Chapter 1

Introduction

1.1 Introduction

Assembly line production is one of the widely used basic principles in a production system. It is in use in many production and manufacturing systems, particularly those involving a large volume of a single product. The basic objective is to go for the division of total work into small sub works so as to maximize the system productivity (Amen, 2001). The configuration of the line and the distribution of work along the line are
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fundamental to the system's efficiency. A complex optimization problem arises when technological constraints and a given objective are also taken into consideration.

The problem of Assembly Line Balancing deals with the distribution of activities among the workstations so that there will be maximum utilization of human resources and facilities without disturbing the work sequence. So, in an Assembly Line Balancing Problem (ALBP), a set of tasks have to be assigned to an ordered sequence of workstations in such a way that precedence constraints (i.e., predecessor task must be completed before successor tasks) are maintained and an efficiency measure is optimized, in respect of the number of workstations or the cycle time. The simplest case, referred to in the literature is SALBP: Simple Assembly Line Balancing Problem (Baybars, 1986; Scholl and Becker, 2006), where a serial line processes a single model of one product. Basically, the problem is restricted by technological precedence relations and the cycle time constrains. On the other hand, GALBP: Generalized Assembly Line Balancing Problems are considered to be those that take into account other attributes like parallel workstations, multiple process or multiple product and system restrictions. A great
diversity of GALBP has been considered in the literature, which include, for example, mixed-models, parallel workstations, U-Shaped lines, unequally equipped workstations and multiple objectives (Becker and Scholl, 2006).

Regarding the conventional terminology (Baybars, 1986; Scholl, 1999), when the objective is to minimize the number of workstations given an upper bound on the cycle time, the problem is referred to as ALBP-1. If the objective is to minimize the cycle time given the number of workstations, the problem is called ALBP-2.

The huge complexity of problems involving assembly alternatives has led to the use of a two-stage approach. The system designer selects one of the possible variants according to criteria such as total processing time, cost, resource allocation, and task parallelism (Lambert, 2006 and Senin et al., 2000).

However, by following this two-stage procedure it cannot be guaranteed that an optimal solution of the global problem can be obtained, because the decisions taken by the system designer restrict the problem as a problem of balancing loss which occurs due to uneven allocation of tasks to workstations. Assembly lines involving human
elements have another pressing problem. “The losses resulting from workers’ variable operation times” is known as system loss (Wild, 2004) which is more important than balancing loss. But unfortunately very little attention has been given on system loss.

Therefore, to increase the efficiency and to solve an ALBP that involves processing alternatives, all possibilities of the balancing process must be considered. For this purpose, in this thesis both the balancing loss problem and the system loss problem are jointly considered.

The Optimum Assembly Line Balancing Problem (OALBP), the new problem firstly introduced, defined and studied in this doctoral thesis, considers the possibility of minimizing both the balancing loss and system loss.

1.2 Structure of the Thesis
This thesis consists of eight chapters and is structured as follows.

Chapter 1 introduces the problem addressed in this thesis and presents the State-of-the-art. It discusses the main concepts related to assembly
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systems and gives an overview of the problems that have been addressed in the literature, including the proposed solution procedures.

Chapter 2 presents existing methodologies, techniques and outlines the aims of this work.

Chapter 3 introduces, defines and characterizes the Simple Assembly Line Balancing and solves the problem using Heuristic approach proposing two different Measures for System Loss.

Chapter 4 presents a mathematical formulation of the Assembly Line balancing problem. Mathematical programming models are proposed and the performances are evaluated by optimization software.

Chapter 5 deals with the stochastic approach to include stochastic time set up for Assembly Line and handling of complex Assembly Line balancing problem.

Chapter 6 handles the problem of integrated model for Assembly Line Balancing with Work station Inventory Management

Chapter 7 introduces the reliability concepts in Assembly Line. A new type of Assembly Line is proposed with solution to maintain a desired level of reliability for the setup.

Chapter 8 presents the conclusions and direction for future research.
1.3 Assembly Line: Basic Concepts and Classification

This section introduces the basic concepts and classifications of assembly lines. It describes classical assembly line balancing problems. For the purpose of problem identification it gives the overview of some classification schemes. It also gives an overview of the variety of problems and solution procedures for various research purposes. Optimization problems involving alternative configurations are presented in order to outline the problem under our study.

