center for Quality of Management Journal***, Vol. 7, No. 2, (Winter 1998), 23-30.
16. Vaghefi, M. R., Wood, L. A., and Huellmantel, A., 2001, "Toyota Story 2: Still Winning the Productivity Game", ***Annual Meeting of the Iranian Academic Association***, Tehran, Iran, (2001).
17. Harrison, A., "Just-In-Time Manufacturing in Perspective", Prentice Hall International (UK), (1992).
18. Thuesen, G. J. and Fabrycky, W. J., "Engineering Economy", 9th Edition, Prentice Hall College Div, (2000).
19. Grant, E. L., Areson, W. G., and Ireson, W. G., "Principles of Engineering Economy", 8th Edition, John Wiley and Sons, (1990).