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## A Study of

 the Effects of Operational Time Variability in Assembly Lines with Linear Walking WorkersAfshin Amini Malaki<br>af_amini@yahoo.com

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#### Abstract

In the present fierce global competition, poor responsiveness, low flexibility to meet the uncertainty of demand, and the low efficiency of traditional assembly lines are adequate motives to persuade manufacturers to adopt highly flexible production tools such as cross-trained workers who move along the assembly line while carrying out their planned jobs at different stations [1]. Cross-trained workers can be applied in various models in assembly lines. A novel model which taken into consideration in many industries nowadays is called the linear walking worker assembly line and employs workers who travel along the line and fully assemble the product from beginning to end [2]. However, these flexible assembly lines consistently endure imbalance in their stations which causes a significant loss in the efficiency of the lines. The operational time variability is one of the main sources of this imbalance [3] and is the focus of this study which investigated the possibility of decreasing the mentioned loss by arranging workers with different variability in a special order in walking worker assembly lines. The problem motivation comes from the literature of unbalanced lines which is focused on bowl phenomenon. Hillier and Boling [4] indicated that unbalancing a line in a bowl shape could reach the optimal production rate and called it bowl phenomenon.

This study chose a conceptual design proposed by a local automotive company as a case study and a discrete event simulation study as the research method to inspect the questions and hypotheses of this research.

The results showed an improvement of about $2.4 \%$ in the throughput due to arranging workers in a specific order, which is significant compared to the fixed line one which had 1 to 2 percent improvement. In addition, analysis of the results concluded that having the most improvement requires grouping all low skill workers together. However, the pattern of imbalance is significantly effective in this improvement concerning validity and magnitude.


## Keywords:

assembly system, discrete event simulation, cross training workers, walking worker assembly line, bowl phenomenon, operational time variability, coefficient of variation imbalance, arrangement of workers

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## I Introduction

This chapter aims at introducing the motivation behind the current study through presenting a brief theoretical background of the subject followed by industrial/practical incentive. Having a clear sense of the problem, objectives have been presented in the form of research questions. Moreover, the scope of the studied problem has been elaborated and the report structure has been elucidated in the end of the chapter.

## I.I Background

The original motivation to build the assembly lines was cost efficient massproduction of standardized products. However, product requirements and thus the requirements of production systems have intensely changed since the times of Henry Ford. Therefore, new technology and production systems have been developed to make assembly lines available to low volume assembly-to-order and mass-customization systems, which are required by increasing variety of customer needs and demand fluctuation in today's market. This guarantees a high practical application of assembly line systems in the near future [5]. Moreover, the assembly process of product takes a considerable proportion of the manufacturing processes. The study [6] indicated that approximately $40 \%$ of product cost is in the assembly phase.

In response to the rapidly varying conditions of the global market and fierce competition, manufacturing companies have applied highly flexible production tools with the use of automated flexible machinery and cross-trained workers. However, several companies, which invested in highly advanced automation, found that automation solution is not sufficiently flexible due to reducing lot size and increasing product variants, thus they reduced their level of automation again [7]. The investigation [1] illustrated that cross-trained workers with performing multiple or all required jobs can significantly improve output over traditional fixed workers. On the other hand, poor responsiveness, little flexibility in system reconfiguration to meet uncertainty of demand, and low efficiency of traditional assembly lines induced manufacturers to apply cross-trained workers who move along the assembly line and carry out their planned jobs in different stations.

The assembly lines, which applied multi-functional workers, are designed in several forms. However, a novel model that is concerned in this study is called the linear walking workers assembly line and is applied with workers who travel along the line, follow the movement of the products and stop in each workstation to carry out assembly jobs of the products. Each cross-trained worker has to fully assemble the product from beginning to end and this feature differentiates this model from other variants of moving workers. A series of studies from University of Bath in UK (e.g. [2], [8], and [9]) has undertaken the research of this type of assembly line and compared it with the traditional fixed-worker assembly line. The investigations results showed significantly high performance of the linear walking worker assembly line over the fixed-worker assembly line, and pointed out some advantages of using this type of assembly lines such as ease of line balancing, high
tolerance of operation time variation, and adjustability of number of operators to respond demand changes, and so forth.

In practice, significant difference in individual capabilities is observable. While with training and appropriate selection the magnitude of differences can be reduced, it has not been proven that they can be omitted [10]. In addition to the deviation of mean operation times, workers differ in the variability of their operation times [3]. In general, individuals cannot perform a series of task repeatedly in the same rate and the result of this is variation in the task times. This variability is usually showed by coefficient of variation (CV) and can be considerably significant [11]. Studies showed that due to variability on operation times which cause blocking and starving in the stations, balanced lines do not result in the optimum performance, but rather particular arrangements of imbalanced stations are suggested to improve line utilization [12]. Hillier and Boling [4] indicated that with unbalancing a line in a bowl shape, i.e. lower mean processing time in the middle stations, could reach optimal production rate. They called this finding the bowl phenomenon. Afterwards, an enormous amount of research has been undertaken to investigate the unbalanced line in different conditions and with different sources of imbalance. El- Rayah [13] examined the effect of different arrangements of stations on the output rate considering unequal CVs and concluded that best output can be obtained when the lower variability stations are gathered in the middle and the higher at the end of the line (bowl shape arrangement). In addition, he showed that the bowl-shaped unbalanced line, in terms of only CV imbalance, yields a maximum output rate significantly higher than the balanced line. Series of other studies also reached similar results, which are implied in the literature review section, although some could not show improvement over the balanced line when the line length increased. Even though the improvement of bowl phenomenon is only about $1 \%$ or $2 \%$, it is still significant and causes large savings for the company since it can be gained with almost no investment and simply through arranging workers with different skills in a specified pattern [14].

In these series of walking-workers assembly lines studies, the difference between workers' performance has been considered by assigning diverse mean times and coefficient of variation to operation times [15], [9], and [8]. However, to our best knowledge, no published study in the linear walking-worker field has investigated the effect of different arrangement of workers. Thus, for the sake of this research gap, current work has undertaken the investigation of the effect of different arrangement patterns of workers with varied skill levels on the throughput of the walking worker assembly line.

The original motivation of this work arose due to a suggested study on the conceptual design of a walking-worker assembly line by a local company in the automotive industry. The company has successfully applied the walking-worker assembly systems for several years and intends to develop additional line for new product with a similar system. The observed problem in the existing lines is efficiency loss due to variability of workers' operation times, caused mainly by their diversity in skills and some minor disruptions. The company's interest is therefore to investigate the effect of workers' operation variability on the line output of the respective conceptual model. It is expected that using the conceptual
model, the production managers/engineers can gain insight or knowledge to improve the real assembly lines.

Therefore, this industrial problem has been chosen as an industrial case study to examine the research questions of this investigation.

## I. 2 Purpose and Research Problem

This study, according to an accomplished literature review, contributes to fill a research gap in the field of linear walking worker and unbalanced assembly lines.

Investigation aims at illustrating the influence of workers' variability and different patterns of imbalances in output, exploring the possibility of improvement without any investment only by arranging workers with different variability in a specified pattern, and examining the existence of bowl phenomenon in this special type of assembly system. The result of this study will partially fulfill the objectives of the company in the industrial case study.

In the following, the research problem has been broken down into the specific research questions and the research hypotheses.

### 1.2.1 Research questions

To achieve these goals, the problems have been formulated in the following research questions:

In a linear walking worker assembly line in which workers have different variability:

1. Does the arrangement of workers in any pattern cause a significant improvement in the throughput of the line?
If so, which pattern would yield the highest throughput?
2. Does the variability level (variation in CV size and range) affect the validity/magnitude of the previous problem?
3. How does variation in the number of walking workers influence the throughput of the line?
4. Can unbalancing a line, in terms of CV , cause any significant improvement in the throughput over the balanced line?

### 1.2.2 Research hypotheses

In order to clarify what we are trying to find in this study and create testable statements, the research hypotheses derived from the above-mentioned research questions as follows:
I. Changing the arrangement of the workers with different operational time variability, e.g. due to different skill levels, will significantly affect the throughput of an assembly line with linear walking workers.
II. Related to hypothesis I, it is believed that the effect of different variability levels will be more pronounced with the increasing degree of imbalance.
III. A bowl-shaped unbalancing of a linear walking worker line, in terms of CV, can improve the throughput when compared with a perfectly balanced line.

## I. 3 Delimitations

Unlike the majority of studies in the field of walking worker assembly line, this study do not compare performance of the liner walking worker assembly line with the fixed worker assembly line.

The studies showed that for improvement of unpaced lines' performance, three issues should be considered. The position of workers with different operation times, different coefficient of variations, and position and size of buffers along the line [11]. This study only investigates the variation of operation times (CVs) and two other factors considered constant in the model. Furthermore, the availability of operators, stations facilities and machines are considered $100 \%$ in the model. However, minor disruptions have been taken into account in the coefficient of variations.

## 2 Literature Review

In this section, a comprehensive literature review of related work in the area of system analysis of assembly lines is presented. This includes:

### 2.1 Assembly line system

Assembly work has been applied by human beings since a long time ago. Our ancestors knew how to create useful objects comprised of several parts. However, it was the automotive industry which applied present-day assembly lines for the first time. Henry Ford invented the assembly lines that caused a revolution in the way cars are produced and how much they cost. He was a pioneer in developing a moving belt in the factory. This concept enables workers to build cars one piece at a time instead of one car at a time. Based on the so-called division of labor principle, the production process is broken down into a sequence of stages and workers are allocated to specific stages. This gives workers the opportunity to be specialized in one specific job rather than being responsible for a number of tasks [16].

In this part, the basic concepts of assembly lines are described according to [16]. These terms are used widely throughout the literature review part and the rest of report.

Assembly: The practice of fitting different parts together to create the final product is called the assembly process. Parts by themselves can be comprised of various components and consequently sub-assemblies.

Work in process (WIP): The unfinished units of a product are called work in process, abbreviated as WIP.

Assembly Line (AL): Flow line production system which consists of number of stations ( $n$ ) which are set up along a conveyor system.

Task: The individual part of the total work in an assembly process which cannot be split into minor work elements without necessary additional work. Task process time is an essential time that a task needs to be performed.

Precedence Constraints: Technological restrictions, which determine the order of tasks performance. For illustrating the relationship between tasks, a precedence graph is a useful tool. The nodes represent tasks and the arrows present precedence connection. Figure 2.1 shows an example of a six task-assembly process.


Figure 2.1 Precedence Graph

Cycle Time (C): Time interval between the exits of two consecutive products from the line. It represents the maximum amount of work performed by each station. Two types of cycle times can be considered: predetermined cycle time, desired $C$, which is required usually by the planning department, on the other hand, effective $C$ or actual $C$ that is based on line performance.

Capacity Supply (CS): The total time available to assemble every product is defined as $C S=n C$. The CS can be equal to or greater than the sum of all task process times.

Work Content (WC): The sum of all task process times ( $\mathrm{T}_{\mathrm{i}}$ ). (WC= $\mathrm{W}_{\mathrm{i}}$ )
Station Time: The work content of a station is called station load and total process time as Station Time.

Imbalance: The measured difference between the Cycle Time and the Station Time is called Imbalance and when ALs is multi-product, this difference is measured for a given variant on each station (Figure 2.2).

Line Efficiency (E): Measures the capacity utilization of the line and is calculated by $\mathrm{E}=\mathrm{WC} / \mathrm{CS}$.

Station Idle Time: The difference between the cycle time and the station time when it is positive is called idle time.

Balance delay: The sum of all station idle times is called delay time or balance delay and calculated by $\mathrm{I}=\mathrm{CS}-\mathrm{WC}$.

Throughput Time: Represents the average time between the start of the first work-piece process and the end of the last finished product process, in other words it is the average process time of a final product in the line.


Figure 2.2 Imbalance for one station, variable task durations due to variant [16]

### 2.2 Assembly line problems and classification

### 2.2.1 Problems

With the development of industrial engineering, some multidisciplinary analysis techniques such as time and motion study and analysis of human performance have been introduced to the industry. On the other hand, with increasing complexity in production, line efficiency turns into a significant problem so that increasing efficiency becomes the main purpose of assembly systems. In order to reach high efficiency, developed analysis techniques with a structural approach should be applied in the designing stage of assembly lines [17].

Assembly line design entails the design of products, processes and plant layout before the construction of the line. Based on classical design for assembly rules and considering precedence constraints between tasks, considerations related to product take into account in line designing. Assembly techniques and modes (manual, automatic) for each task are determined by operating modes and the technique module and assigning tasks to the stations and location of stations and resources in the factory are decided by the line layout module [16].

The line layout problem is comprised of the logical and physical layout. The logical layout involves assigning tasks to the stations along the line, whereas the physical layout determines the placement of stations, conveyer, buffers, resources, etc. on the shop floor. In turn, logical line layout consists of assembly line balancing and resource planning problems [16].

Line balancing problem is allocating tasks to an ordered sequence of stations in such a way that precedence relations are pleased and one or some performance criteria are optimized (such as minimizing the number of stations or balance delay) [18]. Baybars [19] defines this typical problem: "The assembly line is said to be balanced if total slack (i.e., the sum of the idle times of all the stations along the line) is as low as possible." In section 2.2.3 the line balancing problem is discussed in greater detail.

Operations in assembly lines (usually small-sized products) can be performed either manually or automatically. These kinds of assembly lines are called bybrid assembly lines. In such systems, the design problem decides which resources (required equipment to complete the operations) to choose and which tasks to allocate to each resource such that production requirements are satisfied and cost minimized.

### 2.2.2 Classification

In the literature, different classifications for assembly line problems are suggested. This section presents the main categories.

## - Assembly line Models

In companies, based on demand of different products, the appropriate plan of production is developed. Thus, assembly lines according to production plan follow three approaches: single model assembly line, mixed model assembly line, multi-model (batch production) assembly line [16], [20], and [18].

Single product assembly line: It is used for producing only one type of product. If we do not consider the dynamic character of the system, the workload of all stations is constant over time (Figure 2.2.2.1). It is better to use this type of assembly line when the demand of a product is constant, the product must be delivered quickly, or has a different structure from other products and the setup time is considerably long [16]. When the setup times and variations in operating times are not significant, the line which assembles more than one type of product can be treated as single model [20].

Mixed-production assembly line: In these types of assembly lines, the variety of product is more than one. It is typically a family of products, which is a set of distinguished products (variants) usually with a similar function, and different product attributes (customizable attributes which are referred as options). A family of cars with diverse options (sunroof, ABS , etc.) is a typical example
(Figure 2.2.2.2). In this model, setup times between variants should be reduced significantly enough to be ignored [16]. Balancing the mixed-model assembly line is usually converted to the single- model case through the use of a joint precedence graph. This method with calculating the average process times of different variants in regard to their occurrence forms a unique precedence graph [20].

Multi-model or batch production lines: This model is used when multiple different products or a family of products with significant differences in production processes are to be assembled in the same line. Thus, for declining extra costs and set up times, products are assembled in batches (Figure 2.3). This requires solving lot-sizing and scheduling problems in addition to the balancing problem [16], [20].

c. multi-model line

Figure 2.3 assembly line models [21]

## - Line configuration:

In design of assembly lines, several configurations of stations are possible. Initial product analysis and form of plant site are the main factors that are taken into account in line layout decision.

Serial lines: in this configuration, the single stations are settled in a straight line along flow of line [16].

U-shaped lines: recently because of applying just-in-time (JIT) principles in production, U-shaped layout is preferred to traditional serial line. In this type of line, operators are located in the center of U and in case of hybrid lines; a multifunction worker is responsible to multiple machines and operates on each of them once in one cycle time. Figure 2.4 shows a simple U-shape line in which tasks are assigned to stations, but one irregular station is observable in this line which is different in task grouping from other stations (station 1) [22]. These types of stations which are called crossover stations include tasks located on different parts of the production line and operators travel crossover and return distance to


Figure 2.4 a simple U-shape assembly line [22]
move between tasks. Station 1 consists of task 1 in beginning of the line and task 11 at the end [23]. U-lines have several important advantages over straight lines, which include: better visibility and communications because of the close vicinity of workers to each other, workers multi-tasking, better flexibility for output rate changes, less stations requirement since there are more possibilities for grouping tasks into stations [22].

Multi-U lines : Miltenburg in his work [23] introduced Multi-U lines as a developed form of U -lines. This line is combined of $\mathrm{n}-\mathrm{U}$ shape lines in which adjacent U-lines share an identical station. These stations which are called multiline stations include tasks from two neighbor U-lines. Balancing methodologies for these types of assembly lines are disscussed in [22] and [23].

Parallel stations: when the task times in stations exceed cycle time, a common solution is to build stations with parallel posts where performance of an identical set of tasks is assigned to two or more workers. In this way the average task times reduce proporptionally to the number of workers in the station [16].

Parallel lines: when the demand is high enough, compensation is possible due to duplication of the entire line. The advantage of these lines is shortening the assembly line and also, in case of failure in one station, other lines continue to run [16].

## - Variability of tasks process times

The execution times of tasks can vary in time. The variance can be small in simple tasks or large due to the complexity and unreliability of tasks. This phenomenon is considered in assembly line literature as below:

Deterministic or static time: In reality only advanced machines and robots can work permanently at a constant speed which makes zero process time variance possible. In the case of manual assembly lines, this might be possible with highly motivated and skilled workers.

Stochastic time: generally, tasks process times have variance and follow a known distribution function (which might be unknown). Significant variations are usually observable in manual tasks. Non-qualified operators, lack of motivation and training of employees can be the main source of high variance in task times. However, automated lines are also subject to variability, and its source might be a machine breakdown or even defaults of machinery [16], [5]. This subject is discussed more in section 2.3.

Dynamic time: when process times have dynamic variation it should be considered in balancing problems [20]. This variation can be a systematic reduction due to the learning effects of operators or sequential improvements of the production process [16], [5].

## - Line control

Paced lines: in this assembly line system, the given cycle time restricts task process times of all stations. The pace of line is controlled by: 1) continuously advancing material handling devices such as conveyor belts, which compel workers to finish their tasks before work piece leaves the perspective station. 2) so called intermittent transport systems where the workpiece stops in each station according to a given time. In the continuous system, line balance determines the station length. Once the length of the station (multiplied by the movement rate of the line) goes beyond the cycle time, the extra time emerges which might be used
as compensation for task time deviation in either mixed-model production or the stochastic model.

Unpaced asynchronous line: unlike the paced line in which workpieces have to spend given times at stations; in unpaced lines, parts are transferred whenever the tasks processes are accomplished. The passing workpieces, after being processed to the following station, distinguish two types of unpaced lines; synchronous when parts transfer simultaneously and asynchronous when each station decides to transfer individually. In the asynchronous mode, workpieces move to other stations (if not blocked by another workpiece) as soon as all required operations have been completed. Then new workpieces enter the stations unless the preceding station cannot deliver. In order to minimize waiting time, a WIP buffer is established between stations. Thus, in unpaced asynchronous systems, there are three interdependent problem which are (1) determining a line balance (2) allocating buffer storage, (3) estimating throughput (depending on the known distribution function of realized task times).

