Influence of Worker Variability and Number of Workstations in Assembly Line Performance

The effect on cycle time and in the work-in-process

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Abstract: In current manufacturing industries, manual assembly lines play an important role. Assembly line often rely on human elements, thus, a large degree of variability between individuals manifested by the performance of human beings is important to be considered in assembly line. With the objective of studying the influence of workers’ task time variability, commercial software allows simulating these assembly lines. The use of Buffers, namely small inventories allocated between stations of the assembly line, pretend to solve problems related to the existing variability of processing times in different stations. With the objective of quantifying the effect of buffer on the cycle time and on the average level of work-in-progress, several experiments were carried out using the simulation software Simul 8. It is with this motivation that some simulations are created in Simul 8, which includes the simulator of five, fifteen and twenty-five stations, using variables such as CV, buffer size or task time as an integral part of discrete event simulation of the assembly line. The impact of them includes the achievement of cycle time, waiting and blocking time percentage. In addition, it enables managers and senior planners to carry out “what if” analysis to plan for future.

Keywords: assembly line, worker performance, buffer, discrete event simulation.

1. Introduction

In modern manufacturing industry, manual work is the main work force in assembling processes. Whereas a large number of studies have been devoted to analysing the flexibility of manual work, less attention has been paid to the disadvantageous influence of operator behaviour variability. When the assembly system is in operation, workers perform the assembly tasks with some degree of variability, since in one repetition the worker may be quicker and in the next slower. These variations are often disregarded in the early system design stage. Then become a serious problem of the system. Even for the workers who deal with same task with same average time, for every run, they are different from one another because of the deviation, there may be differences in the speed and consistency while performing assembly tasks, some workers might be slower and some might be quicker. Given the nature of manual processing it is worth to study the influence made by variability of operator., figure out what kind of relationship exist between some observable factors. This thesis is about the influence of variation given a representative condition, make assessments regarding the impact of worker performance variation on the output of the assembly line proposed. 5, 15 and 25 workstations lines cases are studied. Beyond this, buffer is applied into the simulation model, which is the intermediate storage area the product joins when a given workstation finishes the work.

2. State of the art

Some background and concepts are introduced, which is helpful to better understand this thesis. Firstly, assembling line, manual work and buffers are introduced as the basic background, secondly, worker’s variability is explained, thirdly, the discrete event simulation is discussed.

2.1 Assembly line

Fixed position layout (also called fixed product layout or project layout), process layout, product layout and cellular layout are four main types of manufacturing systems layouts.

Automation is sometimes implemented in many companies with wrong assumptions on their economic value and often in an inappropriate manner. According to Bley et al. [1], some companies that had invested in high automation have recognized that high automation are not
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Flexible enough, challenges such as fast changing demands, increasing number of variants, cannot be achieved with strategies of high automation. However, human operators are considered as major flexibility enablers, since they are able to quickly adapt to the changing products and market situations [2]. The worker ability to exchange between different workstations and to perform several assembly tasks is also a way of handling with the increasing demand for larger product variability. The extent of customization causes greater number of variants in the final assembly stage, so human workforce is mainly used on this stage due to the high flexibility they provide. Four methods can be considered in the design of an assembly system: manual assembly, semi-automated assembly, flexible assembly and fixed assembly.

At the beginning, fully automated factories were built in order to avoid the cost or variation problems caused by human presence, automation has been introduced in many companies with the false reason regarding return on investment. According to Bley et al. [1], there are proofs that such choice was not appropriate, then so a large number of industries that had invested a huge capital in automation and they have chosen to reduce their level of automation later.

2.2 Buffers

In production line, there are often equipped with additional devices afar from workstations and basic mechanisms for product transport. Buffers are areas of intermediate storage, which is used to collect the intermediate product (work in process) along the line. Usually, each station has a considerable time variation (different operation times) and it needs to maintain a large independence degree, so that its specific efficiency is not affected by fluctuations in production from the previous station. In order to prevent the lack of such independence cause a blockage in the manufacture, placing buffers between workstations (intermediate buffers) is an optimization problem of great importance that designers of these kinds of production systems face. An available buffer space needs to be distributed by intermediate buffers through effective positioning planning, Figure 2 presents the product’s pathway. By using buffers with the correct capacity and location in an automated production line, it is possible to reduce the losses of the entire system, achieving the required rate.

