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Assembly line balancing by using axiomatic design principles: An application from cooler manufacturing industry

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Abstract: The philosophy of production without waste is the fundamental belief behind lean manufacturing that should be adopted by enterprises. One of the waste elimination methods is assembly line balancing for lean manufacturing, i.e. Yamazumi. The assembly line balancing is to assign tasks to the workstations by minimizing the number of workstations to the required values. There should be no workstation with the excessively high or low workload, and all workstations must ideally work with balanced workloads. Accordingly, in this study, the axiomatic design method is applied for assembly line balancing in order to achieve maximum output with the installed capacity. In order to achieve this aim, all improvement opportunities are defined and utilized as an output of the study. Computational results indicate that the proposed method is effective to reduce operators' idle time by 12%, imbalance workload between workstations by 38%, and the total number of workers by 12%. As a result of these improvements, the production volume is increased by 23%.

Key words: lean manufacturing; axiomatic design; assembly line balancing.

1. Introduction

Customer demands are the most important drivers for manufacturers. They want to have high-quality, low-cost products just-in-time and in full. Hence, manufacturing companies should be more robust and responsive to continuous, variable and unpredictable demands from customers. In the fiercely competitive market, manufacturers need to use flexible, adaptive, active, and responsive strategies that meet customer demands at low cost and in a short time. To reach these targets, the lean manufacturing tools can be employed within an effective method. Through the application of lean techniques, manufacturers can enable to eliminate wastes in their operations.

Lean manufacturing includes many tools to eliminate wastes such as kanban, smed, kaizen, value stream mapping, 5S, and visual management. Assembly line balancing is one of the implementations of lean manufacturing, also known as Yamazumi that helps to reduce overproduction, inventory, unnecessary motion, material handling activities, scrap, and operators' idle time. The objective of assembly line balancing problems is to allocate operations to workstations in such a manner to optimize a criterion specified by considering the constraints regarding the accomplishment of the work. Objectives addressed at line balancing problems are classified as two main types, technical and economic criteria. While

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the minimization of the number of workstations for cycle time is the one that is most widely used among technical criteria, the minimization of the cycle time for the number of workstations and minimization of the total idle time are the other technical criteria principally used with regard to the methods developed for assembly line balancing problems. From the operational cost perspective, minimizing the total cost of stations and labors are the most widely used economic criteria (Ghosh and Gagnon, 1989; Yilmaz et al., 2016).

In the current study, assembly line balancing problem (ALBP) is solved by using the axiomatic design approach to reduce waste and improve the system of a cooler manufacturing plant. The AD method was introduced about three decades ago, since then it has been used systematically both for academicians and practitioners in the industry (Suh, 1990). The usefulness of the basic principles in terms of analysis, comparison, and selection is very effective in using AD in many areas such as production, organization, and system improvement. There is a set of important factors affecting the spread of AD. First, design methodologies developed for production systems cannot meet the needs due to continuous change in requirements. Lean and agile manufacturing can easily adapt to rapidly changing conditions. The changes directly affect the production system; however, technological change at the factory level can change the production techniques, the features of the product and the way the workforce is employed (Alcorta, 1999). AD is considered to be a robust approach to the changes in manufacturing systems. Second, the manufacturing enterprises are inherently complex and the external factors affect the sustainability of the companies. The high ability of AD in the systematic propagation of functional requirements to the many aspects of a system design makes it an appropriate procedure in the context of system design (Reynal et al., 1996). Besides, thanks to AD, different levels of a system (in particular manufacturing system) can be interrelated in a holistic manner. Third, the ongoing information revolution can affect the design process. Today, the design is not guided by a decision-maker but it is systematically directed by a stepwise roadmap, which will be so crucial to apply the axioms (Lipson et al., 2000). Fourth, the separation of Whats and Hows in the AD results leads to flexibility providing superiority to AD versus other design methodologies. Therefore, AD is an appropriate method to overcome the difficulties preventing to make decisions on the manufacturing system design (Durmusoglu and Satoglu, 2011). In this paper, we proposed a synthesized solution for an assembly line of the plant by using AD.

The main objective of this study is to show the applicability of AD methodology to balance the assembly line. In this manner, a real case study is presented and a lean-based AD methodology is employed to balance the line by eliminating the waste. The goals with the implementation of the AD methodology are reducing the number of stations, total idle times, workload imbalance, and increasing the production rate.

The scientific contributions of this paper are presented from two different sides as follows.

- From theoretical perspective, the main contribution of this paper is to implement a lean-based AD methodology to balance the assembly line.
- As for the managerial point of view, this study provides several managerial insights related to AD and its application on the assembly line by eliminating the wastes from the production system.