Unpaced synchronous line: all stations wait for the slowest station to finish its operations and then wokpieces are transferred simultaneously. In the case of deterministic task times, synchronous lines will be the same as paced lines with intermittent transport and cycle times will be equal to the slowest station. These kinds of lines have advantages to paced lines when tasks times have variations. When variation causes fast completion of operations, workpieces can transfer to other stations without waiting any fixed time; therefore synchronous lines can promise higher output than pace lines [20].

### 2.2.3 Line balancing problem

On account of the high practical significance, a large proportion of the literature is assigned to assembly line balancing (ALB). In general, the line balancing problem consists of academic works focused on the core problem of the configuration, which is the assignment of tasks to stations, since the first mathematical modeling of ALB by Salveson [24]. Due to the several simplifying assumptions which form the foundation of this basic problem, this field of research is labeled as simple assembly line balancing (SALB) in most literatures [5]. The majority of researchers in the ALB field have devoted their work to simple assembly line balancing problem (SALBP) modeling and solving [25]. According to [5] limiting or simplifying assumptions of classical SALB problem are:
"(1) Mass-production of one homogeneous product
(2) All tasks are processed in a predetermined mode (no processing alternatives exist)
(3) Paced line with a fixed common cycle time according to a desired output quantity
(4) The line is considered to be serial with no feeder lines or parallel elements
(5) The processing sequence of tasks is subject to precedence restrictions
(6) Deterministic (and integral) task times
(7) No assignment restrictions of tasks besides precedence constraints
(8) A task cannot be split among two or more stations
(9) All stations are equally equipped with respect to machines and workers."

Any form of ALB problem intends to find a feasible line balance (allocation of each task to a station in a way that precedence restrictions and other constraints are satisfied) [20]. Nevertheless, different

Table 2.1 Versions of SALBP [25]

| No. of station (n) | Cycle time (c) |  |
| :--- | :--- | :--- |
|  | Given | Minimize |
| Minimize | SALBP-F | SALBP-2 |
|  | SALBP-1 | SALBP-E | versions of the SALB problem can be distinguished by varying the objectives (Table 2.1). SALBP-F is a feasibility problem, which looks for the existence of feasible line balance for a given combination of $n$ (number of stations) and $c$ (cycle time). SALBP-1, for a given fixed cycle time c, minimizes the sum of station idle times or equivalently minimizes the number of opened stations. On the other hand, SALBP-2 minimizes the cycle time c (or maximizes the production rate) when the number of stations ( n ) is given, which results in minimum idle times. SALBP-E is the most common version among these problems. When both the number of stations and the cycle time are changeable, efficiency of line is used to define the quality of a balance. Therefore, the problem consists of maximizing the line efficiency thereby simultaneously minimizing c and n by considering their interrelationship [5], [25]. In addition, a secondary objective for complementing the versions of SALBP is mentioned in the Becker and Scholl study [20], which consists of smoothing station loads, i.e., equalizing the station times. For instance, minimizing the smoothness index $\mathrm{SX}=\sqrt{ } \sum\left(\mathrm{C}-\mathrm{ST}_{\mathrm{i}}\right)^{2}$ for $\mathrm{i}=1$ to n (No. stations) may be one, if the combination ( $\mathrm{n}, \mathrm{c}$ ) is optimal with respect to line efficiency.

In this part, a simple line balancing method has been described. It is based on the two constraints, precedence requirement and cycle time. The fixed cycle time restriction (paced line) refers to the maximum allowed time that a product can spend at each workstation to meet the required production rate. The method follows below in concise steps (term definitions are described in section 2.1):

1. Prepare precedence diagram
2. Calculate desired cycle time $\left(\mathrm{C}_{\mathrm{d}}\right)$ :

$$
\mathrm{C}_{\mathrm{d}}=\text { available production time/desired output }
$$

3. Compute the theoretical minimum number of workstation $(\mathrm{N})$ :
$\mathrm{N}=\sum$ all task times $\left(\mathrm{T}_{\mathrm{i}}\right) / \mathrm{C}_{\mathrm{d}}$
4. Group tasks into stations with considering cycle time and precedence constraints
5. Compute the actual cycle time $(\mathrm{Ca})$ and real number of stations ( n ) for arranged group; and then the efficiency of the line ( E ):

$$
\mathrm{E}=\sum \text { all task times }\left(\mathrm{T}_{\mathrm{i}}\right) / \mathrm{nC}_{\mathrm{a}}
$$

6. Determine whether acceptable efficiency level or theoretical minimum number of workstations has been reached. If not, go back to step four [23].
The balancing of real-world assembly lines requires modification in assumptions of SALBP [21]. The line can be mixed or multi-product; can have parallel stations or parallel subassembly lines; can have stochastic task times; and many other characteristics that are not seen in the SALBP. Baybars [19] explains these extended problems as following:
"Whether the goal is to minimize total slack or to minimize the number of the stations along the line, these problems (which created by relaxing one or any
combination of the SALBP assumptions) will be referred to as the general assembly line balancing problem (GALBP). Thus, GALBP is a generalization of SALBP-1 and SALBP-2."

A summarized classification scheme is presented in [20], which illustrates the work of Boysen et al. [5]. It has briefly characterized a specific assembly system with all possible relevant extensions by a tuple. This scheme, which is provided in appendix 1, and respective studies [5] and [20] are valuable references either to find an appropriate accomplished study, which can be applied to solve real-world problems or to show research gaps in the field of assembly line systems. Plenty of exact and approximated methods are developed for solving SALBP and GALBP, which their discussion is not in the scope of this work. A recent survey of Scholl and Becker [25] presents a respectable review of developed exact and heuristic methods for SALBPs; on the other hand, the studies [20], [21], and [5] are appreciated references for GALBPs.

Once the size of our problem is significant enough, the balancing of line by hand is a cumbersome job. Therefore, software packages have been developed to balance these kinds of problems quickly. For instance, we can use IBM's COMSOAL (Computer Method for Sequencing Operations for Assembly Lines) and GE's ASYBL (Assembly Line Configuration Program). These commercial programs use different heuristics algorithms to balance the line to reach acceptable levels of efficiency. They cannot guarantee optimal solutions [23].

### 2.3 Variability in assembly lines

### 2.3.1 Introduction to Variability

In [26] variability has been formally defined as "the quality of nonuniformity of a class of entities." In manufacturing systems, this nonuniformity emerges in the form of various attributes such as physical dimension, process time, machine failure/repair time, material hardness, setup time, and so on. Variation has been classified into controllable variation and random variation. Controllable variation is the outcome of decisions. For instance, when variant products are produced, the variability will be in the product attributes like their manufacturing time or their dimension. On the other hand, random variation is derived from some events which are not under our immediate control. For example, the time between customers' demands are not under our control, therefore we should expect to have fluctuation in workstation loads. Similarly, the time that a machine might fail is not known and consequently cannot be predicted or controlled, thus, any kind of outage increases the variability of effective process times in a random manner. In this research, random variation is under study.

There are two basic views about the nature of randomness that are interesting to state here. Hopp and Spearman [26] named apparent and true randomness. In apparent randomness, the only reason that systems appear to act randomly is lack of (or imperfect) information. The premise of this view is that in the case of knowing all the laws of physics and having a complete description of the universe, then in theory, all the details of its evolution are predictable with certainty. Therefore, increasing our information about the process will decrease randomness, and thereby variability. In contrast true randomness, while rejecting
the previous premise, believes that processes are truly random. In this notion, the universe actually behaves randomly therefore having a complete description of the universe and the laws of physics would not be enough to foretell the future. ${ }^{1}$

Regardless of types of randomness, the influences are similar. Many aspects of life are inherently unpredictable and manufacturing management is one of them. However, this does not mean that we should abandon managing and controlling processes, instead we only need to find robust policies. A robust policy provides a work that is well most of the time. It is not optimal but usually relatively good. On the other hand, the optimal policy is the best policy for a specific set of circumstances. It may work extremely well for the designed situation but lead to poor results in many others. However, companies tend to spend a huge amount of money for advanced tools to optimize processes that are inherently random. It would not be an astonishment to get a frequently bad result from these tools since the real inputs are random [26].

Hopp and Spearman [26] believe in a stronger tool for managing which is called probabilistic intuition. This beside the appropriate robust policy will improve the performance of enterprises despite the existence of variability. Intuition plays an important role in our everyday life. For example in driving, we slow down our speeds in turns without knowing about complicated automobile physics and it is based on our developed intuition after some time driving. In most cases where what we judge is based on the mean of the random variables, our intuition works well. For instance, when we speed up the bottleneck station, we expect to have better performance. This intuition responds well as long as the variation in the mean quantity is large comparative to the randomness involved.

When the consideration is quantities involving the variance of random variables, our intuition seems to be less practical. For instance, when there is an option to choose between short, frequent machine failure and long, infrequent ones (less disruptive ones). These kinds of situations where variability is involved require much more subtle intuition than when we make decisions based on the mean changes (throughput improvement by raising bottleneck speed) [26].

The above assertions mark the fact that variability studies can support decision maker more than similar studies that consider mean time. This fact emphasizes the importance of this study, which considers the effects of variability (not mean variation) on the assembly line throughput.

To study variability we need to quantify it. This is possible with standard measures from statistics, such as variance and standard deviation. However, these two measures do not appropriately indicate the level of variability when a comparison is supposed to be drawn. Thus, we use a reasonable relative measure of the variability of a random variable, which is called the coefficient of variation (CV), and it results from the division of the standard deviation by the mean. In the book Factory Physics [26], three classes of variability based on the coefficient of variation are considered: low variability when the CV is less than 0.75 , moderate variability when the CV is between 0.75 and 1.33 , and high variability when the

[^0]CV is greater than 1.33 . In manufacturing, high variability can occur when we consider the available outages in process times.

The most common sources of variability in production systems are: natural variability, random outages, setups, operator availability, and rework. In the following, some of these causes are described:

Natural variability: it is the variability inherent in natural process time and consists of minor fluctuations caused by differences in operators, machines, and materials. It does not include random downtimes, setups or any other external effects. Due to the involvement of operators in a majority of these unidentified sources of variability, more natural variability exists in manual lines than in automated ones. In most systems, the variability in the natural process times is low. In other words, the CV is less than 0.75 .

In practice, several detractors influence workstations, which can include machine downtimes, setups, operator unavailability and so forth. These detractors inflate both the mean and the standard deviation of process times, which provide a way to quantify their effects [26].

Outages: outages can be considered in two groups, Preemptive and Nonpreemptive outages. Preemptive outages, which mainly refer to breakdowns, occur whether we want them or not for example in the middle of job. The other probable examples for this group can be power outages, emergency calling away of operators, and running out of consumables e.g. oil for machines. Since these detractors have a similar influence on the behavior of production systems, they can be combined together and treated as machine breakdowns. This allows one to compute unique measurements for analyzing this type of variability. The measurements that are privileged in a machine reliability analysis are MTTF, MTTR, and Availability. MTTF is mean time to failure and determines the frequency of downtimes, MTTR or mean time to repair indicates average time of repair (or getting back to uptime), and Availability is the long-term fraction of time that a machine is not down for repair. The relation between availability (A) and the two previous measurements is according to the following equation:

$$
\mathrm{A}=\mathrm{MTTF} /(\mathrm{MTTF}+\mathrm{MTTR})
$$

Nonpreemptive outages include downtimes that take place unavoidably, but during the occurrence are regularly under control. For instance, when a tool starts to become dull and needs to be replaced. In similar situations, we can stop production after finishing the current piece or job. Another common example from this group is process changeover or setup that is more under control, since we can decide how many to make before changing. Nonpreemptive outages could cover preventive maintenance, breaks, operator meetings, and such events. These outages need different treatment than preemptive outages and since the most common nonpreemptive outage is setup, we can combine all other downtimes from this group and cover them under this term [26].

### 2.3.2 Variability in Task Process Time

As we mentioned in section 2.2, one of the SALBP variants is formed by considering stochastic task process times. The variability discussion in the previous section by describing different sources of variability in manufacturing systems illustrated that assuming deterministic task time is far from reality.

Therefore, considerable amount of research focuses on assembly lines with stochastic task times and the problem of assigning these task times in workstations.

Moodie and Young [27]were among the first people who considered the stochastic task times in detail and presented a procedure for assigning tasks to stations [28]. In this regard, there is great amount of literature which investigates different methods to distribute stochastic tasks among stations to reach ideal situations. Paced assembly lines, since they are not associated with this research, will not be discussed further in this report and the survey [21] is recommended instead as good reference with the outlined accomplished studies.

In deterministic systems, it is apparent that the ideal line is one with a perfect balance in which workloads of stations are equal and idle time is zero. However, this is not true for stochastic cases. It is difficult to define what a proper task assignment is when there is variability in process times [28]. For instance, Kottas and Lau [28], considering incompletion cost (in paced lines), presented a desirable pattern which instead of equal load of work (balanced line), the workload of stations tends to increase as one moves toward the end of the line (more idle time in early stations).

Due to the prevalence of unpaced assembly/production lines in today's industry, huge amounts of investigation focus on improving the efficiency of these lines. [29] takes into account two issues which are effective for the efficiency of production lines, the assigning of tasks to the workstations and the allocation of buffer storage space between workstations. Accordingly, the latest investigation [11] by McNamara et al. has considered stated influencers based on worker approach (discussed in section 2.4). First, the differences in average operation times of operators make the allocation of operators along the line a significant consideration. Further, since in general individuals cannot perform a series of tasks repeatedly at the same rate, variation in the task times operated by workers can be considerably significant; thus, the positioning of operators with a different CV is another consideration. Other factors are the buffer size and placement. Theoretically even allocation of intersection buffers yields to the best result. Nevertheless, due to some technical restrictions this is not possible always, therefore buffer allocation turns into an influencer. Finally, the line length and total buffer space of line are mentioned as the last influencers on the performance of production lines.

Researchers have investigated the effect of these factors individually and as a combination of them on the efficiency of lines. In this research, since only variation in the CV of process times is considered, the buffer size and allocation are not included in the following literature review and just a brief time is taken for presenting mean imbalance.

Similar to paced lines with stochastic task times, the fact that unpaced production or assembly lines are perfectly balanced does not guarantee maximum output rate of the line. This is due to variability on operation times and limitation of interstage storage capacities, which cause blocking and starving in the stations [12]. Blocking and starving situations have been explained in [3]: "when a station temporarily performs its task faster than a succeeding station it will fill its output buffer and thus be blocked and when a station temporarily performance its task faster than a preceding station, it will deplete its input buffer and thus be starved."

Both starving and blocking cause delays in the production and consequently deterioration in output rate. Evidently, the probability of occurrence of these two increase with the growing operation time's variability.

According to the assumption that perfectly balanced lines always produce higher output than other unbalanced equivalents, the majority of studies had considered only perfectly balanced lines. However, a number of researchers tried to test this assumption and suggested different arrangements as the optimal design. Makino [30] tests unequal service rates in the three-station queuing system with exponential distribution and no interstage buffer and found that assigning a lower process time to the middle of the queue improves the efficiency of systems. A number of other authors also suggested different patterns for improving line utilization. However, extended work was accomplished by Hillier and Boling [4]. They investigated and verified Makino's work. They found that with assigning a lower mean service time to the middle station of a three-station production line (exponential distribution) could obtain the optimal production rate [12]. They called this finding bowl phenomenon, because the pattern of this optimal workload assigned to each station (adjustment in mean times achieved by loading works in stations) should be less in the interior stations than that closer to the beginning and end, and this is similar to the bowl shape [29].

The study [31] explicates the reason behind the bowl phenomenon as: "the effects of blocking and starving of a station are greatest on those stations closest to it. The beginning and end stations of a line affect stations in only one direction, while the middle stations affect stations in both directions. Therefore, assigning les work to the middle stations has a more beneficial effect, since it helps to mitigate the blocking and starving due to service time variability in both directions."

Since the design of the line to be perfectly balanced is often technically impossible, this finding allows designers deliberately unbalancing a production line in a specific way, to not just prevent drop of output rate rather easily achieve an optimal output higher than the balanced one. This improvement in output rate, though small, gets significant when it can be collected through the whole life of the production line [12].

According to earlier notes, the variability in the process times as a source of imbalance in stations is the main reason of starving and blocking and consequently existence of bowl phenomenon. Nearly all lines have some degree of imbalance, and operation time means and the coefficient of variation (CV) are considered as the main source of this imbalance [3]. Since the Hillier and Boling study [29], a huge number of researchers has tried to test and extend this phenomenon taking into account the effect of either mean or the CV imbalance of operation time on the production rate. In addition, a limited number has also undertaken the combined effect of these two imbalances.

A number of works which took into account the mean imbalance, are as following: Hiller and Boling's extension work [32]; the El-Rayah study [12] which applied simulation as a method; Hillier and So [14] that extended the 1979-study [32] with increasing line length (up to 9 stations); and their later study [33] on the robustness of bowl phenomenon which showed the superiority of bowl phenomenon over its balanced counterpart in spite of misestimation of the CV or the existence of deviation from bowl allocation.

The effect of unbalancing lines in terms of their CV has been investigated since Anderson's work [34], which found a possibility to get better results in a 4 -station line than a balanced line by arranging stations in a way that begins from a steady station and ends at a variable station. Other initial studies considered an incremental pattern with a high CV towards the end and found a slight increase in output [35]. Discovery of bowl phenomenon encouraged researchers to test the effect of a bowl shaped variability imbalance on the efficiency of a line. Carnall and Wild [36] investigated the efficiency variations of a line induced by different arrangements consisting of constant (automatic machines) and variable stations. They concluded: "Our results support the hypothesis of the existence of a bowlshaped phenomenon and extend it to the case of changing stage variance rather than mean output rate. It is clear from the results that coefficient of variation and buffer capacity affect the magnitude of the bowl phenomenon." The achievable improvement with a CV of 0.5 was equal to $4 \%$ which is a significant effect whereas, Hillier and Boling [4] got only $1 \%$ improvement with mean time unbalancing.

El- Rayah [13] explored two problems: a) the effect of different arrangements of stations on the output rate considering unequal CVs. b) whether unbalancing only the coefficient of variance can enhance output of a balanced line. He considered 3-, 4- and 12-station lines and two levels of variability (CV: 0.15 and 0.3 ) for the first challenge and three levels for the second problem (CVs: 2, 2.25, and 2.5 under the condition that total variability for all considered arrangements is equal). The results of the experiments supported the bowl phenomenon so that the best result for the first problem came from the arrangement in which the lower variability stations gathered in the middle of line and higher at the end. Having the second problem, the same bowl-shape arrangement yielded to the maximum output rate, significantly higher than balanced line one.

De la Wayhe and Wild [37] could increase the idle time by placing stable stations in the middle of three and four station lines, but they could not reach the same result for a twelve-station line. They consider normal distribution with three levels of variance (relatively stable CV: 0.1 ; moderately variable CV: 0.2 , relatively variable CV: 0.3 ) and compare a number of arrangements patterns (including bowl shape) with balanced line. However, they could just make the conclusion that using the strategy of separating relatively variable stations with steadier stations might get relatively close results to the balanced line results in any line length. Recently accomplished work [35] also could prove the superiority of the bowlshaped pattern over balanced line only for short line.

There are several studies in this area which have applied other approaches than simulation such as heuristic approximation or optimization methods, or predictive formula. In [35] a number of these approaches such as [38], [39], and [40] have been listed.