Generally, an assembly line consists of a sequence of $N$, where $N$ is a positive integer, workstations. These workstations are usually connected by a transportation mechanism such as a conveyor belt. Through this belt the product units flow. To produce or manufacture a specific product, each workstation repeatedly performs a set of tasks. Tasks require certain time to be processed. This time is known as task time or assembly time of that particular task. Tasks are related amongst one another according to the existing technological constraints or precedence constraints. By general assumption tasks are indivisible in nature, i.e. one task can be processed in only one workstation.
The famous example of an assembly line is Ford's Assembly Line (see Figure 1.1) between 1908 and 1915. In Automobile industry, Henry Ford used that in his production plant for model-T (see Figure 1.2). Components were manufactured in the moving line and allow mass production at low cost.

Figure 1.1: Ford assembly line in 1913
The Venetian Arsenal, the first factory in the world developed the methods of mass-producing warships in the early 16th century. Production was much faster and required less wood. At the peak of its efficiency, the Arsenal was able to produce nearly one ship per day. In 1799, Eli Whitney introduced the assembly lines in the American manufacturing system. In 1901 Ransom Eli Olds patented the first assembly line concept. His Olds Motor Vehicle Company was the first factory in America to mass-produce automobiles (Wikipedia, 2010).
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For example, simplest motor company assembly line is given below (Figure 1.3 – Figure 1.13)

Figure 1.3: (01) The engine goes on the chassis
Figure 1.4: (02) Radiator assembly

Figure 1.5: (03) Grille assembly
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Figure 1.6: (04) Firewall preparation

Figure 1.7: (05) Dashboard assembly
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Figure 1.8: (06) Under body protection

Figure 1.9: (07) A complete body being readied
Figure 1.10: (08) Body ready to be lowered onto the chassis

Figure 1.11: (09) Three rows of completed cars
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Figure 1.12: (10) The car gets to know gasoline Under its own power

Figure 1.13: (11) A car is driven to the delivery department
Though, Assembly lines are most commonly found in the automobile industry, many other sectors like daily life goods, are also organized in assembly lines. For example, the final assembly of products such as wristwatch, washing machines, refrigerators, radio, TV and personal computers (Amen, 2001). More recently, assembly lines have also gained importance in low volume production of customized products (Scholl et al., 2007).

Basic Concepts

- **Processing tasks or Work elements**: A processing task (work element) \( i \) is an indivisible working unit. This processing task is generally known as task. The time taken by the task for being processed is known as processing time of that task and generally denoted by \( t_r \). The total work required to manufacture a product in an assembly line is divided into a set of \( K \) independent and identifiable tasks.
• **Workstations**: These are the line components where tasks are processed. Workstation can involve a human or robotic operator, certain equipment and some specialized processing mechanisms.

• **Cycle time** \( C \): It is the time available in each workstation. This is the time to complete the tasks required to process a unit of product. The production rate is equal to \( 1/ C \) units of product per time unit. The cycle time is also defined as the time interval between the processing of two consecutive units (Peeters, 2006).

• **Precedence relations**: These are defined by the technological precedence requirements. They determine the partial order in which tasks can be performed in the assembly line. Predecessor should be processed first, then the successor. A task cannot be processed until all its immediate predecessors have already been processed. Precedence diagram or precedence graph generally represents precedence relations.

• **Line balancing**: It is the process of distributing the \( K \) tasks among the \( N \) workstations. The distribution will be in such a way that, precedence constraints and other constraints are satisfied. And at the same time efficiency measure is optimized. Classical objective
is to minimize $N$ for a desired cycle time $C$, or to minimize $C$ for given $N$.

- **Workstation load** $W_j$: It is the total number of tasks assigned to workstation $j$.

- **Workstation time** $t(W_j)$: It is the sum of the task times $t_i$ of all tasks assigned to workstation $j$.

- **Workstation idle time** $L_j$: It is the difference between the cycle time and the workstation time.

According to different criteria and need, there exists a great variety of assembly lines. The characteristics include the layout and the shape of the line. The number of products and models being processed in the line are also taken into consideration. Different types of workstation and the variability of the task processing times are also responsible for variety.

Classification may be summarized for some most relevant attributes based on the research studies of Boysen et al. (2007a, 2007b), Becker and Scholl (2006), Hao (2005), Miralles (2004), Rekiew (2001) and Scholl (1999).
Classification of Assembly Lines

According to the number of products or models

- **Single-model line:** A single model of a unique product type is produced in this line configuration (see Figure 1.14). This type of model neither changes the product type nor changes its setup for production.