The rest of this paper is organized as follows. A comprehensive literature review on AD is provided in Section 2. The principles of AD are presented in Section 3. The implementation of AD to the assembly line balancing problem is given in Section 4. A real case study is given in Section 5. Concluding remarks and future research directions are presented in Section 6.

2. Literature Review

Assembly lines play a significant role in the efficiency of production systems. Setting up or reorganizing a line is a costly investment. Therefore, it is important to organize the line effectively right from the beginning to the end. The basic problem during the design of the assembly line is to balance the workload with regard to workstations on production lines. Unbalanced lines lead to inefficiency in production, increases in costs and further losses in technology and workloads (Cakir, 2006). Performance criteria used in the assembly line balancing problems is usually the minimization of the number of stations or the cycle time (Ağpak et al, 2002; Cevikcan and Durmusoglu, 2011; Yilmaz et al, 2016).

Many reviews of the literature are available for assembly lines design to reach several objectives by several methods (Graves and Lamar, 1983; McMullen and Frazier, 1998; Guschinskaya et al., 2008; Dolgui and Ihnetsenka, 2009).

AD is also one of the tools used in lean manufacturing and offers designers a very useful structure in order to achieve the final design object (Nordlund and Tate, 1996; Matt, 2012). Many companies use AD methodology to develop new products, processes, and approaches. Thanks to the axiomatic approach, functional requirements can be determined by separating the design problem in a hierarchical manner. After AD theory and application principles were first developed by Suh (1990), many studies have been carried out on the application of AD methodology over the last 30 years. In this section, the studies including AD applications are reviewed within four different streams: (i) cellular manufacturing systems, (ii) assembly lines, (iii) lean manufacturing system, and (iv) other types of production systems.

The studies regarding the AD implementation for cellular manufacturing systems are reviewed below. Black and Schroer (1988) adapted the AD methodology to provide flexibility in the cellular manufacturing system. Cochran et al. (2000) applied AD principles together with lean manufacturing principles and separated complex production systems into smaller and manageable systems. Chen et al. (2001) used the independence axiom of AD with a decision support system to enhance the performance of a cellular manufacturing system. Kulak et al. (2005) presented a road map to the design of cellular manufacturing system using AD principles. Durmusoglu and Satoglu (2011) a holistic methodology and road-map are presented to design a hybrid manufacturing system by implementing AD principles. Ertay and Satoglu (2012) used information axiom for a new product introduction to hybrid manufacturing systems. Han et al. (2013) used AD methodology for virtual cellular manufacturing system design by focusing on the system cost and efficiency.

The AD principles are also applied in assembly line design studies reviewed below.

Houshmand and Jamshidnezhad (2004) used the AD methodology, which was developed based on lean manufacturing principles, to redesign a car body assembly line. Matt (2012) used AD principles to control complexity dynamics in a mixed-model assembly system. Matt (2013) proposed a design approach based on AD principles to control the sensitivity of assembly systems to fluctuations. Hager et al. (2017) proposed a methodology for manufacturing system design, in particular assembly lines. Celek et al. (2019) proposed an assembly system design methodology by implementing AD principles for aircraft fuselage structures assembly. Rauch et al. (2019) defined the guidelines to implement the AD approach for designing flexible manufacturing and assembly systems. By doing so, the functional requirements were determined based on customer needs.

To design a lean manufacturing system, AD is employed in several studies reviewed below.

Suh et al. (1995) provided an AD-based model for an ideal production system in line with lean principles. Houshmand and Jamshidnezhad (2002) combined capabilities and value stream mapping tool based on the AD method and developed a design model. Houshmand and Jamshidnezhad (2006) developed an AD Methodology for lean manufacturing system design using process variables (PVs). Nakao et al. (2007) proposed AD methodology for shortening lead time in the manufacturing process of tailor-made products. Matt (2008) developed methodological guidance for the effective use of the axiomatic design in lean manufacturing systems. Vinodh and Aravindraj (2012) used axiomatic modeling for the design process of a lean manufacturing system.

AD principles are also employed for other types of production systems reviewed below.

Gunasekera and Ali (1995) employed the AD method conceptual stage of a metal forming process consisting of three-stage. Suh (1997) proposed a new approach to define, classify, and design the system by considering AD methodology. Babic (1999) developed a decision support system based on AD principles for a flexible manufacturing system. Holzner et al. (2015) proposed AD for the systematic design of small and medium-sized enterprises (SMEs). Khandekar and Chakraborty (2016) proposed fuzzy axiomatic design principles to determine appropriate non-traditional machining processes by considering their importance. Chakraborty et al. (2017) determined the design criteria so as to evaluate the re-manufacturability of products.