In an investigation of the effects of imbalances on production rate, some literature takes the influence of mean and the CV imbalance into account simultaneously. Rao [41] maintains that the two following patterns are possible optimum arrangements:
a) "Load from the interior stages should be transferred to the exterior ones (bowl phenomenon)." (pattern for mean time imbalance)
b) "Load from the more variable stages should be transferred to less variable ones (variability imbalances)." (pattern for CV imbalance)
He suggested that a) is more significant when the differences in CVs of stations are generally less than 0.5 while b) becomes superior when they go above 0.5 .

The [3] investigation demonstrated that the best pattern for decreasing ideal times of line in light of combined imbalance is not similar to when just individual imbalance is considered. The best configuration is resulted when a reverse bowl pattern for mean imbalance and a bowl shaped pattern for CV imbalance are considered.

In addition to the experiments mentioned previously, it is interesting to state a remarkable measurement, which has been conducted by El Rayah [12]. He measured the maximum degree of imbalance, which a considered unbalanced line can bear without decreasing the output rate from the level of its balanced counterpart. This specification of line would intensely support designers in developing efficient production or assembly lines.

### 2.4 Worker differences

Study [42] states three approaches for modeling variability in task process times. The task approach that considers inherent variability of tasks as a major source of variability, the workload approach which assumes the environment (such as temperature, noise, tooling) as a main source of variability and the last, worker approach which postulates the workers operating the task as the most significant source of variability. The authors propose the worker approach because the two earlier approaches ignore the influence of the workers on task process times (or they assume that the same person always performs a job). The task approach models variability by allocating a distribution to each task (mostly assumed normal distribution) and workload approach by setting a distribution (mainly exponential distribution) to the set of tasks in each station. However, the proposed approach models variability in task process times as a function of who performs the task.

Task approach mostly has been used in the studies of stochastic assembly line balancing problems such as [28] and workload approach in the studies of the optimal allocation of imbalances such as [4], [43], and [38] and buffers like [44] and [45] on asynchronous lines.

In this investigation, since operators are a significant source of variability and tasks are performed by different people, the selected viewpoint is worker-based approach.

In planning and designing production systems, usually all workers are assumed equal in their ability to do tasks. Even in stochastic systems when the line is balanced, the task time distributions usually consider the same. Nevertheless, in practice, significant difference in individual capabilities is observable. While, with training and appropriate selection the magnitude of differences can be reduced, it is not proven that they can be omitted [10]. Three categories of slow, medium, and fast, based on workers performance rate, can be considered. Stations with the slowest operators address as bottlenecks and cause delays for other stations and major balancing loss for the line. Besides deviation in mean operation times,
workers differ in the variability of their operation times, which is usually presented by CV [3].

These differences can originate from various sources. The most apparent difference between individuals is in their level of ability. Some people simply perform a task better than others do. This can be due to variances in experience levels, manual dexterity, or just pure discipline. The other easily observed source of distinction is the attitude people have towards their job. Some people prefer responsibility, variety and challenge in their job whereas others want predictability, stability, and a kind of job that lets them leave it behind at the end of the day. In addition to the mentioned observations on workers differences, a distinctive perspective towards life and work can be another source. It causes difference in responses to various forms of motivation. Financial incentives motivate people in different levels and beside that, based on researchers' findings, different social aspects of work play significant roles in motivating workers [26].

Regardless of the causes of individual differences, the effects of them should be considered in operation management strategies. In a number of literatures, this variance has attracted the researchers' attention in forms of the labor turnover problem. The numerous costs that are imposed upon high labor turnover rates are the main motivation of this field of studies. Labor turnover cost is logically considered in three types of separation, replacement, and training costs (input cost). However, the significant output cost is neglected here, which addresses the loss of production. It is obvious that this loss results from the difference between production rate of experienced and trained workers and inexperienced and untrained workers [31]. Under the existence of labor turnover, leaving experienced workers are replaced by new or inexperienced workers. Due to the new workers' learning process, the given task time is longer and more variable than experienced operators' task times [46]. Influence of increased variability in production rate of one new worker is magnified when the throughput of the entire line is considered (due to starving and blocking of other stations) [31]. Hutchinson et al.'s investigation [31] illustrated not only the effects of this personnel variability, but rather an approach to mitigate the negative effects on the throughput of the assembly lines. They concluded that in a perfectly balanced line, a moderate turnover rate of $6 \%$ per month decreased the average annual throughput by at least $12.6 \%$ and in higher turnover case ( $12 \%$ ), a $16.3 \%$ reduction resulted. The approach, which taken by authors to compensate part of this loss, consists of a replacement policy for new workers and unbalancing of workstations' mean time. The best result, in medium to high turnover rate, obtained by fast-medium-slow replacement policy integrated with a high-medium-low method of imbalance, which improved throughput by 1 to $4 \%$. The higher result right after the best result, which also improved the throughput, is made up of bowl arrangement for replacement policy and interval bowl allocation for the imbalance method.

In the line with the investigation of [31], which searched for a solution to ameliorate the effect of variability introduced by labor turnover, Munoz and Villalobos [46] investigated alternative production methods that under corresponding variability can be better than traditional methods. In fact, the considered approach in this research, to handle variable processing times, was applying dynamic work allocation. In this type of allocation, tasks are not assigned to a specific workstation or operator and the restriction of workers to perform a
fixed set of tasks does not exist anymore. Accordingly, the production method that is selected for investigation, due to utilizing the dynamic work allocation, became the Bucket Brigade developed by Bartholdi and Eisenstein [47] and [48]. The result of this study showed that the bucket brigade system combined with operator replacement policy (slow-medium-fast) significantly outperforms traditional system and unbalanced strategy mentioned by [31] (in average 7.4\% over the traditional method) in a high labor turnover environment.

Buzacott [10] investigated the effect of worker differences on output rate considering the bucket brigade method. He explains the bucket brigade production method as following: "in the bucket brigade each worker works along the line, moving with the job from one station to the next (once it is free). Once the last worker in the line completes a job at the last station then she walks back and takes over the job of her previous worker, who in turn walks back and takes over the job of her previous worker and so on. The first worker in the line walks back and starts a new job." When the workers are arranged from slowest to fastest and the task times or speed of workers is considered deterministic, Bartholdi and Eisenstein [47] showed that the bucket brigade approach is very robust to worker differences. The research [10] additionally explored the influence of the combination of differences between individual workers and stochastic task time variability by a given worker and showed that it is possible to reach a performance that is rather insensitive to worker differences.

### 2.5 Walking worker assembly line

The conventional balanced assembly line systems can perform rather inefficiently under the existence of high labor turnover, low operator learning rates, and stochastic processing times [49]. Wang et al. [8] stated that since each station in traditional assembly lines needs at least one operator, the line has to work with full workers in each station all times. This causes a poor reaction to the system's re-configuration and low flexibility in response to variations. The suggested line under fluctuating demand is the flexible manpower line which consists of cross-trained workers who can perform multiple or all kind of jobs in production line. Having multifunctional workers, new assembly methods were developed which disregarded the static-worker convention of traditional lines.

On account of high fluctuation in demand in apparel manufacturing, there was strong motivation in this industry to apply new methods to respond quickly to the market [50]. In this regard, Aisin Seiki Co., a subsidiary of Toyota, commercialized a method which applied fewer workers than stations and workers walk to adjacent stations to continue work on an item. This system was called the Toyota Sewn Products Management System (TSS) which is used in the production of many types of sewn products, comprising apparel, furniture, shoes, handbags, suitcases, and fish nets [47]. The desirable attribute of this system is the flexibility to adjust production rates simply by adding or removing workers, which is difficult in traditional fixed-worker systems [50]. Bischak [50] and Bartholdi and Eisenstein [47] are among the first scholars which investigated this system. The study [50], which has used the 'moving workers' term for this method of assembly/production, assuming identical workers and stochastic process time showed benefits of this system for those manufacturers that have frequent changes in product and having
the buffer is inadvisable. The most known study [47] considered the workers' heterogeneity and process times constant. As mentioned in part 2.4, he called this system the bucket brigade system (since each worker carries and processes items from one station to another and then transfers them to subsequent workers) and showed that by arranging workers from slowest to fastest it is possible to reach the maximum production rate.

However, the novel assembly system, which is investigated in this study, is a version of moving workers with fully multi-functional workers. This system, which is a so-called liner walking worker line, consists of cross-trained workers who travel with a partially assembled product downstream in the line and stop in every station to perform the planned assembly job. Each walking worker must be trained to work in all stations and build a product from start to end (figure 2.5). This is the main difference of this system with the previously mentioned versions of moving workers. Significant reduction in production cost (includes in-process inventory cost and in-process labor cost: the costs of labor production time, labor idle time, and labor waiting time) gained through using this method makes it an appropriate choice for companies which aim to establish lean principles in their assembly line [51].


Figure 2.5 Linear walking worker assembly line [7]
This type of assembly line inherently prevents unnecessary in-process inventory thereby, decreasing the buffer requirement. This is due to the simple fact that the number of items in the system is equal to the number of walking workers who carry them and theoretically it does not exceed this number, therefore the buffer amount in the system is deterministic. Another interesting attribute of this system is that since each worker travels with one item all the time and has to complete a whole product, he or she cannot be starved. This feature minimizes the loss of labor efficiency and maximizes individual labor utilization [51].

In addition to the mentioned qualities of walking workers, human factors also can cause improvement in this system where they may reduce the effect of work time variations in this type of assembly lines. For example, when slow workers cause blocking of other workers behind them, they will have pressure to work faster and this will reduce the blocking rates [51]. Moreover, when one worker is blocked by a downstream worker, he/she can move away and allow the upstream worker to perform the operation. The application of such a rule to the line can result in a significant drop in the blocking rates and improve real line balancing [9].

The main advantages and shortcomings of this system as summarized in the article [7] are:

- Applying cross-trained workers by itself, causes significant improvement in the overall system efficiency in terms of output and cycle times without substantial investment in equipment or labor.
- Fewer buffers are needed so that no buffer is required for low-variation balanced systems.
- WIP level decreases significantly as there are no in-process inventory.
- The performance of every individual operator can easily be measured and the slowest worker (bottleneck) can be identified for more training. This will cause high utilization of labor, and a relatively stable production.
- Based on investigations, tolerance of work time variation is better than the conventional fixed worker line.
- A non-powered simple conveyance system can be just used.
- Since each worker completes his/her own products, quality or defective rates can be monitored easily by their direct responsible and this can improve accountability and responsibility.
And shortcomings that are mostly caused by human factors are:
- Human factors such as different skilled workers, diverse working speeds and different abilities can affect the system efficiency.
- A slower operator can block a faster operator along a linear line.
- The appropriateness of applying a linear walking worker line mainly depends on the nature of assembled products and the level of cross training.
Literature that has investigated the so-called walking worker assembly lines is briefly reviewed in the following (mainly works of a group of researchers in Bath University, UK):

Study [2] compared fixed worker (FW) and walking worker (WW) systems with variable operation times, which is considered normal distribution with mean times in the range of 276 to 324 s and standard deviations that differ from 2.0 to 11.5 percent of the mean times. Authors used output per worker per hour as an efficiency measurement for comparison and considered a function of the number of workstation ( n ) with varying number of operators ( k ). Their results show that when line length increases, the FW line loses efficiency whereas the WWW line acts in the opposite. The Walking worker efficiency keeps increasing up to its maximum where $n=k+1$. Moreover, their simulation result showed that WW lines can result in better output and efficiency than FW lines even if they are operated by fewer workers; this indicated the superiority of the WW system, compared to the FW line, to tolerate work time variations through lower blocking rates. Research [51] inspected the variable behavior of the in-process waiting time of walking workers in a simulation study. It showed that the in-process waiting time in WW systems is predictable and is adjustable by changing the number of walking workers on the line. On account of having fewer walking workers than workstations, the effect of the blocking rate decreases considerably and consequently, in-process waiting time minimized, which in turn results in stable output. Correspondingly, study [7] with a combination of computer simulation and mathematical analysis, and study [52], with just mathematical analysis, investigated the effect of walking workers on in-process waiting time. The result of these studies besides verifying the result of [51] pointed out that the reduction of the bottleneck effect (in-process waiting time) by using the walking worker system, is easily possible. Moreover, optimizing the number of walking workers
(or stations) in the line can adjust and decrease the in-process waiting time and consequently improve the worker utilization.

The [9] study gives a baseline for WW assembly line designers to determine the appropriate number of workstations and workers considering the output rate and worker utilization. The results showed that for a known overall cycle time, raising the number of workers and workstations together will significantly increase production. To reach a maximum production, the number of workers should be equal to the number of stations, whereas adding one or more stations showed some increase to the maximum output. This research also emphasized the better performance of WW lines over the conventional fixed workers line. Authors showed $3.6 \%$ to $11.4 \%$ increase in output, where the number of stations is greater than 3 and is equal to number of workers. In addition, to reach a specified output, it is possible to use fewer workers and workstations than a fixed line requires in similar conditions. The article [15] presents results of a case study in a semiautomated automotive engine assembly line in which traditional assembly systems were re-configured to the walking worker system. The new design, which is created by applying walking workers and adding one more station to each manual section, resulted in an average increase of $6.3 \%$ in productivity. As presented in previous studies, the extra workstation in the walking worker system reduces the effect of unbalanced variation of operation times and consequently minimizes the blocking rate (or in-process waiting times) which bring about stable line output.

In paper [8], the authors examined the effect of randomness on a linear walking worker line by modeling a case study. They used a 10 -station line with variable numbers of walking workers and varying unbalanced levels. The five unbalanced levels are considered and defined as a percentage increase or decrease of the mean process time while the overall cycle time is constant ( $\pm 5 \%, \pm 10 \%, \pm 15 \%, \pm 20 \%$ and $\pm 25 \%$ ). The result showed that the blocking and output rates for different levels of unbalance are relatively equal when the number of workers is increasing up to eight workers. However, after this point, different unbalance showed their effect. It is concluded that the walking worker method has the possibility to reduce the effect of work time variations by simply adjusting number of workers in the line. Having fewer workers than stations, the effect of variable unbalance levels can significantly decrease, and consequently the blocking rate is minimized and the production maximized.

In the recent study [53], authors introduce a design methodology, which intended to improve ergonomics conditions and increase productivity of the walking workers line by modeling the system in simulation software and determining optimal settings by genetic algorithm. They believe that such a methodology will lead to further implementation of WW lines in real production applications.

## 3 Methodology

In this section, the approach chosen to deal with this study is discussed and supported based on the research methodology literature.

### 3.1 The Research approach

In the research philosophy two types of reasoning, deductive and inductive have been developed. In the deductive reasoning, the rationale moves from a general principle to specific instances and it is associated with the hypothesis testing approach and it is used in the positivistic tradition of research. On the other hand, in the inductive reasoning, the direction is from particular instances towards a general principle and it is linked with the hypothesis generating approach and the interpretive tradition of research [54].

The center of the positivistic (or also called quantitative) approach is hypothesis testing [54]. According to Glenn [55]:
"Typical of quantitative tradition is the following of common pattern of research operations in investigating, for example, the effect of a treatment or an intervention. Characteristically studies begin with statements of theory from which research hypotheses are derived. Then an experimental design is established in which the variables in question (the dependent variables) are measured while controlling for the effects of selected independent variables."

Busha and Harter [56] have defined the hypothesis as "a scientific guess about the relationship among variables related to a practical or theoretical problem." Glenn [55] calls it an unproven proposition, which is an empirically testable statement in regards to reality.

According to Williamson [54], a hypothesis should be applied beside research questions when research is carried out by a quantitative approach. He illustrates the design of positivist research as figure 3.1.

Formalized hypotheses consist of independent and dependent variables. The independent variable is a factor that the researchers can control and manipulate in order to find the effects it causes. In fact, it is hypothesized to cause an effect on the dependent variable. The dependent variable is responsive (the effect of cause) to an independent variable and it is observed or measured as a result [55].

According to Karl Popper's hypothetico-deductive model, a hypothesis is subject to falsification (usually by observation) and based on this view, we cannot confirm a hypothesis since it is likely to be shown as false by any future experiments. It means that failure in showing the falsification of a hypothesis does not prove the hypothesis and it is just provisional. Nevertheless, it can be a credible source for action, and we can assume it is true until it is falsified [55]. This is also emphasized in Williamson's book [54] that when the data are consistent


Figure 3.1 Positivist research design [54]
with the hypotheses the theory is temporarily supported; it is corroborated, not proven to be true.

The majority of books in research methodology indicate the analytical approach as a method to generate business knowledge. In this approach, which is based on logic and mathematics, created knowledge is independent of the observer and its ambition is to develop pictures of an objective reality. These pictures, which are simplified prototypes of a piece of reality, are called models [57]. The discussion about different types of models and the appropriate type for modeling the case of this study are elucidated in section 3.3.

The above literature review is accomplished in order to introduce the applied method and taken approach of this study. As stated in [57], the appropriate method is specified by the problem in hand. The research approach to this study considering the problem that has been raised by the local industry and the theoretical framework (developed through the literature review) is quantitative or positivist tradition. The study has followed the hypothetico-deductive model to test the hypothesis, which has been formed based on theories. To test this research hypothesis, the defined variables should be calculated and therefore, the practical case as part of reality should be modeled. This will allow us to design and accomplish experiments in order to support or reject the hypothesis. As mentioned in theory, the analytical approach is appropriate for modeling reality. Among the mathematical models, a discrete-event simulation is proper for our case, which is discussed more in section 3.3. The entire process of the research is elaborated in the next section.

### 3.2 The research process

The research follows the typical design of positivistic research as illustrated in figure 3.1. The initial idea to perform this investigation is raised by an encouraging case study that was proposed by local industry. The primary problems were specified and, due to the preliminary literature review, research gaps in the respective field were determined. As Williamson [54] states, to formulate research hypotheses, a theoretical framework is needed. He declares that the theoretical framework is the base of an entire research project. It describes the research process and helps to direct it. To develop the theoretical framework, especially for a quantitative study, the literature review is required. Therefore, to formulate the theoretical framework and research hypotheses of this study, a comprehensive literature review has been accomplished. There were difficulties in the literature findings due to the applied novel assembly system of the studied case, which is quite unknown in the literature.

As mentioned above, two types of variables for formulating the hypotheses are required. According to the literature review, the throughput of the line, which is the most significant performance evaluation criterion for the manufacturers, was chosen as dependent variable for all the hypotheses and the arrangement of workers and the CV level were defined as independent variables. Then the predicted relations of these variables were formulated to the research hypotheses and questions. After generating hypotheses, they should be tested by designing appropriate experiments. The proposed case study by local industry (described in chapter 4) is an appropriate sample for our problem. Since the case is a conceptual design, all required data has been provided by the company.

Because the simulation study has been chosen to carry out the experiments, the next stages of study have followed the procedure that has been suggested in the literature and is discussed in the following section.