  ![Figure 1.14: Single-model line](image)

- **Mixed-model line:** Different types of products are produced simultaneously in this line (see Figure 1.15). Here, units of different models are produced in a mixed sequence. All the models produced in this line require basically the same manufacturing tasks. As a result, no setup time is involved in this type of production process.

  ![Figure 1.15: Mixed-model line](image)
Multi-model line: In this type of line, different models with significant differences amongst one another are produced. Similar kind of product are grouped together to form batch (see Figure 1.16). Then sequences of batches are processed, containing either the same model or a group of similar models. Here, intermediate setup tasks are involved.

According to task durations

- **Deterministic:** Certainty is there in the deterministic system because here all task processing times are fixed and known.
• **Stochastic line:** This type of setup is full of uncertainty and chance factor. Task processing times may be significantly affected from different causes like the ability or motivation of human operators. The processing time of one or more task is considered to be probabilistic due to the stochastic nature of human behavior.

• **Dynamic line:** In this type of line processing, times vary over time. It can be reduced by improving the assembly process.

**According to the line shape or layout**

• **Serial lines:** Workstations are consecutively arranged in a straight line and products units are processed throughout the line (see Figure 1.17).
Two-sided lines: There are two serial lines in parallel. Pair of opposite workstations generally known as left-hand side and right-hand side simultaneously processes the same task. Automotive industry is a very common example of this type of line (see Figure 1.18).
• **Parallel workstations**: Here, two or more workstations are put in parallel. So the work element can be distributed between several workstations (see Figure 1.19).
Parallel lines: In this configuration, production system involves multiple products. Each line is designed for a particular product or product family (see Figure 1.20).
- **U-Shaped lines**: The workstations are arranged in a U-shaped line where both end of the line are closed to each other (see Figure 1.21).

![U-shaped line](image1)

**Figure 1.21: U-shaped line**

- **Circle/closed lines**: Workstations are arranged around a circular conveyor belt or something like that (see Figure 1.22).

![Circular line](image2)

**Figure 1.22: circular or closed line**
According to the work flow

- **Synchronous lines:** In synchronous lines, all workstations have a common cycle time. Here, production rate is fixed. Start time of all workstations is same and advancement of the work element is constant,

- **Asynchronous lines:** All workstations can work at different speeds. After completion of task they are transferred to the next workstation. If the next workstation is busy in processing another task then the task is stored in the buffer until the next workstation is free.

- **Feeder lines:** These are secondary subassemblies lines. It provides a main line with sub assemble components.

According to the level of automation

- **Robotic lines:** These lines are fully automated and operated by robots generally used in automobile industry (see Figure 1.23).
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Figure 1.23: Robotic line

- **Manual lines:** Tasks are performed by human (see Figure 1.24).

Figure 1.24: Manual line
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To solve a problem of line balancing, first we need the characterization of the line which determines the type of balancing problem. The simplest balancing problem is single-model, serial, paced, deterministic line. Other line configurations come with additional decision problems. For example, mixed model line faces the problem of sequencing along with the balancing problem and lot sizing problem affects multi-model line. Parallel lines suffer from a decision of how many lines to be configured. Assignment of both tasks and robots to the workstations is the problem of Robotic lines. On the other hand buffers and their positioning are needed for Asynchronous lines where as the production rates should be synchronized whenever feeder lines are concerned.

1.4 State-of-the-Art

If we examine the history of industrial advancement we may note that the initial development of infrastructure led to increase in the market size which in turn resulted in improved technological and managerial skills for remaining afloat in the face of growing competition. Different types of production processes have come into existence, each meeting the special
requirement of the demand and or technology of the offer under consideration.

According to Wild (2004), there are basically three types of production process namely mass production, batch production and jobbing. During the days of mass production era, when customization was not an important consideration and the products were more or less standardized, aim of the corporate planners was to enjoy maximum market share by producing the offer at minimum cost. In that context, mass production assumed high priority.

In the recent past, balancing of assembly line has again assumed importance. Breaking down of the country boundaries and formation of a global village has increased the size of the market beyond imagination. As a result, competitors are many in number, each trying to get the maximum foot hold in the market. Throughout the globe, corporate houses have started thinking globally based upon global culture and global standard, except for food and other culturally sensitive items where multi-domestic form is the best choice (Keegan, 1995). Thus, in general there is emphasis on standardization and cost reduction for translation of core competence into competitive advantage. It may therefore be observed that in this age of globalization companies are
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trying their best to increase their volume of production. As these products are more or less globally standardized companies have started re-thinking in terms of balanced flow lines to reduce the time and cost and increase the output.