The buffers size has distinct impact on two cost types according to Battini et al. [3]: downtime of the machines (the presence of micro-faults, maintenance times, setup times, etc.) and WIP cost. Thus, the optimal buffers size corresponds to a multi-objective optimization as indicated by the graphic in Figure 3.

With the aim of minimum number of storage spaces required, buffers are required to uncouple operations and protect the production rate from fluctuations and variations. It is not strictly needed to allocate one buffer between each successive pair of operations considered the overall performance, because these are only needed to improve the overall performance of a production line [4].

2.3 Workers performance variation

Human factors are the main source of variability in the assembly system. The consideration of an average coefficient of variation, which could represent all of the operators, was not sufficient and the interest in variability between workers within a single type of job increased. Efforts were made in order to reduce this variability in many manufacturing and service companies from all over the world.

As described by Baugous [5], the workers typically are integrated in a system and their performance most often contributes to the performance of a system. Especially on an assembly line, the global performance of the system is determined by the output of every single operator. Namely, if any of these individuals vary their level of performance, the effect of such variation grows along the line passing through the sequent stations.
However, it is frequent to detect some designing hypothesis assuming that every operator performs the task with the same time, identical variability and under the same conditions, which might simplify the analyses but they can have a significant effect on the precision of system performance forecast.

### 2.4 Assembly line balance problem

Assembly lines consist in a sequence of tasks with operational processing time and a set of preceding relations. In order to get the best design that is available at the moment, the problem of deciding which features benefit most the final objective of the assembly line is called assembly line balancing problem (ALBP) [6]. Manufacturing a product on an assembly line requires dividing the total amount of work into smaller groups of elementary operations called tasks. Additionally, for technological and organizational reasons there are precedence constraints between tasks that must be respected.

![Figure 5 – Precedence graph and feasible line balance](image)

Precedence graphs show tasks in a visual and summarized way – see Figure 4. Each task is represented inside a circle with its task time indicated next to it, and all precedence constraints are represented by arrows.

In Figure 5 there are 10 tasks represented, the task times vary between 1 and 10 time units and, for example, task 5 can only start if tasks 1 and 4 (directly) and task 3 (indirectly) are completed. The precedence graph can create a basic assembly line balance problem. The time that a worker is waiting to pass the part to the next worker, being that the next worker is still occupied, is the blocked time. The starved time is when a worker has finished his/her job in the part and passes its part to the next but does not have another part available to start working again. The final solution will be an assembly line of 5 workstations with 11s of cycle time presented.

### 2.5 Discrete Event Simulation

There are several ways to study the behaviour of a system, understood as a collection of entities (workers and machines), which act and interact to achieve a certain logical order – see Figure 6.

As it is known that in practice, there are high costs associated with the real system and most often the target system that needs to be studied does not physically, so it is preferred to use mathematical model to study most of the time. Most existing systems that represent the real world are so complex that their mathematical formulation is virtually impossible. In these cases, the system should be studied using discrete event simulation, which allows modeling the behaviour of systems, with any degree of complexity and with a level of detail adjusted to each case. Therefore, as often in analytical models, there is no necessity for simplifying assumptions, as these simplifications can jeopardize the validity of these models, given its inadequacy in relation to reality [7].

![Figure 6 – Ways of studying a system](image)
3. Assembly line simulation model

The aim of this research is to study the influence of worker task time variability based on experimental data. In order to achieve this, several simulation experiments were carried out changing line length (number of workstations) buffer size (number of units per buffer) and task time. Influence could be figured out with the simulation data collected. Furthermore, with these simulation experiments is possible to assess the effect of worker variation and the impact of buffer (trying to soften this variability) on the assembly line Key performance indicators (KPI). Additionally, it is studied the critical buffer size or the proper number of working in process of assembly line.

3.1 Model

The model is a serial assembly line composed by 5 workstations at the beginning, Figure 7. Each workstation has one dedicated worker, and each workstation is intended to perform one indivisible operation. The part transfer between workstations is done asynchronously. This means that when the worker finishes the assembly tasks on his workstation, transfers it to the next workstation if it is starved (waiting for a part). If the next workstation is not waiting, is either working or blocked, then the workstation becomes blocked, the worker has to wait and cannot accept any other part. The first workstation is never starved, given that it has an unlimited resource of parts, and the last station is never blocked, since the storage for the last station is also unlimited. Note that, in a first approach, it is considered that there is not the possibility to buffer parts between workstations. Later on, line length, CV and buffer will be studied as the variable factor.