### 3.3 Simulation study

### 3.3.1 Why Simulation study?

Operations of the real world facility or processes of interest could be considered as a system and there is always a need to study the relationships among the components of such a system or to predict performance of it under new conditions. This kind of study can be accomplished in different ways (figure 3.2). In general, the best way is exploring the real system. However, it is hardly feasible to do this, and sometimes the system does not even exist. Therefore, it is necessary to build a model of the real system to understand how the corresponding system acts. The model can be physical, which is not typical in an operations research study, or mathematical. The mathematical model represents a system in the form of logical and quantitative relationships; therefore, it can be manipulated in order to analyze the system. After building a model, it is studied to answer the raised questions of the relative system. Having a simple model might make it possible to apply mathematical methods to get exact answers. This is called an analytical solution. However, most of the real-world problems are too sophisticated, thus it is not possible to analyze them analytically. The solution in this case is a simulation study. In the simulation solution, a model is exercised numerically and the effects of questioned inputs revealed in the measured performance [58].

A simulation has been defined as "the imitation of the operation of a realworld process or system over time. Whether done by hand or on a computer, simulation involves the generation of an artificial history of a system and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system" [59].
The simulation study has been ranked as the second most used technique and the third most important technique of operation research in two different studies. The first rank belongs to math programming (analytical approach). However, this technique is not practical in some conditions [58].

The literature survey [60] indicates the inefficiency of the analytical approach when a complex manufacturing system with dynamic behavior is under study and implies the major weaknesses of this technique as follows:

- Analytical evaluation is impractical when it encounters stochastic elements that exist in a manufacturing system due to many random and non-linear operations.
- Due to randomness in a dynamic system which changes with time (e.g. in an assembly line, operation times change because of workers' skill), mathematical modeling of a complex dynamic system requires many simplifications and this may cause invalidity of this approach.
A number of other studies such as [61], [62] and [63] also emphasis on the appropriateness of a simulation for manufacturing processes especially when they are stochastic [8].

In general, simulation models are categorized based on three different dimensions. They could be static simulation, a system in which time plays no role, or dynamic simulation, a system that evolves over time. If a simulation model comprises any probabilistic components it would be called stochastic, otherwise it is deterministic model. Systems can be categorized to be discrete or continuous. In the discrete system variables, which describe a system at a particular time (state variables), change at separated points in time. However, in a continuous system they change continuously with respect to time. It is evident that the simulation models of such systems will be different and respectively they are called discrete simulation models and continuous simulation models [58].

A simulation model that is frequently used in operation research and is applied in this study as well is known as discrete-event simulation (DES). Discrete event simulation is a simulation of a discrete system in which the events (which can change the state of a system) occur at only a countable number of points in time [58]. As previously mentioned, the discrete-event simulation applies numerical methods in which the model is run and artificial history is produced from the system assumptions and observations are analyzed to estimate the real system's performance. Since the real-world simulation models are quite large, such runs need enormous amount of data calculation, therefore computers are used to run the models [59].

The discussion above described the available approaches for an operation study and emphasized the conditions for when a simulation study is appropriate to use. To answer the raised questions of the current research, a series of experiments should be carried out and since this is not feasible with an actual system, it requires accomplishing respective experiments with a model of a system. In order to have a practical solution, an industrial case study is considered (discussed in the next section). This real-world example is a rather long assembly line with an enormous amount of components and stochastic behavior. These specifications make applying an analytical approach almost impossible. Therefore, the appropriate solution here is discrete event simulation.


Figure 3. 2 different ways to study a system [58]

### 3.3.2 Processes of simulation study

In most DES books, the procedure of a simulation study is presented in the form of a set of steps. The processes of this simulation study follow the steps of figure 3.3 stated in the book [59]. According to this procedure, first, problems


Figure 3. 3 Steps in a simulation study [59]
should be formulated and thereby the objectives or questions, which the simulation should answer, will be formulated. These steps have been set forth in the introduction part. In the next step, the model of the system is built. It is recommended to start with a simple model and then extend it towards complexity. The concurrent step that is accomplished alongside model building is collecting data. The required type of data is determined through modeling [59]. Since this study applies a conceptual design, the model and data are already provided by the company. However, more required data is obtained during a meeting with the representative of the company. The description of the model and data has been presented in the next section. The constructed model and collected data have to be translated into computer language. Here, this is fulfilled by the aid of specialpurpose simulation software, which is elaborated in chapter four.

The next two steps consider verification and validation of the model. In verification, the properness of the translation of the model to a computer is questioned. In current work, this has been fulfilled by running built models in different settings, repeating the same results, and finally checking with the mentor. "Validation is usually achieved through the calibration of model, and iterative process of comparing the model against the actual system behavior and using discrepancies between the two, and the insights gained to improve the model." [59]. Validation of our model has been fulfilled in the couple of meetings with the representative of the company. The recommended modifications have improved the model and reduced the difference between the model and the considered conceptual design of the company.

After the validation process, the experimental design should be fulfilled. The required alternative must be determined and their parameters should be set. Simulating each design requires a series of decision making regarding the length of simulation run, the length of initialization (warm up) period, and the number of replications for each run [59]. The last two parameters will be elaborated in the following sections. Regarding this study, the alternatives have been determined through the literature review of similar studies and discussions with supervisors. The experiment designs are presented in the second part of chapter four.

In the production run and analysis level, different designed models must be run and analyzed. Running each model generates estimation from system performance and thereby the analysis is carried out and decision made [59]. "Since random samples from probability distributions are typically used to drive a simulation model through time, these estimated are just particular realization of random variables that may have large variances." [58]. Therefore, appropriate statistical analyses must be applied on outputs of simulation runs. In section 3.3.4, the analysis used in this report has been described. Through analyzing the results, the need for a new configuration has been required in some cases that resulted in new experiments.

It is advised to document programming of the model and report the progress of the project to the people involved [59]. In this regard, the model translation of this study has been reported in chapter four. Furthermore, the progress of the project has been reported to the supervisor in several periodic meetings.

The final step is implementation and its success depends upon the properness of the performance of the previous eleven steps.

### 3.3.3 Steady state and replication analysis

Simulation based on the possibility of determining the length of the run may be either terminating or nonterminating. In a terminating simulation, a natural event determines the length of each run. On the other hand, for a nonterminating simulation, there is no such event. This is often used for designing new systems or changing an existing system in which the behavior of a system is investigated in a long time run and when it acts normally. The state in which a system behaves normally is called steady state. The problem here is the effect of initial conditions in a system behavior, which is called the problem of initial transient or the startup problem in the simulation literature. The solution that is suggested for dealing with this problem is to delete some amount of observations from the beginning of the run and use the remaining observations to study the system. This is called warming up the model or initial-data deletion. The question is how to determine this warm up period. The simplest and general technique to answer this question is Welch's graphical model [58].

Since the type of our simulation model is nonterminating, we need to determine the length of simulation runs and the warm up period. Therefore, in chapter 4 we will apply the Welch model to determine the warm up period.

As previously mentioned, the inputs in simulation models usually have random behavior. The variability in inputs results in some variation in the output. Due to these variations in output, it is not appropriate to make a decision based on a single run or replication of the simulation model. Therefore, to reduce errors in the results, the model must be run for a number of simulation replications [64].

The replication analysis determines the appropriate number of replications.
The process starts with selecting an initial number of replications and then the simulation results of these runs are used for specifying whether an extra replications is needed at a particular level of confidence. The common number of initial replication is ten and the calculation that is required is the mean and standard deviation of the mean of ten runs. These statistical measures are used to calculate the standard error of data with the following formula
Standard Error $=\mathrm{t}_{1-\alpha / 2, \mathrm{n}-1} *_{\mathrm{s}} / V_{\mathrm{n}}$
where

$$
\begin{aligned}
& \mathrm{t}=\mathrm{t} \text { distribution for } 1-\alpha / 2 \text { and } \mathrm{n}-1 \text { degrees of freedom } \\
& \mathrm{s}=\text { standard deviation of the replication means } \\
& \mathrm{n}=\text { number of observations in the sample }
\end{aligned}
$$

This standard error is used for determining the final number of replications that we need. In order to do this we should select a suitable level of precision or error. In the next step, the number of replications ( $\mathrm{n}_{\mathrm{r}}$ ), which decreases the standard error to the considered level of precision, must be found.
$\mathrm{n}_{\mathrm{r}}=\left[\left(\mathrm{t}_{1-\alpha / 2, \mathrm{n}-1} * \mathrm{~s} / \sqrt{n}^{\mathrm{n}}\right) / \text { precision level }\right]^{1 / 2}$
The final step is checking that the calculated $n_{r}$ is actually adequate for the considered precision level. This means that the simulation model needs to be run for $n_{r}$ replications, and the standard error is recalculated. If it meets the precision level then our replication number is correct otherwise, we need to recalculate a new number of replications [64].

In this regard, the replication analysis for simulation models of this study has been presented in chapter four.

### 3.3.4 Statistical analysis of the output

As stated, the outputs of simulation runs are obtained through random variables and may have large variances. In a single system, through $n$ independent replications of the model, the estimation of the measurement of the performance of interest becomes possible by a point estimator or confidence interval. In the simulation software, the results are usually presented in the forms of such estimators. However, since in this study the purpose is comparing the results of different systems (configurations), in this section we focus on the statistical analysis of the output from several different simulation models that represent the alternative policies. Since in such studies, the simulation utility depends on the comparison of alternatives, there should be a reliable approach to compare results and draw conclusions. In the following, the chosen approach for comparing desired parameters of different systems is described [58].

We consider here the case of comparing two systems based on their performance measure. A common approach is to apply a hypothesis test to show the significant difference between two observed measurements. However, the applied method in this study is based on reference [58] and it forms the confidence interval for the difference in the two systems. The confidence interval in addition to the reject or fail to reject test of significant difference, can show the quantity of the difference (but hypothesis test cannot).

Once the replication number ( n ) of two systems is equal, we can pair the replication results and calculate the differences ( $\mathrm{Z}_{\mathrm{ij}}=\mathrm{X}_{\mathrm{i}}-\mathrm{X}_{\mathrm{i}}$ ).

To form the approximate $100(1-\alpha) \%$ confidence interval for any $Z_{i j}$, the following equation is applied:

$$
\overline{Z_{\imath \jmath}} \pm t_{n-1,1-\propto / 2} \sqrt{\frac{S^{2}\left(Z_{i j}\right)}{n}}
$$

Where:

$$
\begin{gathered}
\left.\overline{\mathrm{Z}_{\mathrm{ij}}} \text { : average of (all } \mathrm{n}\right) \mathrm{Z}_{\mathrm{ij}} \\
\mathrm{~S}^{2}\left(\mathrm{Z}_{\mathrm{ij}}\right) \text { : sample variance for } \mathrm{Z}_{\mathrm{ij}} \\
\mathrm{t}_{\mathrm{n}-1,1-} \propto / 2 \text { T-student distribution }
\end{gathered}
$$

If the $\mathrm{Z}_{\mathrm{ij}}$ 's follow normal distribution, the confidence interval will be exact, otherwise for a large $n$, the central limit theorem should be considered and it implies that the probability of this interval will be near to $1-\alpha$. This confidence interval is called the paired-t confidence interval. If the confidence interval contains zero, it rejects the existence of any significant difference, and if it misses, the conclusion is fail to reject, i.e. with approximately ( $1-\alpha$ ) percent confidence there is a significant difference between the compared parameters of the systems.

In many studies, there are more than two systems; therefore, we need to compare more alternatives. The chosen approach here is similar to the described method for two systems. Thus, several confidence intervals should be made simultaneously, taking care to adjust their individual levels so that the overall confidence level of all intervals covers the desired level $(1-\alpha)$. To make sure that the overall confidence level is at least $(1-\alpha)$, the Bonferroni inequality is applied, which considers the separate confidence levels as $1-\alpha / c$ (c is number of confidence intervals).

## 4 Modeling and Experiments design

## 4.I Modeling

### 4.1.1 The case study (model conceptualization)

As mentioned in the introduction part, the original motivation of this work arose due to a suggested study on the conceptual design of a walking-worker assembly line by a local company in the automotive industry. This industrial problem has been chosen to be the industrial case study of this research. The walking worker assembly system has been operating in this company for several years and the new line will be developed through the aforementioned conceptual design.

The line has been comprised of 40 manual assembly stations and four buffers (with capacity of one product) have been located between every eight assembly stations (figure 4.1). The products get fixed on the customized pallets and are transported between stations by a special conveyor.

Each operator starts his work on a specific product at the first station and moves with the same product (simultaneously with the conveyor) through the next stations to perform the respective assembly work for that station and this continues until the last station (the fortieth station). Once the operator executes his last assembly job, he walks towards the beginning of the line and starts working on a new product (if another operator does not occupy the station). Since distances between the stations are short, the moving time of workers is negligible and the walking distance from the last station to the beginning of the line takes no more than one minute.

The important parameter in this study is operation time of each operator and it is not constant here. Based on the given data of the company it follows triangular distribution obtained from the similar currently used lines. Due to the scope and


Figure 4.1 the walking worker assembly line case study scheme
intention of this research, which is just studying the variability of operators, the mean time of operation times for all workers is constant and equal to 90 seconds. However, the working speed of individuals (variance in operation times) is inconstant. In order to consider the variability in worker operation times, three skill levels are taken into account. These include high skill (relatively steady), low skill (relatively variable), and moderate skill (medium variable) operators. As mentioned in the literature review, the appropriate variability indicator is coefficient of variation (CV) and is considered for this study as well. Different values for CV are assigned to different skill levels and will be discussed in the following chapters.

In addition to the mentioned parameters, there are the following assumptions that are considered in the modeling of this case study.

- There is a limitless supply of sub-assembled components, parts and materials for whole stations; therefore, no starving could happen due to shortages.
- No machine failure or other outages are considered during the production.
- Only one type of product is assembled in the line.
- Creating a defective product is not considered.


### 4.1.2 Model translation

After conceptualizing the model, we need to translate it to computer language. Siemens Tecnomatix Plant Simulation is a special-purpose simulation software used for this purpose.

In this section, a brief description on implementing the main model from the software is presented. The components, their relation and structures that have built the model are illustrated in figure 4.2. The component details are as follows:

- Forty SingleProcs represent forty workstations.
- Four Buffers (Buffer 1 to Buffer 4) with one capacity represent the considered buffer between every eight stations.
- An Entity (EnginA) is defined as a product which is assembled through forty workstations.
- A Source (EnginA) is assigned to introduce the product to the assembly line.
- The object that is used to simulate the three different walking-worker skill levels is the Container. The Container is a moving object for transferring products (like pallets). Three different Containers (LowSk, ModeratSk, and HighSk) have been defined for this purpose.
- To enter the workers (Containers) into the system, another Source with the name of Operator has been defined. In addition, the Source determines the sequence of entrance of workers. It is connected to the Sequence tables in which the different workers' arrangements are defined.
- Since there is a need to attach the workers to the products, one Assembly object (OperatorSetup) is located in the start of the line, and to send out the workers at the end of the line, a DismantleStation object (OperatorExist) is defined.
- The product exits the system by Drain object after separation from the Container.
- To complete the cycle of workers (or pallets), a buffer (OperatorPool) is defined to store Containers that are separated in DismantleStation and send them back to the assembly line cycle.
- Three Methods are required in this model to control the behavior of some objects.
- The Init Method, which is the trigger in the beginning of a run, determines the workers' arrangement in each run.
- The "OptProcessTime" Method using SkillLevel tables determines the process times of each workstation. In these tables, the CV for the different skill levels is determined.
- The Endsim Method, which is the trigger at the end of each run, is used to gather data and calculate the final desired measurement. This calculation is showed by the ThroughputPerHours variable.
- Like all models, an EvntController object is also defined to specify run and warm-up times.
- ExperimentManager is an efficient object assigned to this software used to design and run experiments. This tool is used to alter arrangements and CV levels and compare the results.

In addition to the main model (figure 4.2), two other models in different frames have been developed to run steady state analysis and operator numbers analysis. These models are just modified versions of the main model and are presented in appendix 2.


Figure 4.2 Simulation of the main model using the Plant Simulation software

### 4.2 Experiments design

After implementing the case study in the software, as mentioned in the previous chapter, the verification and validation of the model have proceeded. In this section, the design of the experiments for testing the first hypothesis and answering the first two research questions have been described. First, the variables of the model should be defined and their values should be specified. Based on the first research question, the arrangement of different skill level workers is variable and the effect of this variable on the throughput per hour is of interest to this study.
To determine the entrance sequence for different skill workers to the line (referred to as the arrangement of workers in this report), four different policies and eleven different patterns have been considered (table 4.1). These patterns have been obtained through a literature review and several trial experiments. They are described as follows:

Table 4.1 Considered arrangement of workers

| - H: High skill workers <br> - M: Moderate skill workers | Policy | Pattern | Arrangement |
| :---: | :---: | :---: | :---: |
|  | A : Random | P1 | Arranged Randomly |
|  | B : Separate Skills | P2 | 1H-1M-1L ... |
| - L: Low skill workers |  | P3 | 2H-2M-2L ... |
| Numbers in arrangements present the quantity of workers placed sequentially In P2, P3, and P4 the displayed pattern is repeated up to 40 workers |  | P4 | 7H-7M-7L ... |
|  |  | P5 | 14H-13M-13L |
|  |  | P6 | 13L-13M-14H |
|  |  | P7 | 13M-13L-14H |
|  | C : Reversed Bowl-shape | P8 | 7H-6M-13L-7M-7H |
|  |  | P9 | 14H-13L-13M |
|  | D : Bowl-shape | P10 | 7L-6M-14H-7M-6L |
|  |  | P11 | 13L-14H-13M |

Policy A: To simulate a condition in which worker arrangement is not taken into account, the workers should be arranged in random order. Therefore, a series of random numbers was generated and assigned by MS Excel to arrange all three types of workers. The result is an arrangement which does not follow any special pattern.

Policy B: In this policy, similar skill workers are grouped separately and in the form of different patterns. Different sizes for skill groups have been considered. Inside the groups in patterns P2, P3, and P4, the variability is ascending. However, in patterns P5, P6, and P7 the other forms are also considered.

Policy C: The concentration of high variability (low skill workers) is in the center of the arrangement. This arrangement forms a reversed bowl shape. For this policy, we can consider two different patterns. The variability might rise gradually from two sides toward the center (P8) or relatively steady and medium variability might be placed separately to the sides of the center (P9).

Policy D: The concentration of low variability (high skill workers) is in the center of the arrangement and it looks like a bowl shape. Similar to policy C, two patterns (P10 and P11) can be considered.

In the second research question, the effect of the degree of imbalance or the variability level has been questioned. Therefore, the Coefficient of Variation as an appropriate indicator of variability should be considered in different ranges and magnitudes to represent the possible different variability in worker operation times. Having considered three levels of skill for the workers, three degrees of CV are required. Thus, the five different sets of CV have been defined to present various possible conditions. However, since in our case study the distribution for the operation times has been considered triangular distribution with equal mean, coefficient of variation cannot be higher than 0.4 . Thus, in order to have higher variance and to examine the hypothesis with a different distribution, the model has applied the Weibull distribution as well. According to [65], in practice, operation times of unpaced lines are described best by this positively skewed distribution. Table 4.2 presents the considered CVs in triangular and Weibull distributions.