The major finding from the review is that, to the best of our knowledge, a road map including all functional requirements of assembly line balancing has not been studied so far. Hence, in this study, a methodology is developed using AD principles in order to fill this gap in the assembly line balancing literature.

3. Principles of Axiomatic Design

The main purpose of using AD is to ensure that design activities are carried out on a scientific basis with a theoretical foundation (Suh, 2001). To this end, a systematic search process is carried out to achieve the best design solution among all alternative solutions. The basis of AD is to separate two important questions: what (objectives) to do and how (means) to do. In AD terminology, the objectives are represented by functional requirements (FR's), while the solutions are represented by design parameters (DP's). In the design process, the best set of design parameters that will meet the functional requirements are determined. The existence of design axiom is one of the most important concepts in AD. In this manner, the Independence axiom corresponds to the first one, while the Information axiom corresponds to the second axiom. They were introduced by Suh (1990) as follows.

Axiom 1. *The Independence Axiom (IA):* Ensure the independence for functional requirements

Axiom 2. *The Information Axiom:* Information content should be minimized

The relationship between the FRs and DPs can be expressed as

$\{FR\}=|A|\{DP\}$

where, {FR} corresponds to the functional requirement vector, {DP} is related to the design parameter vector, and |A| is the design matrix characterizing the design. Each entry a_{ij} of |A| corresponds the i^{th} FR to j^{th} DP. The structure of |A| matrix describes the design type, which is considered by decision maker. So as to ensure the independence axiom, |A| matrix should be in form of uncoupled or decoupled design. |A| matrix is divided into three categories as explained follow.

Uncoupled Design (most preferred): The |A| matrix is a diagonal matrix indicating the independence of FR-DP pairs. Thus, each FR can be satisfied by simply focusing the corresponding DP.

Decoupled Design (second choice): The corresponding |A| matrix is triangular. Hence, the FRs can be satisfied systematically FR_1 to FR_n by just dealing with the first *n* DPs. This design is most commonly encountered in real life.

Coupled Design (undesirable): The |A| matrix does not define a special structure. Thus, even a small change in any DP may have an impact all FRs, simultaneously. Coupled design should be avoided as much as possible while systems are designing.

4. Assembly Line Balancing Model through AD Principles

Several main sources of waste are recognized in the assembly line and some practical solutions are suggested to alleviate these sources by using AD principles. The main waste in assembly lines is caused by the time differences between the operations that lead to idle time for the operators and high work-in-process. As a result, the utilization of the production line decreases. Since the main goal is to meet customer demands on time, these irregularities lead to loose customers who are not satisfied. In order to prevent losing customers and profits, some preventive actions must be considered at the beginning of the system design. Design is not just a random creative issue of an experienced expert but it is the product of systematic reasoning whose bases can be captured and generalized.

When a company tries to become lean and more efficient, it will start to introduce lean concepts. Making use of the AD approach, we analyze the assembly line system and propose a step by step plan toward lean manufacturing. According to the assembly line structure, it is necessary to redesign some of the activities which affect the line performance such as assigning tasks to operators, material handling between the work stations, eliminating non-value added operations, etc.

The axiomatic design theory provides a framework to simplify the whole problem. It is also a hierarchical structure that eliminates all kinds of waste which is a prerequisite for other functional requirements. The FRs represent the goals of the design or what we want to achieve, so they need to be improved by DPs enhancing performance.

At the first stage customer needs and attributes are recognized and formulated as FRs and DP constraints. Constraints establish the bounds on the acceptable design solutions and differ from FRs in that they don't have to be independent. In the following steps, the FRs and DPs are determined from highest to lowest level of the hierarchy by the zigzagging procedure which takes place between domains and specifies the relevant subproblems in the next level of the hierarchy.

Step 1: *Choose FRs in the Functional Domain and mapping of FRs in the physical domain.*

The highest level functional requirement is chosen to be meeting the required production volume on the assembly line. In order to meet customer demand on time, we should redesign the assembly line by eliminating non-value added tasks and make the line balanced. Therefore the relevant design parameter of the function requirement is to balance the line to meet the required production volume.

FR: Meet the required production volume on the assembly line

DP: Balance the line to meet the required production volume

The next step is to decompose the functional requirement that makes the design problem simple and easy to handle.

Step 2. *Decompose FR in the Functional Domain-Zigzagging between the domains.*

The following functional requirements are defined to achieve the highest level of FR. First of all to balance the line, operators and machines should work within the cycle time. Morever, operators should know which task they will do to balance their operations, so their work definitions should have been defined before. Finally, to meet the customer demand on time, we should always be informed. In these requirements, the sequence of FRs is also important. All operators must perform the assigned tasks within predetermined cycle time. To do so, the machines can be operated within the production cycle time. Another crucial decision here is that each operator must be assigned to the tasks in accordance with skill or skill levels. When these requirements met the information flow must be provided in a continuous manner. Otherwise, the improvements cannot be permanent.