![Figure 7 - Representation of the assembly line](image)

The model for second section of study is a serial assembly line composed by n workstations and n-1 intermediate buffers – Figure 8. It is all the same with previous model except added buffers.

![Figure 2 - model of the serial assembly line with buffer](image)

In every simulation, every station performs tasks with identical average time in normal distribution, so as to study the influence of worker behaviour variation. In Simul 8, the model is developed using work entry point, work centre storage area and work complete - Figure 9. Work centre represents the workstations, storage area is the buffer, work entry point is the input and the work complete must be the output.

![Figure 9 Simul 8 model of the 5 WS assembly line with buffer](image)

3.2 Assumption and limitation

- The production line is a serial arrangement of n station. Each station can operate on one unit of a product at a time and has internal storage capacity for that unit.
- There are no overflows or lost parts.
- The first station is never starved, that is, there is always a work unit in front of station 1 waiting to be processed.
- The last station is never blocked. After the last station there is a final product inventory of unlimited capacity.
- No breakdowns occur in the production line, or equivalently, all breakdowns are already included in the processing time distributions.
- No defective parts are produced, or equivalently, all defective parts are already included in the processing time distributions.
- No transit time is required for the movement of work units between stations.
- Each work unit, upon entering the first station, must remain in the line and be completely processed before leaving the system (i.e. no misses).
- A station is starved if it is waiting for the next part to be processed and if upstream buffer is empty.
- A station is blocked if downstream buffer is full and this station is holding a finished part.

3.3 Experimental Design

In this work several assembly line configurations are considered:
- Line length: 5, 15 and 25 stations
- KPI: Cycle time, Work in Progress, Blocking and Starvation time

The line with five workstations with or without buffer will be the one more in-depth studied and conclusions about impact on cycle time, blocking and starvation time. All of the results found will also be analysed and compared with longer lines, which is 15 and 25. It will be evaluated how line length affects the cycle time, blocking and starving time by comparison between these different line lengths.

Then it comes to buffers section. By adding buffers to soften workers task time variability effect, that model with buffers repeat the impact study which is
analysed in the model without buffer. “Optimal buffer size or WIP number” analysis is a kind of experiment where a low amount of capacity is available over the line and it must be allocated in an optimal way through the stations. Depends on the length of the line, every possible buffer allocation is tested the impact on cycle time. At the end, by comparison, small impact is neglected and the optimal buffer size is found.

An addition study about the influence of different average task time on cycle time, blocking and waiting time is presented in the end. Task time will be the only single variable in 5 workstations model without and with buffer.

3.4 Model results stabilization

Given that workers can have different performances from variability, even with same average task time, for this behaviour to be simulated in the program, random numbers were used. For the study to be as realistic as possible every worker needed to have a random behaviour, respecting their normal distribution performance. Each sequence of random numbers is defined by a parameter named seed.

In order to make the result more convincing, it is necessary to simulate the assembling line to get an ideal simulation period, which the influence of random behaviour from seed is small enough to neglect. The preparing simulation model performed in Simul8 is characterized by the following basic settings, chosen as described in the following

• Warm-up period of 1 hour
• 1 run
• Average finish time of 15 seconds of each station
• Normal distribution with 5 seconds of standard deviation

The term warm-up designates the time one assembly line takes to really start working properly, meaning the line is steady and working without the influence of its empty initial state. 1 hour of warm-up period in this simulation is enough obviously considering the average 15 seconds task time of each station.