Table 4.2 CV (1) to CV (5): triangular distribution and CV (6) to CV (8): Weibull distribution

| Description | Workers' <br> Skill level | High <br> Skill | Moderate <br> Skill | Low <br> Skill |
| :--- | :--- | :--- | :--- | :--- |
| small value \& small difference | CV (1) | 0.05 | 0.1 | 0.15 |
| large value \& small difference | CV (2) | 0.3 | 0.35 | 0.4 |
| medium value \& medium difference | CV (3) | 0.1 | 0.2 | 0.3 |
| large value \& medium difference | CV (4) | 0.2 | 0.3 | 0.4 |
| large value \& large difference | CV (5) | 0.05 | 0.2 | 0.4 |
| large value \& medium difference | CV (6) | 0.2 | 0.3 | 0.4 |
| High level variability | CV (7) | 0.3 | 0.5 | 0.99 |
| large value \& large difference | CV (8) | 0.2 | 0.5 | 0.8 |

As described in the table, the CVs are defined based on the values and differences between skills.

Before running the model, we need to set the initial parameters to run the model i.e. the warm up period, the length of run, and the replication number.

### 4.2.1 Steady state analysis

Steady state analysis (as stated in section 3.3.3) is used to determine the warm up period, or as specified in Tecnomatix Plant Simulation (TPS), the period in which the statistics of simulation runs are not collected. The selected method for this analysis is the Welch model. The procedure based on [58] has been described in four steps as follows.

Step 1- the model run for length of m units (here 200 hours) and n replications (here 10 observations) and observations of each unit is recorded.

Step 2- the average number of observations of n replications for each unit is calculated and illustrated in a plot (figure 4.3).

Step 3- to smooth out the high frequency of plot, the moving average method is used and the result is a smoother plot (figure 4.4).

Step 4- once the quite smooth curve is obtained from the moving average, the length of the warm up period can be determined by finding the $x$-value at which the curve starts becoming steady).


Figure 4.3 Ten replication average for throughput per hour


Figure 4.4 Moving average for ten replications for throughput per hour and warm up period
The experiment which is analyzed here is using pattern P2 and CV (5). The analysis has been accomplished by MS Excel software and, as illustrated in figure 4.4, the $x$-value 38 is the point at which a steady state starts. This means that the data between 0 and hour 38 should not be collected in the simulation run. This procedure has been carried out for all experiments. However, since the
experiments should be compared with each other, it is better to specify identical conditions for all experiments. Thus, the warm up period is considered hour 48, which covers all the results of steady state analyses.

The length of run for all the experiments, after some trial runs and a discussion with mentors, was specified as 480 hours.

### 4.2.2 Replication analysis

On account of variability and randomness, it is not correct to make a decision based on a single run of the simulation model. Thus, to reduce the error of the result, we need to find an appropriate number of replications. The method for replication analysis has been described in section 3.3.3. Here, the result of the experiment used in the previous section has been illustrated.

The initial replication that has been selected is 10 and the level of confidence is considered $95 \%$.

The calculation is according to table 4.3. It is observable from the table that the standard error is a very small value and it is lower than the common level of precision. Therefore, there is no need to continue the procedure in this case.

Table 4.3 calculation of standard error in replication analysis

| No. replications | MEAN | STDEV | Standard error |
| :--- | :--- | :--- | :--- |
| 10 | 30.15 | 0.029 | 0.02 |

This procedure has been repeated for all experiments and the results were similar. Thus, the replication number was decided to be 10 for all experiments to have identical conditions.

### 4.2.3 The number of workers

Before considering the arrangement of the workers, we need to determine the number of workers in the line. As mentioned in the literature review part, the pick of production rate is reachable when the number of workers is equal to the number of stations [9]. Since the effect of the number of workers is important in this study, we designed a series of experiments to investigate this problem and choose an appropriate number.
In this simulation, the workers were only considered from one type and the condition with no buffer was taken into account as well. Thus, the four experiments were formed as follows: the low skill workers (CV of 0.15 ) with and without buffers and high skill workers (CV of 0.05 ) with and without buffers.

Then the number of the workers is defined as variable. The result of the simulation run is illustrated in table 4.4. The table shows that in both low skill and high skill, the experiment with forty workers results in highest throughput when the buffer is not considered. However, when the buffer is considered, the maximum throughput requires more workers. Due to considering the buffer, the throughput rate is higher than in the corresponding situation without a buffer. Therefore, a balance should be kept between the numbers of workers and throughput level. According to these experiments and consulting with an
industrial mentor, we decided to consider 40 workers (the optimum number according to literature) in all experiments of this study.

Table 4.4 Simulation results considering different numbers of high and low skill workers with and without a buffer
Just Low Skill (CV: 0.15) without buffer

| No. of <br> Workers | Experiment | Throughput <br> PerHours | Standard <br> Deviation | Minimum | Maximum | Left <br> interval | Right <br> interval |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 38 | $\operatorname{Exp~1~}$ | 33.56273148 | 0.01274667 | 33.546296 | 33.583333 | 33.55361 | 33.57186 |
| 39 | $\operatorname{Exp} 2$ | 33.70578704 | 0.01241541 | 33.685185 | 33.719907 | 33.6969 | 33.71468 |
| 40 | $\operatorname{Exp~3}$ | 33.71157407 | 0.00708869 | 33.699074 | 33.722222 | 33.7065 | 33.71665 |
| 41 | $\operatorname{Exp} 4$ | 33.71157407 | 0.00708869 | 33.699074 | 33.722222 | 33.7065 | 33.71665 |
| 42 | $\operatorname{Exp~5}$ | 33.71157407 | 0.00708869 | 33.699074 | 33.7222222 | 33.7065 | 33.71665 |
| 43 | $\operatorname{Exp} 6$ | 33.71157407 | 0.00708869 | 33.699074 | 33.722222 | 33.7065 | 33.71665 |
| 44 | $\operatorname{Exp~7~}$ | 33.71157407 | 0.00708869 | 33.699074 | 33.722222 | 33.7065 | 33.71665 |

Just Low Skill (CV: 0.15) with buffer

| 38 | Exp 1 | 33.65 | 0.01923758 | 33.627315 | 33.685185 | 33.63623 | 33.66377 |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 39 | Exp 2 | 33.92384259 | 0.00797781 | 33.909722 | 33.935185 | 33.91813 | 33.92955 |
| 40 | Exp 3 | 34.06574074 | 0.01145515 | 34.050926 | 34.090278 | 34.05754 | 34.07394 |
| 41 | Exp 4 | 34.13773148 | 0.01574717 | 34.108796 | 34.159722 | 34.12646 | 34.14901 |
| 42 | Exp 5 | 34.15578704 | 0.01069446 | 34.143519 | 34.178241 | 34.14813 | 34.16344 |
| 43 | Exp 6 | 34.15439815 | 0.01431322 | 34.134259 | 34.180556 | 34.14415 | 34.16465 |
| 44 | Exp 7 | 34.15833333 | 0.01570742 | 34.134259 | 34.180556 | 34.14709 | 34.16958 |

Just High skill: CV: 0.05 without buffer

| 38 | Exp 1 | 36.5925 | 0.00950146 | 36.579167 | 36.604167 | 36.58066 | 36.60434 |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 39 | Exp 2 | 37.28 | 0.00684653 | 37.275 | 37.291667 | 37.27147 | 37.28853 |
| 40 | Exp 3 | 37.65166667 | 0.00631906 | 37.645833 | 37.6625 | 37.64379 | 37.65954 |
| 41 | Exp 4 | 37.65666667 | 0.00631906 | 37.65 | 37.666667 | 37.64879 | 37.66454 |
| 42 | Exp 5 | 37.65666667 | 0.00631906 | 37.65 | 37.666667 | 37.64879 | 37.66454 |
| 43 | Exp 6 | 37.65666667 | 0.00631906 | 37.65 | 37.666667 | 37.64879 | 37.66454 |
| 44 | Exp 7 | 37.65666667 | 0.00631906 | 37.65 | 37.666667 | 37.64879 | 37.66454 |

Just High skill: CV: 0.05 with buffer

| 38 | Exp 1 | 36.59541667 | 0.00634952 | 36.583333 | 36.604167 | 36.59087 | 36.59996 |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 39 | Exp 2 | 37.29125 | 0.00772052 | 37.283333 | 37.304167 | 37.28572 | 37.29678 |
| 40 | Exp 3 | 37.73375 | 0.00888238 | 37.725 | 37.75 | 37.72739 | 37.74011 |
| 41 | Exp 4 | 37.84916667 | 0.00645497 | 37.841667 | 37.858333 | 37.84455 | 37.85379 |
| 42 | Exp 5 | 37.87875 | 0.00634952 | 37.866667 | 37.8875 | 37.8742 | 37.8833 |
| 43 | Exp 6 | 37.88166667 | 0.00814604 | 37.866667 | 37.891667 | 37.87583 | 37.8875 |
| 44 | Exp 7 | 37.88208333 | 0.01058658 | 37.858333 | 37.9 | 37.8745 | 37.88966 |

## 5 Results and Analyses

## 5.I Worker arrangement \& degree of imbalance

### 5.1.1 Comparison of different arrangements

After defining variables and simulation parameters, the model is ready to run. In TPS software, the ExperimentManager tool is used for running numerous experiments at the same time. This tool makes it possible to compare the throughput of different arrangements. To investigate the first research question we need to run our identified patterns ( $\mathrm{P} 1-\mathrm{P} 11$ ) with one of the determined CV levels. The chosen level for this stage is CV (5). Therefore, the simulation model according to the previous stated settings has been prepared and run. The result obtained from ExperimentManager is presented in table 5.1.

Table 5.1 The results of ExperimentManager for 11 patterns and CV (5)

| Experiment | Throughput <br> PerHours | Standard <br> Deviation | Minimum | Maximum | Left interval <br> bound | Right interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Exp 01 | 30.24468 | 0.025194 | 30.19676 | 30.27778 | 30.22664 | 30.26271 |
| Exp 02 | 30.15185 | 0.029183 | 30.10417 | 30.19213 | 30.13096 | 30.17274 |
| Exp 03 | 30.24537 | 0.034765 | 30.16667 | 30.29398 | 30.22048 | 30.27026 |
| Exp 04 | 30.67454 | 0.043665 | 30.61806 | 30.75694 | 30.64328 | 30.7058 |
| Exp 05 | 30.84282 | 0.022534 | 30.80556 | 30.87963 | 30.82669 | 30.85896 |
| Exp 06 | 30.84491 | 0.024643 | 30.80324 | 30.88194 | 30.82726 | 30.86255 |
| Exp 07 | 30.84583 | 0.031022 | 30.79398 | 30.88657 | 30.82362 | 30.86804 |
| Exp 08 | 30.88542 | 0.051197 | 30.82407 | 30.97685 | 30.84876 | 30.92207 |
| Exp 09 | 30.85023 | 0.029825 | 30.79398 | 30.89583 | 30.82888 | 30.87158 |
| Exp 10 | 30.87778 | 0.02992 | 30.82176 | 30.92593 | 30.85636 | 30.8992 |
| Exp 11 | 30.85347 | 0.033153 | 30.80324 | 30.90278 | 30.82974 | 30.87721 |

The experiment numbers ( $\operatorname{Exp} 01, \operatorname{Exp} 02$...) correspond to the patterns. The second and third columns respectively present the Mean and Standard Deviation of 10 replications of the average throughput per hours. The fourth and fifth columns show the range of the results and the last two columns are based on the

$95 \%$ confidence interval. Figure 5.1 illustrates the results of 11 experiments in a chart where the Mean and Confidence interval for throughput per hours has been displayed.

To analyze the results we prepared table 5.2 based on the average throughput-per-hours ranked in descending order.

In the first research question, we questioned the existence of any significant effect of the workers' arrangement on the throughput of the line. In the "difference from bottom" column, the effect of different arrangements is observable. For example, the difference between the average throughput per hours of pattern P11 and pattern P2 (the lowest result) is 0.7 . The difference between other patterns is also calculable.

Table 5.2 Simulation result of $\mathrm{CV}(5)$ in descending order. (H.skill: 0.05, M.skill: 0.2, L.skill: 0.4 ).

|  | Arrangement | Throughput <br> PerHours | Difference <br> from bottom | Standard <br> Deviation | Left <br> interval | Right <br> interval |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| P8 | 7H-6M-13L-7M-7H | 30.88541667 | $\mathbf{0 . 7 3 3 5 6 4 8 1}$ | 0.051197 | 30.84876 | 30.92207 |
| P10 | 7L-6M-14H-7M-6L | 30.87777778 | $\mathbf{0 . 7 2 5 9 2 5 9 3}$ | 0.02992 | 30.85636 | 30.8992 |
| P11 | 13L-14H-13M | 30.85347222 | $\mathbf{0 . 7 0 1 6 2 0 3 7}$ | 0.033153 | 30.82974 | 30.87721 |
| P9 | 14H-13L-13M | 30.85023148 | $\mathbf{0 . 6 9 8 3 7 9 6 3}$ | 0.029825 | 30.82888 | 30.87158 |
| P7 | 13M-13L-14H | 30.84583333 | $\mathbf{0 . 6 9 3 9 8 1 4 8}$ | 0.031022 | 30.82362 | 30.86804 |
| P6 | 13L-13M-14H | 30.84490741 | $\mathbf{0 . 6 9 3 0 5 5 5 6}$ | 0.024643 | 30.82726 | 30.86255 |
| P5 | 14H-13M-13L | 30.84282407 | $\mathbf{0 . 6 9 0 9 7 2 2 2}$ | 0.022534 | 30.82669 | 30.85896 |
| P4 | 7H-7M-7L ... | 30.67453704 | $\mathbf{0 . 5 2 2 6 8 5 1 9}$ | 0.043665 | 30.64328 | 30.7058 |
| P3 | 2H-2M-2L ... | 30.24537037 | $\mathbf{0 . 0 9 3 5 1 8 5 2}$ | 0.034765 | 30.22048 | 30.27026 |
| P1 | Random | 30.24467593 | $\mathbf{0 . 0 9 2 8 2 4 0 7}$ | 0.025194 | 30.22664 | 30.26271 |
| P2 | 1H-1M-1L ... | 30.15185185 | $\mathbf{0}$ | 0.029183 | 30.13096 | 30.17274 |

As we discussed in section 3.3.4, the comparison of alternatives should be statistically analyzed. Thus, according to the described method, to draw a conclusion based on results, differences of ten replications and their confidence intervals should be calculated. Table 5.3 indicates these calculations for CV (5) which is done by MS Excel. The last three columns are the results of calculation. They indicate the paired-t confidence intervals for the difference between the random pattern ( P 1 ) and all other patterns. As we can see in the last column, excluding pattern P3, all other patterns with almost $95 \%$ confidence are different from the random pattern. To reach (1-0.05) overall confidence level (according to the Bonferroni inequality), the individual confidence level for each pair has been considered (1-0.005).

According to this analysis, arranging workers with three different skill levels in a specific order can significantly improve the throughput of the line. This result corroborates the first hypothesis of this study which states that changing the arrangement of the workers with different variability significantly affects the throughput of a linear walking worker assembly line. The maximum improvement in this comparison is the difference between pattern P8 and pattern P1. This is in fact the improvement which can be obtained by arranging workers in specific pattern of P8 rather than just a random or unplanned arrangement. As it is observable from the table, the improvement in the throughput is on average 0.64 $(2.12 \%)$ or it is with a probability of 0.95 between $1.88 \%$ and $2.35 \%$.

Table 5.3 The paired-t confidence intervals for differences between random patterns and ten other patterns with an overall confidence level of 0.95 and an individual confidence level of (1-0.005).

| Rep. | Pattern | Pattern | Pattern | Pattern | Pattern | Pattern | Pattern | Pattern | Pattern | Pattern |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| No. | $\mathbf{1 \& 2}$ | $\mathbf{1 \& 3}$ | $\mathbf{1 \& 4}$ | $\mathbf{1 \& 5}$ | $\mathbf{1 \& 6}$ | $\mathbf{1 \& 7}$ | $\mathbf{1 \& 8}$ | $\mathbf{1 \& 9}$ | $\mathbf{1 \& 1 0}$ | $\mathbf{1 \& 1 1}$ |
| $\mathbf{1}$ | -0.085648 | -0.032407 | 0.3518519 | 0.5925926 | 0.6064815 | 0.62037 | 0.585648 | 0.6296296 | 0.636574 | 0.5717593 |
| $\mathbf{2}$ | -0.085648 | -0.006944 | 0.4791667 | 0.5416667 | 0.6041667 | 0.604167 | 0.650463 | 0.5833333 | 0.648148 | 0.6111111 |
| $\mathbf{3}$ | -0.12037 | -0.013889 | 0.4791667 | 0.625 | 0.5763889 | 0.594907 | 0.604167 | 0.6087963 | 0.62037 | 0.5856481 |
| $\mathbf{4}$ | -0.106481 | 0.0439815 | 0.4351852 | 0.6018519 | 0.599537 | 0.604167 | 0.715278 | 0.6111111 | 0.634259 | 0.6597222 |
| $\mathbf{5}$ | -0.076389 | 0.0162037 | 0.4236111 | 0.5787037 | 0.6111111 | 0.56713 | 0.75 | 0.6435185 | 0.648148 | 0.6435185 |
| $\mathbf{6}$ | -0.152778 | -0.090278 | 0.4027778 | 0.6041667 | 0.5856481 | 0.613426 | 0.578704 | 0.6018519 | 0.592593 | 0.5972222 |
| $\mathbf{7}$ | -0.113426 | 0.0300926 | 0.4212963 | 0.5925926 | 0.5787037 | 0.55787 | 0.634259 | 0.6041667 | 0.615741 | 0.5532407 |
| $\mathbf{8}$ | -0.037037 | 0.0462963 | 0.4027778 | 0.6296296 | 0.6134259 | 0.587963 | 0.601852 | 0.6180556 | 0.599537 | 0.5810185 |
| $\mathbf{9}$ | -0.12037 | -0.020833 | 0.4143519 | 0.5833333 | 0.5486111 | 0.608796 | 0.587963 | 0.5393519 | 0.652778 | 0.5902778 |
| $\mathbf{1 0}$ | -0.030093 | 0.0347222 | 0.4884259 | 0.6319444 | 0.6782407 | 0.652778 | 0.699074 | 0.6157407 | 0.68287 | 0.6296296 |
| Avg | -0.092824 | 0.0006944 | 0.4298611 | 0.5981481 | 0.6002315 | 0.601157 | 0.640741 | 0.6055556 | 0.633102 | 0.6023148 |
| Confidence | $-\mathbf{0 . 1 3 7 4 1 2}$ | $-\mathbf{0 . 0 4 8 9 9 4}$ | $\mathbf{0 . 3 8 0 3 1 9 9}$ | $\mathbf{0 . 5 6 6 1 8 6}$ | $\mathbf{0 . 5 6 0 6 7 9 2}$ | $\mathbf{0 . 5 6 9 7 8 8}$ | $\mathbf{0 . 5 6 9 5 0 1}$ | $\mathbf{0 . 5 7 2 5 2 1}$ | $\mathbf{0 . 6 0 1 5 9 8}$ | $\mathbf{0 . 5 6 3 3 0 4 2}$ |
| interval |  |  |  |  |  |  |  |  |  |  |

In table 5.2, we can detect the maximum difference or improvement. Based on average throughput per hours, the difference between the top pattern (P8) and the bottom pattern (P2) is 0.73. In other words by arranging workers in the P8 pattern, we can improve the throughput over the worst pattern by up to 2.43 percent (or with $95 \%$ probability it will be between ( $2.30 \%, 2.57 \%$ )).
Since throughput improvement through different arrangements of workers was confirmed in the analysis above, the second part of the first research question can be investigated. The requirement is determining a pattern(s) which yield to the highest throughput. Only considering the average throughput according to table 5.2, pattern P8 will be the best alternative. However, this should be statistically analyzed to demonstrate significant differences between P8 and other patterns. It is evident from figure 5.1 that the results of patterns P5, P6... and P11 are close together. Therefore, we decided to examine the difference between pattern P8 and six other patterns. Since the overall confidence level is set to 0.95 , each individual pair should be considered (1-0.0083). According to the results, the confidence intervals do not show any significant difference between the compared patterns (table 5.4). However, if we do not consider the comparisons simultaneously, the confidence level for each pair can be set at $95 \%$, which then means that P8 will be superior to P6 and P11. There is a common characteristic among these patterns such that all low level skills have been placed together. Although pattern P10 looks excluded, the following description would reject this difference.