FR1: Make operators work within the production cycle time

FR2: Operate machines within the production cycle time

FR3: Ensure that operators are allocated to tasks according to their skills

FR4: Provide the continous information flow

Step 3. *Find the Corresponding DPx's by Mapping FRx's in the Physical Domain.*

To satisfy the four FRs defined above, we define the design parameters in the physical domain corresponding to the functional domain. To operate operators and machines within the production cycle time, firstly we should know that their working times. The first parameter is related to operators' working times and it should be checked to control whether the requirement is met or not. The next parameter is also related to the second requirement. Because it is not possible to assign any worker to a task without knowing the skill or skill levels, it must also be checked. The system must be designed to provide continuous information flow, which is related to the fourth requirement.

DP1: Check operators' working times

DP2: Check machines' working times

DP3: Check operators' skill/skill levels (knowledge)

DP4: Design a system which strengthens the continous information network

Step 4. *Determine the Design Matrix.*

After FRs and DPs are defined, the corresponding Design Matrix is constituted. It is important that the Design Matrix (DM) must satisfy the independence axiom (IA) of AD principles.

The design equation and the DM corresponding to the FR-DP sets are as follows.

$$\begin{bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \end{bmatrix}$$

The design matrix at this level is an uncoupled design and satisfies IA of AD. In the DM above, a symbol X represents a strong relationship between the corresponding FR-DP pair.

Step 5. *Decomposition of FRXs and DPXs*

FRXs and DPXs are very comprehensive parameters and cannot be applied directly. Therefore, decomposition is inevitable to acquire a practical hierachy. First of all, FR1 is decomposed to the following sublevels. The processing times first need to be determined, after that non-value added tasks should be defined to be eliminated. The cycle time must not be exceeded while assigning the operators to them.

FR11: Define processing times

FR12: Define non-value added task

FR13: Allocate task to the operators without exceeding the cycle time

The first requirement necessitates time study ensuring to be conducted by the first parameter which is required by all FRs. ECRS analysis is at the core of the second parameter which must be carried out for second and third FRs. Lastly, the third parameter is strongly related to the third requirement.

The corresponding DPs may be stated as:

DP11: Time study

DP12: Improve operations with ECRS (eliminate, combine, rearrange, simplify) analysis

DP13: Balance the assembly line

The design matrix for the above set of FRs and DPs are

$$\begin{bmatrix} FR11 \\ FR12 \\ FR13 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{bmatrix} DP11 \\ DP12 \\ DP13 \end{bmatrix}$$

This is a decoupled design satisfying IA of AD. Allocation of task to operators may become practicable just after the tasks are defined and processing times are determined subject to cycle time.

The functional requirement FR2 (Operate machines within the production cycle time) may be decomposed with DP2 (Check machines' working times) as follows:

FR21: Define machine operation times

FR22: Define non-value adding operations effecting machine operation times

FR23: Allocate operations to machines without exceeding the cycle time

The time study for machines must be carried out for all requirements. Machine operations need to be improved by implementing ECRS analysis and it is used both second and third FRs. Balancing machine times is just used by the third FR.

The corresponding DPS are as follows:

DP21: Time study for machines

DP22: Improve machine operations with ECRS analysis

DP23: Balance machine times

The design equation and the DM corresponding to the FR-DP sets are as follows.

$$\begin{bmatrix} FR21 \\ FR22 \\ FR23 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{bmatrix} DP21 \\ DP22 \\ DP23 \end{bmatrix}$$

Once again, this is decoupled design satisfying IA of AD. Before balancing machine times, machine operation times are defined by using time study and non-value adding operations are determined and improved by ECRS analysis.

The functional requirement FR22 (Define non-value adding operations effecting machine operation times) may be decomposed with DP22 (Make improvements with ECRS analysis) as follows:

FR221: Reduce material handling

FR222: Reduce walking time

FR223: Reduce failures in machines

FR224: Minimize movements

FR225: Prevent waiting

FR226: Prevent overproduction

FR227: Reduce mistaken operations

In these relations, except first DP, each DP must be conducted for the corresponding FR. The first DP is also used by second FR reducing walking times. When FRs are examined, it is observed that each of them is independent of others. For this reason, constructing independent DPs is more plausible to carry out requirements.