A stochastic convergence is when a sequence of random or unpredictable events can occasionally settle down into a behaviour, which usually happen under a large number. So, the random numbers, will influence the cycle time for a small produced parts. The value of the tc will have too large fluctuations to take any type of conclusion about its variability. This leads to a study to understand from which number of parts produced could minimize the fluctuation, so that the results are not dependent on the sequence of random numbers used. For this analysis a line with 5 workstations (as proposed) Using 5 different sequences of random numbers, called seeds, a graphic was obtained comparing the cycle time with the number of parts produced. The parts start with a simulation period of 600 minutes till 24000 minutes.(Figure 10)

when simulation period higher than 19200 minutes the assembly line production is stable. It is checked that the average cycle time of 19200min simulation period only changes in the third decimal place so that 19200 minutes of simulation period is stable. Also, there is no influence of different seeds in 10 runs of 5 stations and 10 runs of 15 stations in 19200 minutes of simulation period, it is safe to say that it is stable with 19200 minutes of simulation period.

4. Result analysis

In this chapter all of the analysis will be centred in the behaviour of the entire assembly line. It will be analysed an assembly line composed by five, fifteen and twenty-five workstations in order to understand the influence of variability and effects of the buffers over the line performance. cycle time. Blocking, starvation time, and average level of the buffer (WIP) are investigated and commented.

• Warm-up period of 1 hour
• 10 run
• Simulation period of 19200 minutes
• Average task time of 15 seconds (default)
• Normal distribution with 5 seconds of deviation (default)

4.1 Influence of variability

The simulation results of the 5 WS assembly line will be reported in order to assess the effect of the CV on cycle time and waiting & blocking time. Suppose all the operators’ performance are equal, following normal distribution. Figure 11

Figure 11 - Simul 8 simulation model of 5 work stations

In a first approach, a set of results about number of work completed were collected by Simul 8. (Table 1) With that, cycle time can be easily calculated. The result shows that when CV is equal to 0, the cycle time is 15s as
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Table 1 - Number of work complete and cycle time on CV for 5 work stations

<table>
<thead>
<tr>
<th>Std Dev(s)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>0</td>
<td>0.07</td>
<td>0.13</td>
<td>0.20</td>
<td>0.27</td>
<td>0.33</td>
<td>0.40</td>
<td>0.47</td>
<td>0.53</td>
<td>0.60</td>
<td>0.67</td>
</tr>
<tr>
<td>number complete</td>
<td>76800</td>
<td>72079</td>
<td>67906</td>
<td>64192</td>
<td>60862</td>
<td>57862</td>
<td>55142</td>
<td>52666</td>
<td>50412</td>
<td>48334</td>
<td>46421</td>
</tr>
<tr>
<td>cycle time</td>
<td>15</td>
<td>15.98</td>
<td>16.96</td>
<td>17.95</td>
<td>18.93</td>
<td>19.91</td>
<td>20.89</td>
<td>21.87</td>
<td>22.85</td>
<td>23.83</td>
<td>24.82</td>
</tr>
</tbody>
</table>

For the varies behaviours of workers, TC (cycle time) is decided by the slowest worker. Because CV is the factor to indicate how stable of the behaviour of worker, the possible slower behaviour could exist in the assembling line if CV increase, even though in this case, some workers may cost less than 15s to finish their single task, they need to wait the slowest worker to finish.
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It is nominally the blocking and waiting time of operator as the other aspect of the influence of variable. Because of the behavior variability, one operator probably has to wait for the former operator to finish and pass the product working in process, otherwise he has nothing to do but wait, which is waiting time of the operator. Oppositely, it happens that the former operator is blocked to pass the product to next operator when the next operator is working, which is blocking time for the former one. To understand the changes in blocking and waiting time 3 CVs were used: 1.67%, 6.67% and 20%. (Figure 13, Figure 14)

It shows the worker of the first position have 0 of waiting time because of unlimited arrivals and last one have 0 of blocking time because of availability of exit point. Higher level of CV responds to higher percentage of waiting time and blocking time. Focusing on one specific CV, the waiting time increases but blocking time decreases along the assembling line from the beginning workstation to the end workstation, because the waiting time accumulates continuously from beginning to end and blocking time accumulates form end to beginning. For the workstation 5, it need to wait for workstation 4, at the same time, workstation 4 need to wait for workstation 3, and so on. These make the end workstation keep the most percent of time spent on waiting. Inversed method on blocking time.

A linear trend attached helps to figure out the value of slope. (Figure 14, Figure 15) with adjustment on x axe. linear assumption is a good approximation and allows for a good fitting of slope with CV. Higher CV responds to the large absolute value of slope, because higher variance responds to wider range. (Figure 16, Figure 17) the value of slope on different CV is plotted, the trend line is very linear with R² = 0.99, from the test made, it is fortunately to conclude, CV have a linear impact on the gradient of workstation’s waiting or blocking time one by one form the beginning workstation to the end workstation.