Table 5.4 The paired-t confidence intervals for comparisons between pattern P8 and patterns P5, P6, P7, P9, P10, and P11 with an overall confidence level of (1-0.05) and an individual confidence level of (1-0.0083).

| Rep. No. | Pattern 8\&5 | Pattern 8\&6 | Pattern 8\&7 | Pattern 8\&9 | Pattern 8\&10 | Pattern <br> $8 \& 11$ |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 1 | -0.00694 | -0.02083 | -0.03472 | -0.04398 | -0.05093 | 0.013889 |
| 2 | 0.108796 | 0.046296 | 0.046296 | 0.06713 | 0.002315 | 0.039352 |
| 3 | -0.02083 | 0.027778 | 0.009259 | -0.00463 | -0.0162 | 0.018519 |
| 4 | 0.113426 | 0.115741 | 0.111111 | 0.104167 | 0.081019 | 0.055556 |
| 5 | 0.171296 | 0.138889 | 0.18287 | 0.106481 | 0.101852 | 0.106481 |
| 6 | -0.02546 | -0.00694 | -0.03472 | -0.02315 | -0.01389 | -0.01852 |
| 7 | 0.041667 | 0.055556 | 0.076389 | 0.030093 | 0.018519 | 0.081019 |
| 8 | -0.02778 | -0.01157 | 0.013889 | -0.0162 | 0.002315 | 0.020833 |
| 9 | 0.00463 | 0.039352 | -0.02083 | 0.048611 | -0.06481 | -0.00231 |
| 10 | 0.06713 | 0.020833 | 0.046296 | 0.083333 | 0.016204 | 0.069444 |
| Avg | 0.0425926 | 0.0405093 | 0.0395833 | 0.0351852 | 0.0076389 | 0.0384259 |
| Confidence | -0.0319072 | -0.0154638 | -0.0343185 | -0.0234327 | -0.0475914 | -0.0034331 |
| interval | $\mathbf{0 . 1 1 7 0 9 2 4}$ | $\mathbf{0 . 0 9 6 4 8 2 3}$ | $\mathbf{0 . 1 1 3 4 8 5 1}$ | $\mathbf{0 . 0 9 3 8 0 3 1}$ | $\mathbf{0 . 0 6 2 8 6 9 1}$ | $\mathbf{0 . 0 8 0 2 8 4 9}$ |
| Result | Not different | Not different | Not different | Not different | Not different | Not |
| 7 lifferent |  |  |  |  |  |  |

The bowl and reversed-bowl arrangements have been discussed in the literature as the main considered patterns, of which the bowl shape pattern could improve the line most and the reversed bowl would usually result in low performance. However, here the condition is different due to the walking aspect of this line. As stated before, the arrangement of workers here actually illustrates the sequence of the workers' entrance to the line. Thus, after the entrance of all 40 workers to the line, the pattern will be repeated by returning the first workers to the beginning of the line so that the low skill workers in the end of the pattern will be combined with the first ones and therefore, all the low skill workers will be grouped together (figure 5.2). In addition, as shown in figure 5.2, the repetition of the pattern causes the bowl and reversed bowl shape to be present in the same sequence. This is same for the patterns which are just different in the skill level orders.


Figure 5.2 Scheme of pattern P10, repetition of the pattern with returning workers to the beginning of the line.

According to figure 5.1 and table 5.2, after analyzing the top patterns, we could consider pattern P4 ranked as second, and patterns P3 and P1 ranked as third and last, as mentioned, is P2 at the bottom. This is supported by statistical analysis as well.

In summary, the comparison of the considered patterns in the CV (5) level of variability concluded the following points:

- Arranging different skill workers in the specific patterns would lead to improvements in the throughput of walking worker assembly lines.
- The best policy to achieve high throughput is grouping all low skill workers together, which includes patterns P5 to P11 in this study.
- In the separate skill policy of the worker arrangements, the more same skill workers that are sequentially placed together, the better the result (patterns P5, P6, and P7 with the highest union showed better results than P4, and in turn P4 better than P3 and, at the bottom, P2 with completely separate skills).
- As discussed, the orders of skill levels would not change the patterns due to the repetition of patterns by the walking workers. Therefore, despite fixed assembly lines, the order of skill levels does not significantly affect the throughput (pattern P5, P6, and P7 are not significantly different). Due to the same reason, the bowl and reversed bowl shaped patterns are not different from each other.


### 5.1.2 Degree of Imbalance

This section intends to investigate the second research question or hypothesis. In the previous section, the effect of the arrangement of workers with different variability on the throughput was corroborated. However, the influence of the variability level or degree of imbalance on the validity/magnitude of this effect was not discussed. Experimental design has determined the different variability levels through different sets of coefficient of variations that were stated in section 4.2: the five CV sets for the triangular distribution and the three sets for the Weibull distribution. In this part, the same experiment from the prior part has been repeated for new CVs. In addition, analysis of these experiments can support the conclusions drawn from the previous part.
In each experiment, by assigning the right quantity to the variable "SkillsVar", the process times of stations were set to the desired variability level. The other settings are the same as the previous experiments. The results from the software, separately for each CV level, in descending order and with a column to show the improvement over the worst result are presented in appendix 3.
Table 5.5 exhibits the average throughput difference between each pattern and worst pattern (potential improvement). Moreover, it shows the rank of each pattern based on the improvement quantity. This analysis helps to compare the results of different CV levels and the effect of the probability distribution of operation times. As we mentioned in the experiment design section, the considered distribution for the case study is triangular distribution. However since we need to examine high levels of variability, we decided to consider another distribution as well (the Weibull distribution). This would give a possibility to
examine the effect of the different probability distributions on the throughput. In setting the coefficient of variations, the mean quantity was considered the same as triangular distribution, 90 seconds. By creating different variances, the three different CVs were determined. The CV (6) has been set almost at the same level of CV (4) to compare the two distributions' results. Table 5.6 has illustrated this comparison.

Table 5.5 The comparison of different CV levels; the numbers below each CV respectively display the value of the coefficient of variation of high, moderate, and low skill workers.

| Considered CV levels |  |  |  | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 | P11 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| CV (1) |  |  | Improvement <br> Rank | 0.03 | 0.00 | 0.03 | 0.17 | 0.26 | 0.25 | 0.26 | 0.27 | 0.25 | 0.28 | 0.25 |
| 0.05 | 0.1 | 0.15 |  | 10 | 11 | 9 | 8 | 3 | 7 | 4 | 2 | 6 | 1 | 5 |
| CV (2) |  |  | Improvement <br> Rank | 0.01 | 0.00 | 0.02 | 0.05 | 0.06 | 0.06 | 0.06 | 0.07 | 0.04 | 0.06 | 0.06 |
| 0.3 | 0.35 | 0.4 |  | 10 | 11 | 9 | 7 | 4 | 5 | 6 | 1 | 8 | 3 | 2 |
| CV (3) |  |  | Improvement <br> Rank | 0.05 | 0.00 | 0.04 | 0.28 | 0.41 | 0.40 | 0.39 | 0.44 | 0.40 | 0.43 | 0.40 |
| 0.1 | 0.2 | 0.3 |  | 9 | 11 | 10 | 8 | 3 | 5 | 7 | 1 | 4 | 2 | 6 |
| CV (4) |  |  | Improvement <br> Rank | 0.03 | 0.00 | 0.03 | 0.16 | 0.23 | 0.24 | 0.23 | 0.26 | 0.23 | 0.25 | 0.24 |
| 0.2 | 0.3 | 0.4 |  | 9 | 11 | 9 | 8 | 7 | 4 | 6 | 1 | 5 | 2 | 3 |
| CV (5) |  |  | Improvement <br> Rank | 0.09 | 0.00 | 0.09 | 0.52 | 0.69 | 0.69 | 0.69 | 0.73 | 0.70 | 0.73 | 0.70 |
| 0.05 | 0.2 | 0.4 |  | 10 | 11 | 9 | 8 | 7 | 6 | 5 | 1 | 4 | 2 | 3 |
| CV (6) |  |  | Improvement <br> Rank | 0.06 | 0.00 | 0.06 | 0.23 | 0.32 | 0.32 | 0.31 | 0.34 | 0.31 | 0.35 | 0.31 |
| 0.2 | 0.3 | 0.4 |  | 9 | 11 | 10 | 8 | 3 | 4 | 7 | 2 | 6 | 1 | 5 |
| CV (7) |  |  | Improvement <br> Rank | 0.16 | 0.00 | 0.09 | 0.47 | 0.74 | 0.70 | 0.71 | 0.74 | 0.70 | 0.74 | 0.68 |
| 0.3 | 0.5 | 0.99 |  | 9 | 11 | 10 | 8 | 2 | 6 | 4 | 1 | 5 | 3 | 7 |
| CV (8) |  |  | Improvement <br> Rank | 0.11 | 0.00 | 0.08 | 0.40 | 0.54 | 0.53 | 0.56 | 0.59 | 0.56 | 0.56 | 0.53 |
| 0.2 | 0.5 | 0.8 |  | 9 | 11 | 10 | 8 | 5 | 7 | 3 | 1 | 4 | 2 | 6 |

According to this table and corresponding chart (figure 5.3), the difference is significant just in the patterns with low throughput (P1, P2, P3). The difference might be a result from the approximation which had to be considered in setting the CVs for these two distributions. However, in this comparison, the importance for our study is the effect of different patterns on the throughput. Based on the figure 5.3, the stated effect for two distributions is quite similar.

Return to table 5.5, the highest improvement (Rank 1) of each CV level, which is identified in the table, can be a criteria to compare these CV levels. CV (7) and CV (5) have produced the best results and on the other hand, the least improvement is through CV (2), which is not a significant amount (just 0.07 or $0.24 \%)$. Therefore, there is a significant difference (greatest is 0.67 ) between the improvements obtained from different CV levels. This is evidence that can answer our second research question, which examines the effect of variability levels on the validity or magnitude of the results from the previous section. The differences mentioned in the improvements through the change of CV levels emphasize the effect of CV (variability) on the magnitude of the first hypothesis. On the other hand, the insignificant improvement that resulted (CV (2)) implies
that the validity of hypothesis one depends on the CV or more precisely the variability level of worker operation times.

| CV (4) \& CV (6): |  |  |  |
| :--- | :--- | :--- | :--- |
| (H.skill:0.2, M.skill:0.3, L.skill O.4) |  |  |  |
|  | Triangular | Weibull | Difference |
| P1 | 29.175 | 29.116667 | 0.058 |
| P2 | 29.1474537 | 29.053935 | 0.094 |
| P3 | 29.175 | 29.11088 | 0.064 |
| P4 | 29.30439815 | 29.283565 | 0.021 |
| P5 | 29.37615741 | 29.372222 | 0.004 |
| P6 | 29.38425926 | 29.368981 | 0.015 |
| P7 | 29.37800926 | 29.359491 | 0.019 |
| P8 | 29.40347222 | 29.391435 | 0.012 |
| P9 | 29.38055556 | 29.36713 | 0.013 |
| P10 | 29.39699074 | 29.4 | -0.003 |
| P11 | 29.39027778 | 29.367593 | 0.023 |

Table 5.6 The average throughput result of Weibull and triangular distributions and their difference at the same CV level.


Figure 5.3 The comparison of Weibull and triangular distributions at the same CV level.

Other observations through the results of the experiments of this section are outlined as follows:

- The difference among the coefficient variations in CV(1) and CV (2) is equal to 0.1 , however $\mathrm{CV}(1)$ which has lower coefficient of variation size $(0.05$, $0.1,0.15)$ compared to CV (2), led to higher improvement, this is true for CV (3) and CV (4).
- Through a comparison of CV (2) and CV (5), both having large CV size, CV (5) causes considerably higher improvement compared to CV (2).
- The last two CV levels have been applied to examine the effect of moderate level variability. CV (7) with the highest variability ( 0.99 ) could just improve the throughput up to $\mathrm{CV}(5)$ which has small variability of 0.4 , and CV (8) cannot even reach to the improvement of CV (5).


### 5.2 Modification of worker numbers

In this section, we intend to examine the influence of worker numbers in the throughput of the line when different skill levels are considered for walking workers. The investigation enables the third research question to be answered. In the experiments design, we analyzed the numbers of workers when only one type of worker is considered. However, when different skills are considered, their arrangement is important.

The selected patterns for these experiments are P9 (14H.Skill-13L.Skill13M.Skill) and P8 (7H.Skill-6M.Skill-13L.Skill-7M.Skill-7H.Skill) and CV (5) has been considered for the variability level. The object is decreasing some numbers of workers to observe the extent of the effect on the throughput. Table 5.7 demonstrates the results of two series of experiments. The upper part of the table
is related to pattern P9 which shows the reduction results of low and high skill workers, and the lower part is similar to the result for pattern P8. The column with the Effect label displays the influence of changes on the throughput (negative numbers express the reduction of throughput). The interesting result here is the increase in the throughput (about 0.03 highlighted in the table) through the reduction of one low skill worker. This increase (tested for pattern P8) based on the paired-t confidence interval with $95 \%$ confidence is statistically significant.

Table 5.7 The results of reduction of workers on the throughput.

| Pattern 9: 14HighSk-13LowSk-13ModSk |  |  |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| $\begin{aligned} & \hline \text { Change of } \\ & \text { workers' No. } \end{aligned}$ | Experi ment | Throughput PerHours | Effect | Standard Deviation | Minimum | Maximum | Left interval bound | Right interva bound |
| No change | $\operatorname{Exp} 1$ | 30.85023 | 0.000 | 0.02983 | 30.79398 | 30.89583 | 30.82888 | 30.87158 |
| 1 LowSk drop | $\operatorname{Exp} 2$ | 30.87986 | 0.030 | 0.02086 | 30.84954 | 30.90741 | 30.86493 | 30.89480 |
| 2 LowSk drop | Exp 3 | 30.81944 | -0.031 | 0.03346 | 30.77083 | 30.89352 | 30.79549 | 30.84340 |
| 3 LowSk drop | Exp 4 | 30.66296 | -0.187 | 0.03575 | 30.59954 | 30.70602 | 30.63737 | 30.68856 |
| 5 LowSk drop | Exp 5 | 30.10139 | -0.749 | 0.02058 | 30.07176 | 30.13194 | 30.08665 | 30.11612 |
| 1 HighSk drop | Exp 6 | 30.66319 | -0.187 | 0.01453 | 30.64815 | 30.68981 | 30.65279 | 30.67360 |
| 2 HighSk drop | Exp 7 | 30.37153 | -0.479 | 0.01989 | 30.33565 | 30.41204 | 30.35729 | 30.38577 |
| 3 HighSk drop | Exp 8 | 30.01736 | -0.833 | 0.02527 | 29.96528 | 30.04861 | 29.99927 | 30.03545 |
| 4 HighSk drop | Exp 9 | 29.08542 | -1.765 | 0.03227 | 29.04167 | 29.12963 | 29.06232 | 29.10852 |
| Pattern 8: 7HighSk-6ModSk-13LowSk-7ModSk-7HighSk |  |  |  |  |  |  |  |  |
| Change of workers' No. | Experi ment | Throughput PerHours | Effect | Standard Deviation | Minimum | Maximum | Left interval bound | Right interval bound |
| No change | Exp 01 | 30.88542 | 0.000 | 0.05120 | 30.82407 | 30.97685 | 30.84876 | 30.92207 |
| 1 LowSk drop | Exp 02 | 30.92384 | 0.038 | 0.02097 | 30.89352 | 30.95833 | 30.90883 | 30.93886 |
| 2 LowSk drop | Exp 03 | 30.8419 | -0.044 | 0.03026 | 30.81019 | 30.91435 | 30.82023 | 30.86356 |
| 3 LowSk drop | Exp 04 | 30.67616 | -0.209 | 0.03641 | 30.60417 | 30.72685 | 30.65009 | 30.70223 |
| 4 LowSk drop | Exp 05 | 30.43773 | -0.448 | 0.03451 | 30.39815 | 30.49769 | 30.41302 | 30.46244 |
| 5 LowSk drop | Exp 06 | 30.1044 | -0.781 | 0.04114 | 30.05556 | 30.17824 | 30.07494 | 30.13385 |
| 1 HighSk drop | Exp 07 | 30.69537 | -0.190 | 0.02778 | 30.65509 | 30.73148 | 30.67548 | 30.71526 |
| 2 HighSk drop | Exp 08 | 30.40694 | -0.478 | 0.03041 | 30.35417 | 30.45602 | 30.38517 | 30.42872 |
| 3 HighSk drop | Exp 09 | 30.04005 | -0.845 | 0.02266 | 30.00926 | 30.07407 | 30.02383 | 30.05627 |
| 4 HighSk drop | Exp 10 | 29.60093 | -1.284 | 0.03083 | 29.55556 | 29.63889 | 29.57885 | 29.62300 |

According to the results, once the low skill workers' reduction goes beyond one, the throughput decreases as expected. The throughput fall is steep for the high skill workers' reduction. The results provoked the idea of comparing the effect of reductions and the result of the wors pattern (P2) to evaluate the gained improvement through the arrangemnt of workers. Since the selected patterns


Figure 5.4 Low skill worker reduction compared with P2. are among the best arrangements, their throughput while they have less workers can be compared with the throughput of wors pattern (or random arrangement). As illustrated in


Figure 5.5 High skill worker reduction compared with P2. figure 5.4, a decrease of low skill workers can continue up to four and still produce a higher throughput than pattern P2. In figure 5.5, this number for the high skill workers is two.
These observations signify that in pattern P9/P8, the number of workers in the line can be decreased up to four low skills/two high skills whereas the throughput remains higher than pattern P2. This result implies the significance of the gained improvement through arranging workers. In other words, the improvement through arranging workers in a specific order can save the cost of using four low skill workers or two high skill workers.

These experiments have been selected as example of possible modifications to emphasize the significance of our results, of course other results through the alterations of moderate skill workers or modification of workers for other patterns might be interesting as well.

### 5.3 Unbalanced Vs. Balanced line

In the literature review, the bowl phenomenon is discussed and different investigations regarding it are presented. Therefore, in this section, we intend to examine the existence of this phenomenon in walking worker assembly lines.