The corresponding DPs may be stated as:

DP221: Put equipments near the machines

DP222: Place machines close to each other

DP223: Apply Jidoka

DP224: Modify layout

DP225: Feed the line on time

DP226: Establish pull system

DP227: Apply poka-yoke

The design matrix for the above set of FRs and DPs are

$$\begin{bmatrix} FR221 \\ FR222 \\ FR223 \\ FR224 \\ FR225 \\ FR226 \\ FR227 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & X & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP221 \\ DP222 \\ DP223 \\ DP224 \\ DP225 \\ DP226 \\ DP227 \end{bmatrix}$$

Moreover, the functional requirement FR3 (Ensure that operators know which operations they will do) are decomposed with DP3 (Check operators' knowledge).

FR31: Define operations

FR32: Measure operators' current knowledge about the operations

FR33: Define required trainings and apply them

FR34: Visualization of results

Applying standard operation procedures must be carried out for all requirements. For instance, the results cannot be visualized without procedures. The second parameter is required by the last three FRs. Constructing a training matrix can be used to plan training and visualize the results. The skill matrix can just be employed for visualization.

Design parameters of these FRs are as follows:

DP31: Apply standard operation procedures

DP32: Make examination during the operation process

DP33: Training matrix

DP34: Skill matrix

The design matrix for the above set of FRs and DPs are

$$\begin{bmatrix} FR31 \\ FR32 \\ FR33 \\ FR34 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ X & X & X & X \end{bmatrix} \begin{bmatrix} DP31 \\ DP32 \\ DP33 \\ DP34 \end{bmatrix}$$

This a decoupled design satisfying IA of AD. To constitute training matrix, operations should be defined and the operators' ability on these operations should be measured. Then, to see the effects of trainings on operators, skill matrix is formed.

Training is one of the most important functions to perform the line balancing. By applying training plan, workers should be equipped with different abilities to compensate their operations and also reduce the number of operators. Therefore, the functional requirement FR33 (Define required trainings) are decomposed with DP33 (Training matrix) as follows:

FR331: Improve operators skill level to do one more operation

DP331: Multi-functional operator training programme

Finally, the functional requirement FR4 (Provide the continous information flow) is decomposed as follows:

FR41: Ensure continuity of information flow between departments

DP41: Application of report system and visualization

Without applying a report system and visualization, continuous information flow cannot be ensured.

The FRs of FR41 level are as follows:

FR411: Define required data to improve the continous information flow

FR412: Hold up to date information

The corresponding DPs can be stated as

DP411: Install new data system or improve current system

DP412: Update the system continuously

Current system improvement is necessary for both improving continuous information flow and up to date information. On the other hand, updating the system is just used by holding up to date information.

The design matrix for the above set of FRs and DPs are

$$\begin{bmatrix} FR411 \\ FR412 \end{bmatrix} = \begin{bmatrix} X & 0 \\ X & X \end{bmatrix} \begin{bmatrix} DP411 \\ DP412 \end{bmatrix}$$

This is decoupled design satisfying ındependence axiom of AD again.

The functional requirement of FR412 and the design parameter related with this FR are as follows:

FR4121: Control and track data system

DP4121: Assign responsible operator

Assigning a responsible operator is necessary to control and track the data system.

This decomposition generally shown in Figure 1 is then applied to our case performed in a cooler manufacturing company.

5. An application from cooler manufacturing industry

The developed balancing design is applied to one of the assembly lines in SFA Cool Company in Turkey. We chose the assembly line of the product 'Slim' including 26 different task and 32 operators to perform these tasks. The workstations, the assigned tasks and the assigned operators are shown in Table 1. Figure 2 shows the precedence relationship diagram.

Table 1. Assembly line before AD.

Before			After		
Work-station	Assigned Task	Assigned Operator	Work-station	Assigned Task	Assigned Operator
1	Body Assembly (1)	1-2	1	Body Assembly (1)	1-2
2	Evaporator Assembly (2)	3	2	Evaporator (2) and Compressor Assembly (3)	3
3	Compressor Assembly (3)	4	3	Welding Preperation (4) and Welding (5)	4
4	Welding Preperation (4)	5	4	Condanser Fan Assembly (6)	5
5	Welding (5)	6	5	Evaporator Fan Cable Assembly (7)	6
6	Condanser Fan Assembly (6)	7	6	Condanser Assembly (8)	7
7	Evaporator Fan Cable Assembly (7)	8	7	Thermostat Assembly (9)	8
8	Condanser Assembly (8)	9	8	Compressor Fan Assembly (10)	9
9	Thermostat Assembly (9)	10	9	Helyum Test (11)	10
10	Compressor Fan Assembly (10)	11	10	Eva. Styr. Ass. (12) and Int. Metals Ass (13)	11
11	Helyum Test (11)	12	11	Glass and Led Ass. (14) and Glass Clean. (15)	12-13
12	Evaporator Styraphor Assembly (12)	13	12	Sticker (16)	14
13	Internal Metals Assembly (13)	14	13	Shelf Assembly (17)	15
14	Glass and Led Assembly (14)	15-16	14	Top Cover Assembly (18)	16-17
15	Glass Cleaning (15)	17	15	Vacuum (19)	18
16	Sticker (16)	18	16	Gas Pomp (20)	19
17	Shelf Assembly (17)	19	17	Electrical Gas Leakage Test (21)	20
18	Top Cover Assembly (18)	20-21	18	Performance Test (22)	21
19	Vacuum (19)	22	19	External Metal Assembly (23)	22-23
20	Gas Pomp (20)	23	20	Cleaning (24)	24
21	Electrical Gas Leakage Test (21)	24	21	Quality Control (25)	25
22	Performance Test (22)	25	22	Packaging (26)	26-27-28
23	External Metal Assembly (23)	26-27			
24	Cleaning (24)	28			
25	Quality Control (25)	29			
26	Packaging (26)	30-31-32			