Though line balancing problem assumed importance during the mass production era (Roy, 2006), the first analytical treatment of assembly line balancing made an inroad in the literature during 1950s with the works of Bryton (1954) and Salveson (1955). Salveson (1955) and Bowman (1960) considered the linear programming approach to arrive at an optimum solution for this problem. However, in view of the complicated nature of the problem their optimum solutions turned out to be impractical and occasionally unusable. These difficulties led to introduction of heuristic methods by Kilbridge and Wester (1961), Assembly Line balancing using the ranked positional weight technique by Helgerson and Birnie (1961), Moodie and Young (1965) and Mansoor (1968). Later Dar-El (1973) suggested a heuristic technique, namely MALB, for balancing large but single-model assembly lines.

Over the years interesting usage of simulation approach is also available for solving the line balancing problem. A general method for machine scheduling by Charlton and Death(1969), assembly line
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balancing using Best Bud search by Nevins (1972), and simulation to Generate the Data to Balance an Assembly Line by Grabau, Maurer, and Ott (1997) are now available with the production planners for a close workstation management.

Use of simulated annealing to solve a multi-objective assembly line balancing problem with parallel workstations has been studied by McMullen and Frazier (1998). During the last few decades several researchers have made serious attempts to handle this problem of line balancing by mainly using optimization techniques. Earlier references are those of Hoffman (1963), Mansoor and Yadin (1971) and Geoffrion (1976) where the purpose of mathematical programming was to give a clear insight into this complex but important problem. Buxey (1974) emphasized on the configuration of multiple workstations. Vrat and Virani (1976) presented a cost model for optimal mix of balanced stochastic assembly line and the modular assembly system for a customer oriented production system. Later, Van Assche and Herroelen (1979) have proposed an optimal procedure for the single-model deterministic assembly line balancing problem. Graves and Lamer (1983) used an integer programming procedure for designing an assembly system and Talbot and Patterson (1984) used the same for
solving the assembly line balancing problems. In fact in the mid 80's some researchers gave emphasis on application part like application of operational research models and techniques in flexible manufacturing systems (Kusiak, 1986) and application of a hierarchical approach for solving machine grouping and loading problems of flexible manufacturing systems (see Stecke, 1986). Sarin and Erel (1990) developed a cost model for the single-model stochastic assembly line balancing problem for the objective of minimizing the total labour cost and the expected incompletion cost arising from tasks not completed within the prescribed cycle time. For the multi-product assembly line balancing problem, Berger et al (1992) adopted Branch-and-bound algorithms and the problem of balancing assembly lines with stochastic task processing times using simulated annealing was addressed by Suresh and Sahu (1994). The study of Nkasu and Leung (1995) adopted the methodology of stochastic modeling, whereby various probability distributions are integrated within a modified COMSOAL algorithm, as a means of addressing the uncertainties associated with key assembly line balancing variables, such as cycle time and task times. In 1998, Pinnoi and Wilhelm dealt with the problem of system design using the branch and cut approach. In 2002, Nicosia et al introduced the concept
of cost and studied the problem of assigning operations to an ordered sequence of non-identical workstations, which also took into consideration the precedence relationships and cycle time restrictions. Their purpose was to minimize the cost of the assignment by using a dynamic programming algorithm. Erel et al (2005) presented a beam search-based method for the stochastic assembly line balancing problem in U-lines. In 2006, Zhao et al dealt with sequence-to-customer goal with stochastic demands for a mixed-model assembly line. For minimizing the number of stations and task duplication costs in the mixed-model assembly line balancing problem, Bukchin and Rabinowitch (2006) proposed a branch-and-bound based solution. Agarwal and Tiwari (2008) proposed a collaborative ant colony algorithm to stochastic mixed-model U-shaped disassembly line balancing and sequencing problem. Gamberini et al (2009) presented a multiple single-pass heuristic algorithm solving the stochastic assembly line rebalancing problem developed for the purpose of finding the most complete set of dominant solutions representing the Pareto front of the problem.

Though the trend in heuristic solution has dampened down over years, yet a few new approaches have been suggested as may be seen
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from the survey of algorithms for the simple assembly line balancing problems by Baybars (1986). Subsequently, Whitley (1989) has suggested the “GENITOR algorithm” and Scholl and Becker (2003) have suggested State-of-the-art to deal with the balancing problem.

From the literature it is clear that for all those existing methods the main consideration was balancing loss and there were mainly three streams of attack such as heuristic approach, simulation approach and programming approach to handle balancing loss in assembly line balancing problem.