In order to do this experiment we need to set a new series of arrangements for workers. The experiments are designed according to the points below and are summarized in Table 5.8:

- The line with 40 moderate skill workers is the balanced line and the unbalanced lines are considered with the three skill levels.
- The unbalanced patterns are arranged based on pattern P8 (reversed bowl shape). This pattern, as we explained before, is equal to the bowl shape and results in the best average throughput per hour in most of the previous experiments.
- The sum of CVs in the unbalanced patterns should be equal to the balanced one. Therefore, the numbers of high and low skill workers should be equal.
- Unbalanced patterns are considered with a different degree of imbalance which means that the variability in the line is controlled by considering different numbers of high or low skills workers.
- This experiment uses three levels of variability to examine this phenomenon; CV (1), CV (3), and CV (8).

Table 5.8 Unbalanced line patterns

| Experiment | Balanced line |
| :--- | :--- |
| Exp 1 | 40 Moderate Skill |
|  | Unbalanced patterns |
| Exp 3 | $7 \mathrm{H}, 7 \mathrm{M}, 13 \mathrm{~L}, 7 \mathrm{M}, 6 \mathrm{H}$ |
| Exp 4 | $6 \mathrm{H}, 9 \mathrm{M}, 11 \mathrm{~L}, 9 \mathrm{M}, 5 \mathrm{H}$ |
| Exp 5 | $4 \mathrm{H}, 12 \mathrm{M}, 8 \mathrm{~L}, 12 \mathrm{M}, 4 \mathrm{H}$ |
| Exp 6 | $2 \mathrm{H}, 16 \mathrm{M}, 4 \mathrm{~L}, 16 \mathrm{M}, 2 \mathrm{H}$ |
| Exp 7 | $7 \mathrm{H}, 5 \mathrm{M}, 15 \mathrm{~L}, 5 \mathrm{M}, 8 \mathrm{H}$ |
| Exp 8 | $11 \mathrm{~L}, 11 \mathrm{H}, 18 \mathrm{M}$ |

The eight experiments have been run in the software and the results for the three levels of variability/CV are displayed in Table 5.9.

The results are ranked in descending order according to the throughput, and the column Difference shows the difference between the balanced line and unbalanced patterns. As it is observed in this column, there are no patterns which could surpass the balanced line. The closest result to the balanced line throughput is the Exp5 with CV (1) result. This means that according to our results, based on our experiment set up, there is no unbalanced pattern which could improve the balanced line.

Table 5.9 Results of comparison between unbalanced patterns and balanced line
CV (8): Weibull Dis. H.skill 0.2, M.skill 0.5, L.skill 0.8

| Experiment | oot.Throug <br> hputPerHo <br> urs | Difference | Standard <br> Deviation | Minimum | Maximum | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Exp 1 | 24.370833 | 0 | 0.026747 | 24.328704 | 24.412037 | 24.351685 | 24.389982 |
| Exp 5 | 23.737731 | 0.6331019 | 0.070297 | 23.650463 | 23.856481 | 23.687404 | 23.788059 |
| Exp 4 | 23.302778 | 1.0680556 | 0.0383915 | 23.238426 | 23.347222 | 23.275293 | 23.330263 |
| Exp 8 | 23.300926 | 1.0699074 | 0.0501365 | 23.231481 | 23.393519 | 23.265032 | 23.33682 |
| Exp 3 | 22.976389 | 1.3944444 | 0.0447637 | 22.907407 | 23.032407 | 22.944342 | 23.008436 |
| Exp 7 | 22.922917 | 1.4479167 | 0.0700934 | 22.824074 | 23.037037 | 22.872735 | 22.973098 |
| Exp 2 | 22.791204 | 1.5796296 | 0.0495728 | 22.733796 | 22.905093 | 22.755713 | 22.826694 |
| Exp 6 | 22.572454 | 1.7983796 | 0.0582963 | 22.488426 | 22.666667 | 22.530718 | 22.614189 |

CV (3): Trinagular Dis. H.skill 0.1, M.skill 0.2, L.skill 0.3

| Experiment | Throughpu <br> tPerHours | Difference | Standard <br> Deviation | Minimum | Maximum | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Exp 1 | 32.340046 | 0 | 0.0133401 | 32.314815 | 32.356481 | 32.330496 | 32.349597 |
| Exp 5 | 32.171528 | 0.1685185 | 0.0192886 | 32.138889 | 32.203704 | 32.157719 | 32.185337 |
| Exp 4 | 32.084259 | 0.255787 | 0.0257351 | 32.046296 | 32.122685 | 32.065835 | 32.102684 |
| Exp 8 | 32.043981 | 0.2960648 | 0.0236821 | 32.00463 | 32.074074 | 32.027027 | 32.060936 |
| Exp 3 | 32.019444 | 0.3206019 | 0.0180034 | 31.988426 | 32.046296 | 32.006555 | 32.032333 |
| Exp 7 | 31.986806 | 0.3532407 | 0.0170121 | 31.956019 | 32.006944 | 31.974626 | 31.998985 |
| Exp 2 | 31.972222 | 0.3678241 | 0.0205601 | 31.951389 | 32.016204 | 31.957503 | 31.986942 |
| Exp 6 | 31.941898 | 0.3981481 | 0.0157925 | 31.918981 | 31.967593 | 31.930592 | 31.953204 |
| CV (1): Trinagular Dis. H.skill 0.05, M.skill 0.1, L.skill 0.15 |  |  |  | Left <br> interval <br> bound | Right <br> interval <br> bound |  |  |
| Experiment | Throughpu <br> tPerHours | Difference | Standard <br> Deviation | Minimum | Maximum |  |  |
| Exp 1 | 35.821759 | 0 | 0.009387 | 35.800926 | 35.833333 | 35.815039 | 35.82848 |
| Exp 5 | 35.70787 | 0.1138889 | 0.0109557 | 35.68287 | 35.722222 | 35.700027 | 35.715714 |
| Exp 4 | 35.65162 | 0.1701389 | 0.0110342 | 35.636574 | 35.671296 | 35.643721 | 35.65952 |
| Exp 8 | 35.630787 | 0.1909722 | 0.0090807 | 35.615741 | 35.643519 | 35.624286 | 35.637288 |
| Exp 3 | 35.619444 | 0.2023148 | 0.0080336 | 35.604167 | 35.62963 | 35.613693 | 35.625196 |
| Exp 7 | 35.594907 | 0.2268519 | 0.0093233 | 35.578704 | 35.608796 | 35.588233 | 35.601582 |
| Exp 2 | 35.594213 | 0.2275463 | 0.0077966 | 35.583333 | 35.604167 | 35.588631 | 35.599795 |
| Exp 6 | 35.571296 | 0.250463 | 0.0134445 | 35.543981 | 35.592593 | 35.561671 | 35.580922 |

## 6 Discussion and conclusions

## 6.I Discussion of findings

In general, individuals cannot perform a series of tasks repeatedly at the same rate and the result of this is variation in the task times [11]. Besides deviation in mean operation times, workers differ in the variability of their operation times, which is usually presented by CV [3].

These differences can originate from various sources. The most apparent difference among individuals is in their level of ability. This can be due to variances in experience levels, manual dexterity, or just pure discipline. The other easily observable source of distinction is the attitude people have towards their jobs. A distinctive perspective towards life and work can be another source. It causes different responses to various forms of motivation. Financial incentives motivate people at different levels and besides that, based on researchers' findings, different social aspects of work play significant roles in motivating workers [26].

Regardless of the causes of individual differences, the effect of this considerably significant variability on the assembly lines is discussed in the literature as an imbalance problem. Since Hillier and Boling's findings[4], which indicated that an unbalanced line can produce even higher throughput than a balanced line, an enormous amount of research has been undertaken to investigate the unbalanced line in different conditions and with different source of imbalance.

In this regard, current investigation aimed at studying the influence of variability imbalance on the output of walking worker assembly lines. The investigation, which had not been considered thus far, can be highly esteemed in practice since it has explored the possibility of improvement without any investment; only by arranging workers with different variability in the specified patterns.

In the final chapter of report, we intend to discuss the findings from the previous chapter and link them to the objects of the study. The research problem as presented in the introduction part has been broken down into specific research questions and hypotheses. Therefore, to ease the follow of discussion, we have subdivided the section into the research questions as follows:

### 6.1.1 Does the arrangement of workers in any pattern cause a significant improvement in the throughput of the line? If so, which pattern would yield the highest throughput?

In the fixed-worker assembly line literature, the problem of arranging workers with different variability has been discussed more clearly in El- Rayah's work [13]. The result of his experiments which investigate the effect of different station arrangements on the output rate considering unequal CVs , indicated significant improvement in the output through the arrangement of workers in bowl-shape.

The effect of worker differences on output rate has been investigated for moving worker (bucket brigade) assembly lines as well [10]. The research [47] shows that when the workers are arranged from slowest to fastest and the task
times or speed of workers is considered deterministic, the bucket brigade approach is very robust to worker differences.

Regarding this problem, the study [8] investigates the effect of randomness on the output of the walking worker assembly line. However, the order of different variabilities has not been considered in this study. The results showed a significant decrease on the effect of variable unbalance levels by using fewer workers than stations.

In this study, to examine the effect of arrangement on the throughput of the walking worker assembly line, eleven different patterns were considered. As illustrated in the results and analyses chapter, based on the outcomes of simulation runs and statistical analysis, the considered patterns could show significant improvement over the pattern P1 (randomly arranged pattern) which simulate a condition in which the workers' arrangement is not taken into account. This result in addition to answering the first part of the research question, corroborates the first hypothesis "Changing the arrangement of the workers with different operational time variability, e.g. due to different skill levels, will significantly affect the throughput of an assembly line with linear walking workers."

Based on average throughput per hour, pattern P8 (7H-6M-13L-7M-7H) showed the maximum output. It could improve the throughput over the worst pattern (P2) by up to 2.43 percent (with $95 \%$ probability between ( $2.30 \%$, $2.57 \%$ ). The gained improvement is significant compared to the corresponding improvements in the fixed assembly line, which is about 1 to 2 percent [14].

Based on the results of section 5.1, the patterns that yield the highest throughput have common characteristics such that all low level skills have been placed together. Therefore, the best policy to achieve high throughput is grouping entire low skill workers together, which includes patterns P5 to P11 in this study. These patterns have not significantly been affected by the bowl or reversed bowl shape. This is in conflict with fixed assembly line cases (mentioned in the literature review part) which based on bowl phenomenon, best throughput results through the bowl shape pattern [13] and[35]. Although we could not show the superiority of the bowl shape pattern statistically, with just considering average throughput, bowl or reversed-bowl shape patterns (P9 \& P8) are ranked number one in all the results of different CV levels (section 5.1.2).

In the previous chapter, it was shown that the order of skill levels in the considered patterns, despite fixed assembly lines, does not affect the result. In fact, the patterns with order displacement are the same patterns due to walking workers and repetition of patterns. Therefore, the order of skill levels does not significantly affect the throughput (patterns P5, P6, and P7 are not significantly different). Due to the same reason, the bowl and reversed bowl shaped patterns are not different from each other.

### 6.1.2 Does the variability level (variation in CV size and range) affect the validity/magnitude of the previous problem?

The second research question considers the effect of CV levels on the previous problem. The variability, which is indicated by CV here, could reflect several detractors that are available in the workstations or created by operators if they just vary the variance (mean time is constant here). Non-qualified operators, lack of motivation and training of employees can be the main sources of high variance in
task times [16], [5]. Different considered variability/CV levels might represent a condition in the real world.

Based on the previous chapter and concerning the second research question, different obtained improvements through the change of CV levels make it evident that the variability level influences the magnitude of the first hypothesis. On the other hand, the insignificant improvement (CV (2)) showed that output differences through the arrangement of workers can be minor and this implies that the validity of hypothesis one depends on the variability level of worker operation times.

In addition to the stated finding, the following interpretations can be gained by the analyzing the result of the previous chapter.

- Due to a comparison of the result of two considered distributions, it seems that probability distribution of the operation times is not significantly effective on our problem validity/magnitude.
- In the comparison of CV (2) with CV (1) and CV (3) with CV (4), it was found that for each pair the differences among CVs of three skills are equal, but not the size of CVs. According to the results, once the workers have low variability (CV size is small), higher improvement through arranging workers is expected.
- On account of the CV (2) and CV (5) comparison, higher improvement is expected through the large differences among the CVs of the three skills.
- In the worker arrangement policy of separate skills and through comparing the results of different CV levels, it can be concluded that the more same skill workers are sequentially placed together, the better the results will be. The patterns P5, P6, and P7 with the highest union showed better results than P4 and in turn, P4 better than P3, and at the bottom P2 with completely separate skills.
- In the literature [26], three classes of variability based on the coefficient of variation are considered: low variability when the CV is less than 0.75 , moderate variability when it is between 0.75 and 1.33 , and high variability when it is more than 1.33. Based on this description, the last two considered CV levels include moderate variability. However, according to the obtained results, no special effect is observable due to this level of variability except that having a higher CV size does not lead to increased improvement.
The last finding is to some extent in conflict with hypothesis II, which claims that the effect of different variability levels will be more pronounced with the increasing degree of imbalance. Therefore, since the increase of variability in the last two CV levels can be considered an increase in the degree of imbalance, hypothesis II is rejected based on observations.

According to our literature review, no comprehensive investigation for the influence of the degree of imbalance concerning unbalancing or arrangement problems could be found.

### 6.1.3 How does variation in the number of walking workers influence the throughput of the line?

In linear walking worker assembly lines, the effect of the blocking rate and inprocess waiting time decrease considerably by optimizing the number of walking workers, which results in stable output [51], [7], and [52]. Therefore, in this type of assembly line, tolerance of work time variation is better than the conventional fixed worker line [7].

In the experiments design, we investigated selecting the number of workers when only one type of worker is considered. However, when different skills should be taken into account, their arrangement would be important.

This research question was formed based on the investigations in the literature, which have considered the modification and optimization of the number of workers. Since a nearly optimum number of workers was selected in the experiment design, the reduction of workers, whether low skill or high skill workers, is expected to influence the throughput negatively. However, an unexpected result is an increase in the throughput (about 0.03) through the reduction of one low skill worker. This implies a significance negative effect of low skill workers on the line.

The comparison of the results of worker reductions with the results of the worst pattern (P2) enabled the evaluation of the gained improvement through the arrangemnt of workers based on the best patterns. The observations signify that in pattern P9/P8, the number of workers in the line can be decreased by up to four low skills/two high skills, whereas the throughput still remains higher than in pattern P2. The result implies the significance of the gained improvement by arranging workers. In other words, improvement through the arrangement of workers in the specific order can save the cost of using four low skill workers or two high skill workers.

These results, in addition to existing literature which emphasizes good tolerance of walking worker assembly lines against work time variation, shows that by just arranging workers in a specific order could gain even more benefits when the variability of task times matters.

### 6.1.4 Can unbalancing a line, in terms of CV, cause any significant improvement in the throughput over the balanced line?

This research question inspects the bowl phenomenon which has been elucidated in the literature review. Hillier and Boling [4] found that assigning a lower mean service time to the middle station of a three-station production line could obtain the optimal production rate. In other words, the findings mean that in some conditions an unbalanced line can produce better output than a balanced line.

The effect of unbalancing assembly lines in terms of CV has been addressed in several research studies such as [35], [36], and [13] and their results indicate improvement over the balanced line due to bowl phenomenon. However, some research such as [35] and [37]could not see any improvement in the cases with long lines.

Due to our results, there is no evidence to prove the superiority of the bowlshaped (or reversed bowl shape) pattern over the balanced line. However, since we could not consider all possible conditions, the conclusion is only true in this particular setting. Therefore, based on the results, hypothesis III cannot be proved.

The conclusion which can be drawn through the results is that with a lower coefficient of variation as well as a low degree of imbalance (considering less imbalances which here means low or high skill workers) might get relatively close results to the balanced line results.

### 6.2 Conclusions

The purpose of this study is to investigate the influence of operational time variability and different imbalance patterns on the output of the flexible assembly system, which is called a linear walking worker assembly line. Special attention is given to exploring the possibility of improving throughput without any financial investment, only by arranging workers with different variability in a specified pattern. The method used to examine the research questions and hypotheses is a simulation study and for this purpose, an industrial case study is chosen as the model. The research concludes that arranging such workers in a special pattern would result in significant improvement in the throughput of the line. The patterns that could improve the system the most have a common characteristic; all low skill workers are grouped together. To emphasize the importance of the findings, an analysis was carried out with a reduction of workers. The improvement in the throughput due to arranging workers in a specific order could save the cost of employing four low skill workers or two high skill workers. This is highlighted further when we consider that this improvement is possible without any significant investment; only by arranging workers with different variability in the specified patterns. These findings can be highly applicable when a line is undergoing labor turnover.

The different patterns of imbalance influence the output in different ways. However, the main conclusion is that the variability level can affect the magnitude and validity of the findings of this study. The final conclusion, which has been drawn through the results of a series of new experiments, is that the bowl phenomenon or the superiority of the bowl shape line over the balanced line could not be shown in the walking worker assembly lines.

This work, as mentioned earlier, intends to make a contribution to fill a research gap in the field of linear walking worker and unbalanced assembly lines. According to the literature, the main sources of imbalance are the operation time means and the coefficient of variation. In this study, only the coefficient of variation has been considered, which means that a future study is required to examine the effect of operation time means. In addition, another research opportunity is to develop this study to consider two imbalance sources at the same time.