4.2 Influence of variability VS line length

To understand the influence of line length on cycle time waiting and blocking time, 15 and 25 workstations studies are added. CV 33.33% is considered as a default value be set in waiting and blocking part.

Essentially, the number of line length is the number of workstation, cycle time usually depends on the slowest worker among the assembly line, thus, based on the condition that all of the workers with same average task time of 15s, for certain CV, the impact is more significant when there are more workers. - Figure 19. It is noticed that the slope of line increases with the increasing of line length.

Figure 19 - Cycle time comparison of 3 line lengths on CV

Figure 20 - Waiting time percent on CV of 5, 15 and 25 WS

Figure 21 - Blocking time percent on CV of 5, 15 and 25 WS

Figure 22 – Blocking and waiting time percentage of 25 WS

It shows the waiting time increases and blocking time decreases sharply in the head and tail. (Figure 20, 21) The important thing is the S shape in the figure becomes more obvious as the length increases to 25. That’s the point which didn’t observed in the case of 5 workstations with the limit of the length. Also, majority of workstations cost 15% to 25% of blocking time and 5% to 15% of waiting time because the points of 15 and 25 WS are intensive.

It must be noticed that the curves of blocking time and waiting time are symmetric. (Figure 25) sum of waiting and blocking line is a straight line around 29%. Which indicates 71% of time is distributed to the real working for every worker. This scenario shows for each workers, position makes no difference on real working percent.
4.3 Influence of Buffers VS Variability

The capacity of the buffer, in other words, the buffer size, is an important variable to be consider. The cycle time drops when buffer size increases to small size, more specific, size smaller than 7, then the decrease speed of cycle time is pretty low. The limitation of cycle time decreases to 15.06s when buffer size is set to be unlimited. (Figure 23)

![Figure 23 - Cycle time on buffer size of 5 WS](image)

Optimal production management aims to minimize work in process (WIP). Work in process requires storage space, represents bound capital not available for investment and carries an inherent risk of earlier expiration of shelf life of the products. A queue leading to a production step shows that the step is well buffered for shortage in supplies from preceding steps, but may also indicate insufficient capacity to process the output from these preceding steps. (Figure 24)

![Figure 24 - Cycle time on WIP of 5 WS](image)

Assembling line with buffer, the cycle time decreases because of the decrease of waiting and blocking time. Buffer level 1, 5, 10, 15 are selected to analyse waiting and blocking time in Figure 25 and Figure 26. It is found that the impact of buffer size from 1 to 5 is stronger than the rest case of buffer size is 10, 15. In the case of buffer size 10, the maximum waiting time and maximum blocking time percentage is less than 3%, which indicate in the view of whole line, this percent is pretty small, in other words, if the buffer size continues to increase, very little time could be save considering the maximum time percent is less than 3%, this point is verified in the case of buffer size 15. In conclusion, there is no doubt that efficiency of assembling line will increase when buffer size increase, however, it must be noticed that this impact is gradually weaker, thus, the cost of buffer and the effect of buffer need to be balanced to make a good decision. (Figure 27)

![Figure 25 - Waiting time of 5 WS with buffer of 1,5,10 and 15](image)

![Figure 26 - Blocking time of 5 WS with buffer of 1,5,10 and 15](image)

![Figure 27 - Value of slope on buffer size of 5 station](image)

4.4 Influence of Buffers VS Line Length

In this section, the simulation results of the assembly line will be reported with workers with 5 stations, 15 stations and 25 stations. Table 2 shows there is slight difference between different line length. cycle time decreases at the beginning rapidly, then it slowly decreases gradually, even unlimited capacity of the bin is set, the results of cycle time are 15.06, 15.12 and 15.16 for 5, 15 and 25 WS respectively. There is a point where influence afterwards is reduced significantly. For 5 and 15 workstations cases, the optimal buffer size is 7 and it is 6 for 25 workstations case since the reduction afterwards is less than 0.2 seconds.