1.5 Simple Assembly Line Balancing Problems (SALBP)

SALBP is completely restricted by the technological precedence relations and the cycle time constraints. A huge amount of research work has been devoted to this type of problem (Baybars, 1986; Ghosh and Gagnon, 1989; Scholl, 1999 and Becker and Scholl, 2006). This type of assembly line processes is a unique model of a single product. All the input parameters are known. Task processing times are of deterministic type. These times are also independent of the workstations. Setup times are considered to be negligible. None of the task processing times is greater
than the cycle time. All workstations should be equally equipped so that any workstation can process any one of the tasks. Tasks must be processed only once. It cannot be split among workstations and should be completed in one workstation only. There is technological precedence. So, task cannot be processed in arbitrary sequences. All tasks must be processed. Precedence relations and cycle time constraints are the restrictions. Apart from these two, no other restriction is to be considered.

**Versions of SALBP**

According to Scholl (1999), there are four versions of SALBP:

- **SALBP-1**: minimizes the number of workstations $N$ given a cycle time $C$.
- **SALBP-2**: aims at minimizing the cycle time $C$ given the number of workstations $N$.
- **SALBP-E**: seeks to maximize the line efficiency $E$, where $E = \frac{T_{\text{sum}}}{(N \cdot C)}$ and $T_{\text{sum}}$ is the summation of all task processing times.
- **SALBP-F**: is a feasibility problem that tries to establish whether a feasible task assignment exists for a given cycle time $C$ and a number of workstations $N$. 
Most of the research works, done on SALBP, keep SALBP-1 in mind. But, SALBP-2 appears to be more relevant than SALBP-1 (Miralles, 2004). It is because SALBP-1 is suitable only for designing an assembly line. But, every time for balancing and rebalancing of an existing line, SALBP-2 is required.

1.6 Generalized Assembly Line Balancing Problems (GALBP)

In generalized assembly line balancing problems one or more assumptions of the simple case are relaxed (Baybars, 1986; Scholl and Becker, 2006). Some common GALBP are:

**U-Shaped Assembly Line Balancing Problem (UALBP)**

This is U-shaped lines. This configuration is considered to be more flexible. It allows more possibilities on how to assign tasks to workstations. The reason for this is that tasks can be assigned when either its predecessors have already been assigned, whereas with serial lines a task can be assigned only when its predecessors have been assigned. Its variants are: UALBP-1, UALBP-2 and UALBP-E respectively (Baybars, 1986).
Mixed-model Assembly Line Balancing Problem (MALBP)

Kubiak and Suresh (1991), Bard et al. (1992), Bukchin (1998), Merengo et al. (1999), Bukchin et al. (2002), Karabati and Sayin (2003), Ponnambalam et al. (2003), Spina et al. (2003), Bukchin and Rabinowitch (2006) have addressed MALBP in their works. Different models of the same product are inter-mixed. On the same line these products are to be assembled. So, the sequence of different models has to be determined. MALPB-1, MALPB-2 and MALPB-E are the different types present here.

Robotic Assembly Line Balancing Problem (RALBP)

Robotic line is considered here. Problem considers the assignment of set of tasks and the set of robots to workstations (Rubinovitz and Bukchin, 1993; Tsai and Yao, 1993; Hong and Cho, 1999).

Multi-objective Assembly Line Balancing Problem (MOALBP)

Several optimization objectives are considered simultaneously. Agpak and Gokcen (2005) deal with a problem that seeks to minimize both the number of workstations and the total assembling cost or the amount of
resources. Most GALBP are multi-objective (Kim et al., 1996; Malakooti and Kumar, 1996; McMullen and Frazier, 1998; Bukchin and Masin, 2004).

The characteristics of the line and the layout of the system

Bukchin and Rubinovitz (2003) addressed a problem of parallel workstations. Multiple workstations are considered by Buxey (1974) and problem involving parallel tasks was addressed by Pinto et al. (1975). There are also many other problems including two-sided lines (Kim et al., 2000; Bartholdi, 1993), buffered or parallel lines commonplace in a multi-model context (Suer, 1998), multi-product lines (Pastor et al., 2002) and complex layouts involving lines with different shapes (Bukchin et al., 2006).

Task durations

Task durations are of different type. Processing times may be dependent on the sequence (Spina et al., 2003) or operator (Corominas et al., 2008). Given this backdrop in terms of classification and characterization of assembly lines we propose to review the existing methodologies for arriving at a balancing solution.