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## 8 Appendices

## 8.I Appendix I

The classification scheme for ALB [20]

Precedence Graph Characteristics

| Product specific precedence graphs: $\alpha_{1} \in\{$ mix,mult, 0$\}$ |  |  |  |
| :---: | :---: | :---: | :---: |
| $\mathrm{a}_{4}=$ mix | Mixed-model production | $\beta_{1}=\circ \lambda \lambda$ | Paced line; with $\lambda \in\{0$, each,prob $\}$ and $v \in\{0$, div $\}$ |
| $a_{1}=$ mult | Multi-model production |  | $\lambda=0$; (Average) work content restricted by cycle time |
| $\mathrm{a}_{1}=$ 。 | Single-model production |  | $\lambda$ =each: Each model must fulfill the cycle time |
| Structure of the precedence graph: $\alpha_{2} 6$ (spec, ) \} |  |  | $\lambda=$ prob: Cycle time is obeyed with a given probability |
| $\mathrm{a}_{2}=$ spec | Restriction to a special precedence graph structure |  | $\mathrm{v}=0$ : Single global cycle time |
| $\mathrm{a}_{2}=0$ | Precedence graph can have any acyclic structure |  | ve div: Local cycle times |
| Processing timess $\alpha_{3} \mathrm{e}\left(\mathrm{t}^{\text {ºj}}, \mathrm{t}^{6 y}, 0\right]^{*}$ |  | $\beta_{1}=$ unpac $^{\text {k }}$ | Unpaced line; with $\lambda \in$ [ $0, s y \mathrm{sc}$ ] |
| $a_{3}=t^{40}$ | Stochastic processing times |  | $\lambda=0$ : Asynchronous line |
| $a_{3}=y^{\text {dy }}$ | Dynamic processing times (e.g. learning effe |  | $\lambda=$ syn: Synchronous line |
| $a_{3}=$ o | Processing times are static and deterministic | Line layout: $\beta_{2} \in\left\{0, \mathrm{u}^{2}\right\}$ |  |
| Sequence-dependent task time increments: $a_{4} \in\left\{\Delta \mathrm{t}_{\text {din }} \Delta \mathrm{t}_{\text {sedir }} \text { 어 }\right\}^{*}$ |  | $\beta_{2}=$ 。 | Serial line |
| $a_{4}=\Delta t_{\text {dir }}$ | Caused by direct succession of tasks (e.g. tool change) | $\beta_{2}=u^{2}$ | U-shaped line; with $\lambda \in[0, \mathrm{n}]$ |
| $\mathrm{a}_{4}=\Delta \mathrm{t}_{\text {iear }}$ | Caused by succession of tasks (tasks hinder each other) |  | $\lambda=0$ : The line forms a single U |
| $\mathrm{a}_{4}=0$ | Sequence-dependent time increments are not considered |  | $\lambda=n$ : Multiple Us forming an $n-U$ line |
| Assignment restrictions: $a_{5} \in[\text { link, inc,cum,fix,excl,type,min,max,o }]^{*}$ |  | Parallelization: $\beta_{3} \in$ (pline ${ }^{2}$,pstat ${ }^{2}$,ptask ${ }^{2}$,pwork ${ }^{2}$, of ${ }^{*}$ |  |
| $a_{\text {c }}=$ link | Linked tasks have to be assigned to the same station | $\beta_{3}=$ pline $^{2}$ | Parallel lines |
| $a_{5}=$ inc | ompatible tasks cannot be combined at a station | $\beta_{3}=$ pstat ${ }^{2}$ | Parallel stations |
| $\mathrm{a}_{5}$ =cum | Curmulative restriction of task-station-assignment | $\beta_{3}=$ ptask $^{2}$ | Parallel tasks |
| $a_{5}=$ fix | Fixed tasks can only be assigned to a particular station | $\beta_{3}=$ pwork ${ }^{2}$ | Parallel working places within a station |
| $0_{5}$-excl | Tasks may not be assigned to a particular station | $\beta_{3}=0$ | Neither type of parallelization is considered |
| $a_{5}=$ type | Tasks have to be assigned to a certain type of station | he $(0,2,3, \ldots)$ : Maximum level of parallelization; $0=$ unrestricted |  |
| $\mathrm{a}_{5}=$ min | Minimum distances between tasks have to be observed | Resource assignment: $\beta_{4} \in\left[\right.$ equip,res ${ }^{2}$, o ]* |  |
| $a_{5}=$ max | Maximum distances between tasks have to be observed | $\beta_{4}$ \#cquip | Equipment selection problem |
| $a_{5}=0$ | No assignment restrictions are considered | $\beta_{4}=$ res $^{2}$ | Equipment design problem; with $\lambda \in\{0,01 \text {,max }]^{*}$ |
| Processing alternatives: $\alpha_{0} \in\left[\mathrm{pa}^{2}, 0\right]$ |  |  | $\lambda=01$ : If two task share a resource, investment costs are reduced at a station |
| $a_{5}=\mathrm{pa}^{2}$ | Processing alternatives; with $\lambda \in\{0$,prec,subgraph $\}$ |  | $\lambda=$ max: Most challenging task defines the needed qualification level of a resource |
|  | $\lambda=0$; Processing times and costs are altered |  |  |
|  | $\lambda=$ pree: Precedence constraints are additionally altered |  | $\lambda=0$; Other type of synergy and/or dependency |
|  | $\lambda=$ subgraph: Subgraphs are additionally altered | $a_{0}=0$ | Processing alternatives are not considered |
| $a_{6}=0$ | Processing alternatives are not considered | Station-dependent time increments: $\beta_{y} \in\left[\Delta t_{\text {ury }}\right.$, ) $]$ |  |
|  | Objectives | $\beta_{5}=\Delta \mathrm{t}_{\text {uep }}$ | Unproductive activities at a station are considered |
| Objectives: $\gamma \in\left[\mathrm{m}, \mathrm{c}, \mathrm{E}, \mathrm{Co}, \mathrm{Pr}, \mathrm{SSL}^{2}, \text { score }, \mathrm{o}\right]^{*}$ |  | $\beta_{5}=0$ | Station-dependent time increments are not regarded |
| $\gamma=\mathrm{m}$ | Minimize the number of stations m | Additional configuration aspects: $\beta_{0} \in\{$ buffer,feeder,mat,change, 0 \} |  |
| $\gamma=\mathrm{c}$ | Minimize cycle time c | $\beta_{0}=$ buffer | Buffers have to be allocated and dimensioned |
| $\gamma=\mathrm{E}$ | Maximize line efficiency E | $\beta_{6}=$ feeder | Feeder lines are to be balanced simultaneously |
| $\gamma=\mathrm{Co}$ | Cost minimization | $\beta_{0}=$ mat | Material boxes need to be positioned and dimensioned |
| $\gamma=\mathrm{Pr}$ | Profit maximization | $\beta_{6}=$ change | Machines for position changes of workpieces required |
| $\mathrm{Y}=\mathrm{SSL}^{2}$ | Station times are to be smoothed; with $\lambda . \in$ [stat,line] | $\beta_{0}=\square$ | No additional aspects of line configuration are regarded |
|  | $\lambda=$ stat: Within a station (horizontal balancing) |  |  |
|  | $\lambda=$ line: Between stations (vertical balancing) |  |  |
| $\gamma$ =score | Minimize or maximize some composite score |  |  |
| $\gamma=0$ | Only feasible solutions are searched for |  |  |

### 8.2 Appendix 2

The screen shots for two other models in Tecnomatix Plant Simulation


### 8.3 Appendix 3: the simulation result of section 5.1.2

The simulation results of different CV levels:

- The results from software ranked in the descending order based on the average throughput per hour
- The third column has been added to show the average amount of improvement over the worst pattern

1. The result for $\mathbf{C V}$ (1): $\mathbf{0 . 0 5}, \mathbf{0 . 1}, \mathbf{0 . 1 5}$

|  | Throughput <br> PerHours | Differe <br> nce <br> from | Standard <br> Deviatio <br> $\mathbf{n}$ | Minimum | Maximu <br> $\mathbf{m}$ | Left <br> interval <br> bottom | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Pattern 10 | 35.63773148 | 0.28 | 0.010134 | 35.625 | 35.65278 | 35.63048 | 35.64499 |
| Pattern 8 | 35.63194444 | 0.27 | 0.010747 | 35.61806 | 35.65278 | 35.62425 | 35.63964 |
| Pattern 5 | 35.62013889 | 0.26 | 0.010492 | 35.60185 | 35.63194 | 35.61263 | 35.62765 |
| Pattern 7 | 35.61851852 | 0.26 | 0.00662 | 35.6088 | 35.63194 | 35.61378 | 35.62326 |
| Pattern 11 | 35.61365741 | 0.25 | 0.008895 | 35.59722 | 35.62731 | 35.60729 | 35.62003 |
| Pattern 9 | 35.61157407 | 0.25 | 0.009989 | 35.59722 | 35.625 | 35.60442 | 35.61873 |
| Pattern 6 | 35.61041667 | 0.25 | 0.010122 | 35.59491 | 35.625 | 35.60317 | 35.61766 |
| Pattern 4 | 35.5287037 | 0.17 | 0.00818 | 35.51389 | 35.54167 | 35.52285 | 35.53456 |
| Pattern 3 | 35.39652778 | 0.03 | 0.008596 | 35.38657 | 35.41435 | 35.39037 | 35.40268 |
| Pattern 1 | 35.39351852 | 0.03 | 0.016477 | 35.3588 | 35.41204 | 35.38172 | 35.40531 |
| Pattern 2 | 35.36180556 | 0.00 | 0.01086 | 35.34722 | 35.38426 | 35.35403 | 35.36958 |

2. The result for $\mathbf{C V}(\mathbf{2}): \mathbf{0 . 3}, \mathbf{0 . 3 5}, \mathbf{0 . 4}$

|  | Throughput <br> PerHours | Difference <br> from <br> bottom | Standard <br> Deviation | Minimum | Maximum | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Pattern 8 | 28.34398 | 0.07 | 0.02411 | 28.31713 | 28.38194 | 28.32672 | 28.36124 |
| Pattern 11 | 28.34120 | 0.06 | 0.01181 | 28.33102 | 28.36806 | 28.33275 | 28.34966 |
| Pattern 10 | 28.33981 | 0.06 | 0.01154 | 28.32407 | 28.35880 | 28.33155 | 28.34808 |
| Pattern 5 | 28.33657 | 0.06 | 0.02959 | 28.29398 | 28.37731 | 28.31539 | 28.35776 |
| Pattern 6 | 28.33565 | 0.06 | 0.02474 | 28.28704 | 28.36806 | 28.31794 | 28.35336 |
| Pattern 7 | 28.33519 | 0.06 | 0.02360 | 28.29861 | 28.37269 | 28.31829 | 28.35208 |
| Pattern 4 | 28.32662 | 0.05 | 0.01717 | 28.30093 | 28.35648 | 28.31433 | 28.33891 |
| Pattern 9 | 28.31991 | 0.04 | 0.01854 | 28.30093 | 28.34954 | 28.30663 | 28.33318 |
| Pattern 3 | 28.29722 | 0.02 | 0.01925 | 28.26389 | 28.33333 | 28.28344 | 28.31100 |
| Pattern 1 | 28.28958 | 0.01 | 0.01522 | 28.26620 | 28.32176 | 28.27869 | 28.30048 |
| Pattern 2 | 28.27731 | 0.00 | 0.01842 | 28.25231 | 28.30324 | 28.26413 | 28.29050 |

3. The result for CV (3): $\mathbf{0 . 1}, \mathbf{0 . 2}, \mathbf{0 . 3}$

|  | Throughput <br> PerHours | Difference <br> from <br> bottom | Standard <br> Deviation | Minimum | Maximum | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Pattern 8 | 32.04768519 | 0.44 | 0.027696 | 32.00231 | 32.09259 | 32.02786 | 32.06751 |
| Pattern 10 | 32.04467593 | 0.43 | 0.023226 | 32 | 32.07407 | 32.02805 | 32.0613 |
| Pattern 5 | 32.01712963 | 0.41 | 0.029386 | 31.97222 | 32.0625 | 31.99609 | 32.03817 |
| Pattern 9 | 32.01365741 | 0.40 | 0.021727 | 31.97454 | 32.03935 | 31.9981 | 32.02921 |
| Pattern 6 | 32.01180556 | 0.40 | 0.022745 | 31.97685 | 32.04398 | 31.99552 | 32.02809 |
| Pattern 11 | 32.00717593 | 0.40 | 0.019776 | 31.9838 | 32.04861 | 31.99302 | 32.02133 |
| Pattern 7 | 31.99907407 | 0.39 | 0.015707 | 31.97222 | 32.03009 | 31.98783 | 32.01032 |
| Pattern 4 | 31.8900463 | 0.28 | 0.024985 | 31.8588 | 31.92593 | 31.87216 | 31.90793 |
| Pattern 1 | 31.65601852 | 0.05 | 0.021693 | 31.62037 | 31.69907 | 31.64049 | 31.67155 |
| Pattern 3 | 31.64861111 | 0.04 | 0.016067 | 31.61806 | 31.67593 | 31.63711 | 31.66011 |
| Pattern 2 | 31.61018519 | 0.00 | 0.012013 | 31.58565 | 31.62269 | 31.60158 | 31.61879 |

4. The result for CV (4): $\mathbf{0 . 2}, \mathbf{0 . 3}, \mathbf{0 . 4}$

|  | Throughput <br> PerHours | Difference <br> from <br> bottom | Standard <br> Deviation | Minimum | Maximum | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Pattern 8 | 29.40347222 | 0.26 | 0.021133 | 29.36111 | 29.43287 | 29.38834 | 29.4186 |
| Pattern 10 | 29.39699074 | 0.25 | 0.017262 | 29.36806 | 29.42593 | 29.38463 | 29.40935 |
| Pattern 11 | 29.39027778 | 0.24 | 0.029366 | 29.34722 | 29.43519 | 29.36925 | 29.4113 |
| Pattern 6 | 29.38425926 | 0.24 | 0.036175 | 29.33102 | 29.42361 | 29.35836 | 29.41016 |
| Pattern 9 | 29.38055556 | 0.23 | 0.01544 | 29.35648 | 29.40278 | 29.3695 | 29.39161 |
| Pattern 7 | 29.37800926 | 0.23 | 0.026641 | 29.34491 | 29.42361 | 29.35894 | 29.39708 |
| Pattern 5 | 29.37615741 | 0.23 | 0.028814 | 29.31944 | 29.41435 | 29.35553 | 29.39679 |
| Pattern 4 | 29.30439815 | 0.16 | 0.015287 | 29.27315 | 29.32407 | 29.29345 | 29.31534 |
| Pattern 1 | 29.175 | 0.03 | 0.032867 | 29.11343 | 29.22685 | 29.15147 | 29.19853 |
| Pattern 3 | 29.175 | 0.03 | 0.0215 | 29.1412 | 29.19907 | 29.15961 | 29.19039 |
| Pattern 2 | 29.1474537 | 0.00 | 0.025382 | 29.09722 | 29.17824 | 29.12928 | 29.16563 |

5. The result for CV (6): Weibull distribution $0.2,0.3,0.4$

|  | root.Throu <br> ghputPerH <br> ours | Differe <br> nce <br> from <br> bottom | Standard <br> Deviation | Minimum | Maximum | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Pattern 10 | 29.4 | 0.35 | 0.0247588 | 29.358796 | 29.435185 | 29.382275 | 29.417725 |
| Pattern 8 | 29.3914352 | 0.34 | 0.0200751 | 29.356481 | 29.412037 | 29.377063 | 29.405807 |
| Pattern 5 | 29.3722222 | 0.32 | 0.018831 | 29.326389 | 29.391204 | 29.358741 | 29.385704 |
| Pattern 6 | 29.3689815 | 0.32 | 0.0186531 | 29.349537 | 29.409722 | 29.355627 | 29.382336 |
| Pattern 11 | 29.3675926 | 0.31 | 0.0343828 | 29.30787 | 29.4375 | 29.342977 | 29.392208 |
| Pattern 9 | 29.3671296 | 0.31 | 0.0214167 | 29.337963 | 29.407407 | 29.351797 | 29.382462 |
| Pattern 7 | 29.3594907 | 0.31 | 0.0267748 | 29.31713 | 29.407407 | 29.340322 | 29.378659 |
| Pattern 4 | 29.2835648 | 0.23 | 0.018071 | 29.259259 | 29.310185 | 29.270627 | 29.296502 |
| Pattern 1 | 29.1166667 | 0.06 | 0.025526 | 29.074074 | 29.155093 | 29.098392 | 29.134941 |
| Pattern 3 | 29.1108796 | 0.06 | 0.0193194 | 29.081019 | 29.145833 | 29.097048 | 29.124711 |
| Pattern 2 | 29.0539352 | 0.00 | 0.0160022 | 29.030093 | 29.076389 | 29.042479 | 29.065391 |

6. The result for $\mathbf{C V}$ (7): Weibull distribution $\mathbf{0 . 3 , 0 . 5 , 0 . 9 9}$

|  | root.Throu <br> ghputPerH <br> ours | Differe <br> nce <br> from <br> bottom | Standard <br> Deviation | Minimum | Maximu <br> m | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Pattern 8 | 20.8377315 | 0.74 | 0.0684379 | 20.6875 | 20.912037 | 20.788735 | 20.886728 |
| Pattern 5 | 20.830787 | 0.74 | 0.0470926 | 20.787037 | 20.930556 | 20.797073 | 20.864502 |
| Pattern 10 | 20.8305556 | 0.74 | 0.0685366 | 20.740741 | 20.958333 | 20.781489 | 20.879622 |
| Pattern 7 | 20.8078704 | 0.71 | 0.0441773 | 20.724537 | 20.861111 | 20.776243 | 20.839498 |
| Pattern 9 | 20.7979167 | 0.70 | 0.1192376 | 20.581019 | 21.006944 | 20.712552 | 20.883281 |
| Pattern 6 | 20.7923611 | 0.70 | 0.0729079 | 20.625 | 20.884259 | 20.740165 | 20.844557 |
| Pattern 11 | 20.7763889 | 0.68 | 0.1006476 | 20.652778 | 20.93287 | 20.704333 | 20.848445 |
| Pattern 4 | 20.5680556 | 0.47 | 0.0612073 | 20.481481 | 20.69213 | 20.524236 | 20.611875 |
| Pattern 1 | 20.2553241 | 0.16 | 0.0886376 | 20.171296 | 20.409722 | 20.191867 | 20.318782 |
| Pattern 3 | 20.1886574 | 0.09 | 0.0841315 | 20.074074 | 20.305556 | 20.128426 | 20.248889 |
| Pattern 2 | 20.0939815 | 0.00 | 0.0823791 | 19.914352 | 20.212963 | 20.035005 | 20.152958 |

7. The result for $\mathrm{CV}(8)$ : Weibull distribution, $0.2,0.5,0.8$

|  | root.Throu <br> ghputPerH <br> ours | Differe <br> nce <br> from <br> bottom | Standard <br> Deviation | Minimum | Maximum | Left <br> interval <br> bound | Right <br> interval <br> bound |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Pattern 8 | 22.8923611 | 0.59 | 0.0577442 | 22.789352 | 22.949074 | 22.851021 | 22.933701 |
| Pattern 10 | 22.86875 | 0.56 | 0.0552229 | 22.789352 | 22.94213 | 22.829215 | 22.908285 |
| Pattern 7 | 22.8625 | 0.56 | 0.0535274 | 22.766204 | 22.923611 | 22.824179 | 22.900821 |
| Pattern 9 | 22.8615741 | 0.56 | 0.0244442 | 22.833333 | 22.912037 | 22.844074 | 22.879074 |
| Pattern 5 | 22.8416667 | 0.54 | 0.0565034 | 22.770833 | 22.918981 | 22.801215 | 22.882119 |
| Pattern 11 | 22.8405093 | 0.53 | 0.0349265 | 22.814815 | 22.921296 | 22.815505 | 22.865514 |
| Pattern 6 | 22.8349537 | 0.53 | 0.0637128 | 22.738426 | 22.916667 | 22.78934 | 22.880567 |
| Pattern 4 | 22.7046296 | 0.40 | 0.0661801 | 22.62963 | 22.821759 | 22.65725 | 22.752009 |
| Pattern 1 | 22.4127315 | 0.11 | 0.0599974 | 22.3125 | 22.511574 | 22.369778 | 22.455685 |
| Pattern 3 | 22.3828704 | 0.08 | 0.064189 | 22.256944 | 22.458333 | 22.336916 | 22.428825 |
| Pattern 2 | 22.3060185 | 0.00 | 0.0362704 | 22.24537 | 22.344907 | 22.280052 | 22.331985 |


[^0]:    ${ }^{1}$ These two premises, as two schools of thought in physics, were among highest striking subjects in early 20th century. Einstein was defender of first view (incomplete knowledge) and Bohr and others support second view (random universe). Proponents of first view, especially philosophers, criticize the opposite interpretation due to apparent violation of cause-and-effect principle. In return, the followers of the second view point to more fundamental quantities (that are not influenced by randomness: quantum numbers) as a description to the criticized violation.