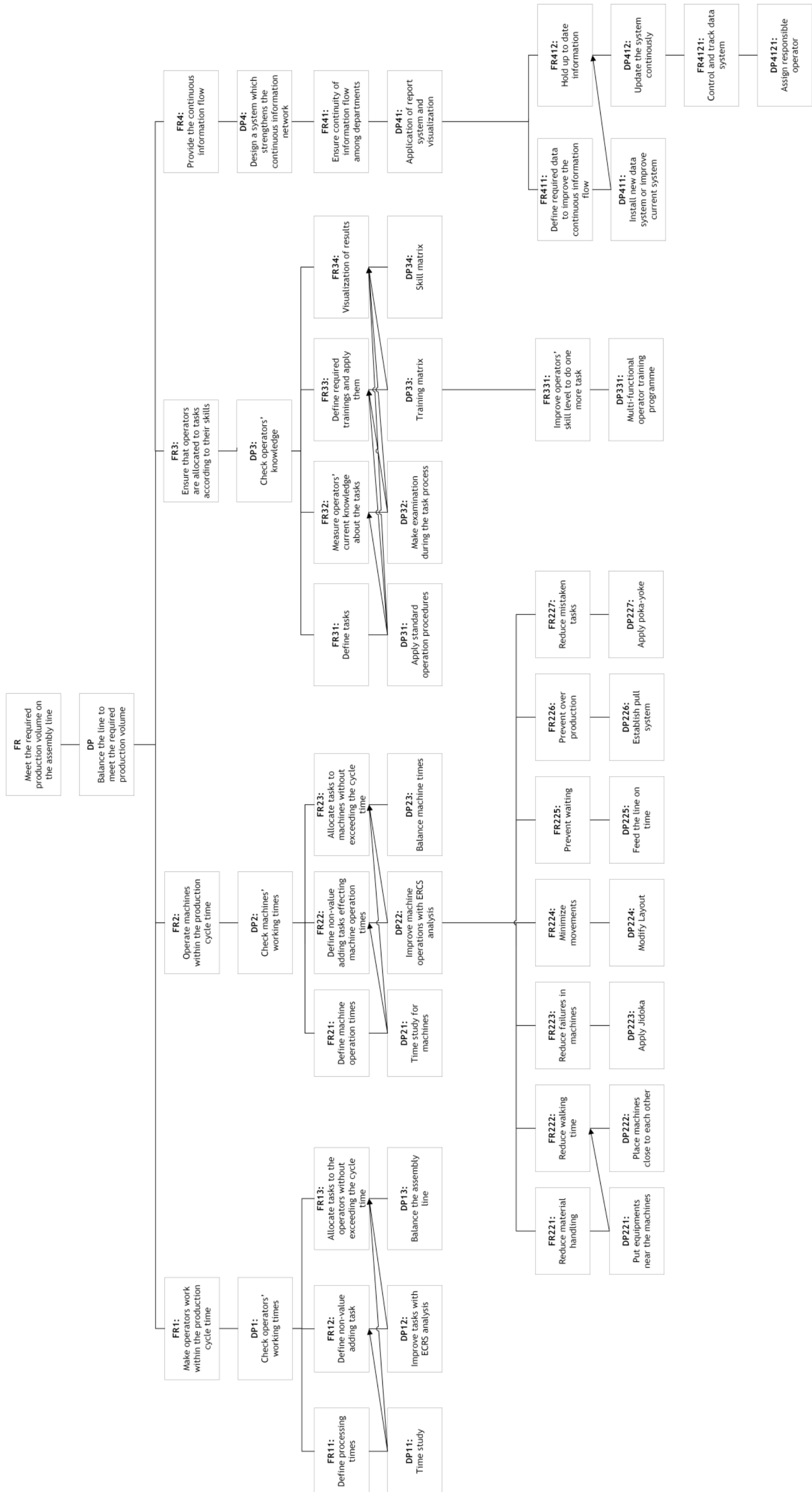

Figure 1. The Decomposition of Assembly Line Balancing System.

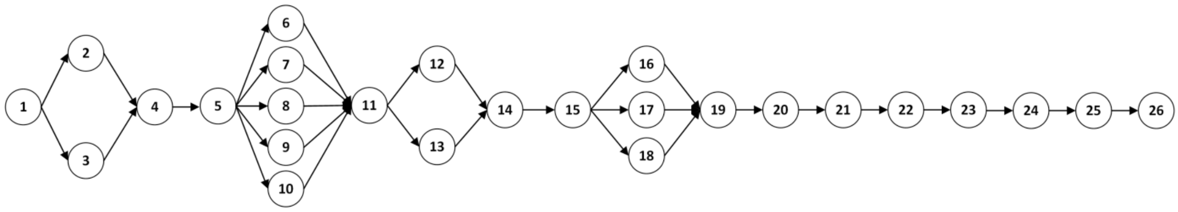

Figure 2. Precedence relationship diagram.

5.1. Current Situation of the Assembly Line

The company works for 540 minutes per shift. 155 units of slims should be produced per shift. Therefore the cycle time of slim product is (540×60)/155=167 seconds/product. There are 32 operators working to produce slims whose operating times are shown in Figure 3 before line balancing. As can be seen in Figure 3, there is no balance in the line in terms of workload. Some are above and some are below the cycle time. The aim is to balance the line, balance the workload and also reduce the idle times of workers and then providing effectively working balanced line.

Line balancing aims to reduce non-value added operations in the system. When these operations are eliminated, the idle times are shown in Figure 4.

Moreover, average efficieny of the line is 55% which is calculated by summing all efficiencies of 32 operators after dividing by the number of operators. Then the balancing ratio is calculated as 42% which is aimed to increase at least 80%. This ratio is important to have a good balanced line calculated by dividing the average of all 32 operator's operating time by the maximum operating time of all operators.

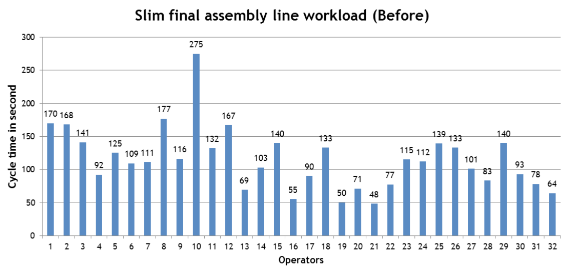

Figure 3. Operating times of the operators before line balancing.

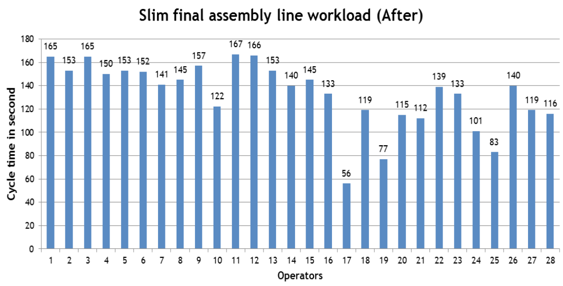

Figure 4. Operating times of the operators after balancing.

5.2. Improvements by Axiomatic Design Principles

Firstly, AD method is applied defined in the previous section and then mention about the line improvements which are the results of AD method. Here, some important FR&DP pairs are considered.

The following FR&DP pair is related to FR3 (Ensure that operators are allocated to tasks according to their skills) and DP3 (Check operators' knowledge) pairs**.** When the standard operation procedures are defined, operators know which operation should be done and they perform their operations following the standard operation procedures. In order to ensure this functional requirement, standard operation procedures are prepared for products and according to these procedures, training plan for operators is determined. After the training is completed, skill matrices are prepared for operators showing their capacity about the operation.

In order to increase and ensure the continuity of information flow, key performance indicators are defined and charts are prepared to track them.

FR41: Ensure continuity of information flow between departments

DP41: Application of report system and visualization

After that, boards are prepared, which contain all these indicators for every department to ensure visualization. Hence everybody can see whenever they want to learn values of indicators. If there is a problem, when the department operative visits this board he/she can see the problem and communicate with the related department or person and solve the problem easily.

FR4121: Control and track data system

DP4121: Assign responsible operator

To prevent that, area responsibles are determined who are responsible for entering data. For example, at the end of every hour these operators write production amount to the production table. If they have a problem or stoppage etc. during the production, they enter these data to the boards and give information to the department supervisor. Some examples of tracking boards applied in the company are quality problems board, performance indicators (performance, productivity, quality) tracking board, area audit board, hourly production figures board, the department's request and the last one is the production plan board.

After this point, we study on balancing the workload, reduce the idle times and increase efficiency of the line. According to the following principles, some improvements are achieved and changes:

- Distribute the tasks to operators. The operators should be occupied with tasks to reduce their idle times.
- The general instruction is that operator's working time should not exceed the available time.
- Try different combinations of tasks allocation, aiming at balancing the working time per operator till the best scenario is found.

5.3. Results of the improvements

When the assembly line is balanced, operators' efficiency, productivity, saturity etc. changed. By considering the differences between the operating times of the operators, their working times are balanced as well. The operation times of the operators are shown in Figure 5 for the new situation.

The idle time of the operators is also reduced by an application of assembly line balancing. The average idle time was 155 seconds and the longest idle time was 222 seconds before balancing. After balancing, the idle times are reduced for each operator. For instance, the longest idle time is 147 seconds and average 70 seconds (see Figure 6).

The other performance indicators of the new assembly line system are summarized in Table 2.

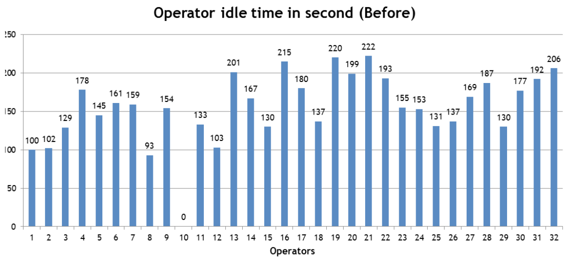

Figure 5. Idle time of the operators before line balancing.

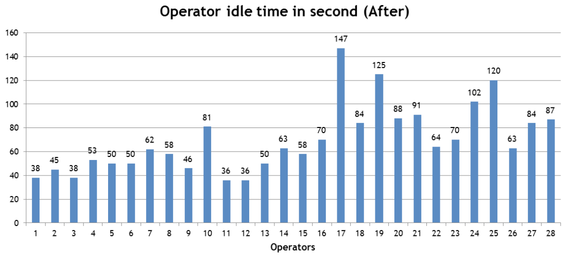

Figure 6. Idle times of the operators after balancing.

The number of operators reduced to 28 from 32. Before balancing, 118 units are produced per shift and the demand cannot satisy. After balancing, 155 units are produced per shift. To do so, the customers' demands are met for this model. Besides, the determined balancing ratio is reached and 32% saving is obtained. Productivity is the most effective and important indicator for balancing. That shows how much labor required assembling this product. Before balancing, 0.52 manhours are required to produce 1 unit. After balancing, this value changed to 0.40 manhours. That is, 0.12 manhours are gained and productivity is increased to 0.40 manhours.

Table 2. Performance indicators of the assembly line.

	Before Balancing	After Balancing	Savings
Number of Operators	32	28	4
Output (unit)	118	155	37
Balancing ratio (%)	42	80	38
Productivity (manhour/unit)	0.52	0.40	0.12

6. Conclusions

In today's globalizing world and international competition, enterprises have become aware that the key to industrial success is effective manufacturing systems, and geared their attention to how such systems may be set up with low costs. In the new system, the way to reduce manufacturing costs involves producing standardized products in large volumes which is only possible by assembly lines.

Assembly line balancing (ALB) is one of the most important problems for assembly lines to increase productivity. Therefore, in this study, the ALB problem is investigated from a different perspective in which the design of the assembly line has a strong impact on balancing. The main novelty of this study is that the AD method is employed as a line balancing tool by using lean principles. By doing so, line balancing improvements, reducing material handling, increasing communication, and better tracking of data are achieved. Implementation of AD leads to determine the wastes that need to be eliminated to boost the system performance. The functional requirements are determined following the lean principles to balance the line effectively. These requirements answer the question of "what the system needs". After the requirements are specified, the design parameters are determined to answer the question of "how the requirement can be met".

The proposed method is applied to the cooler manufacturing plant where the SLIM product is considered. In order to balance the assembly line, firstly the current situation is analyzed. After that potential improvement points are identified in the direction of axiomatic design results. At the end of all these improvements, the line is balanced to a ratio of 80%. The expected ratio is 75%, but better results are achieved. Also, the production volume increased from 118 units to 155 units per shift. The operators' idle time reduces and it is used as effective production times. The main contribution of this study is to apply the axiomatic design to balance the assembly line with lean principles.

This study can be extended in several directions: (i) the vagueness inherent of processes can be considered through fuzzy, stochastic or robust modeling, (ii) AD method can be extended to a methodology by considering cellular manufacturing features, and (iii) other performance criteria can be taken into consideration.

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