Equally, to make it clear. Instead of a specific time, define reduction rate ≤ 1 as the criteria which is presented in the Table 3, the result is the same.

\[
\text{reduction rate} = \frac{t_{c_n} - t_{c_{n+1}}}{t_{c_n}}
\]
Table 2 - Cycle time comparison on different buffer size of 5, 15 and 25 WS (unit: s)

<table>
<thead>
<tr>
<th>Buffer Size</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>infinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 WS</td>
<td>19.91</td>
<td>19.28</td>
<td>18.54</td>
<td>17.7</td>
<td>16.76</td>
<td>16.23</td>
<td>16</td>
<td>15.68</td>
<td>15.64</td>
<td>15.54</td>
<td>15.14</td>
<td>15.12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 WS</td>
<td>20.98</td>
<td>19.97</td>
<td>18.71</td>
<td>17.9</td>
<td>16.39</td>
<td>16.7</td>
<td>16.7</td>
<td>15.77</td>
<td>15.64</td>
<td>15.54</td>
<td>15.14</td>
<td>15.12</td>
<td></td>
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</tr>
<tr>
<td>25 WS</td>
<td>21.21</td>
<td>20.08</td>
<td>18.68</td>
<td>17.25</td>
<td>16.47</td>
<td>16.07</td>
<td>15.84</td>
<td>15.69</td>
<td>15.59</td>
<td>15.52</td>
<td>14.56</td>
<td>15.16</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 3 - Cycle time reduction percentage comparison of 5, 15 and 25 WS (unit s)

<table>
<thead>
<tr>
<th>Buffer Size</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<th>9</th>
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<th>15</th>
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<tbody>
<tr>
<td>5 WS</td>
<td>3.20%</td>
<td>3.80%</td>
<td>4.50%</td>
<td>3.60%</td>
<td>4.90%</td>
<td>1.40%</td>
<td>2.00%</td>
<td>0.30%</td>
<td>0.60%</td>
<td>0.90%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 WS</td>
<td>4.80%</td>
<td>6.30%</td>
<td>4.30%</td>
<td>4.70%</td>
<td>3.90%</td>
<td>2.40%</td>
<td>1.40%</td>
<td>0.90%</td>
<td>0.60%</td>
<td>0.40%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 WS</td>
<td>5.30%</td>
<td>7.00%</td>
<td>7.70%</td>
<td>4.50%</td>
<td>2.40%</td>
<td>1.40%</td>
<td>0.90%</td>
<td>0.60%</td>
<td>0.50%</td>
<td>0.40%</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

WIP products number is an important factor need to be noticed during the experiment, buffer size decides the WIP capacity, the real WIP is the average current storage of the bin. One thing need to explain firstly, in reality, it is not possible to have an assembly line with unlimited buffer size, here the assumed unlimited buffer size is designed for finding the possible maximum number of WIP. Which is 211, 417 and 561 for 5, 15 and 25 WS. WIP products gives an option to worker that new product could be start no matter the former one is completely finished or not or the later one is waiting or not. This impact is huge in the beginning and become pretty weak after the certain point.

4.5 Influence of task time

Workstation of assembly line obtain different task time depends on the product, thus it is useful to study task time as a variable in this section by adding two other task times, 30s and 45s. all these three cases are based on 5 workstations assembly line with fixed CV of 33.33%. The aim of this part is to understand the influence of the task time on the cycle time, blocking and waiting time. So the task time is the only single variable during the 5 WS simulation, the rest parameter remains constant.

The data of the cycle time of each task time case is presented in the Figure 29. For all these three cases, the cycle time linearly increasing with the increasing of the CV, which confirm the conclusion in section 4.1 about the linear relationship. It must be noticed the slope increases with the increasing of task time. The explanation of that could be, for a certain fixed CV with a significant value, the variance increases with the increasing of average task time, the cycle time is considered that it is decided by the slowest worker which is related to variance of the worker behavior.
buffer maximum influence on cycle time is very significant. Compared to the condition with buffer size equal to zero, as the first point of lines - Figure 30, (0,19.91), (0, 39.81) and (0, 59.70), it can be calculated that approximate 25% of cycle time could be reduced by buffer

![Graph showing cycle time on buffer size of 5 WS with 15s, 30s and 45s task time](image)

**Figure 30 - Cycle time on buffer size of 5 WS with 15s, 30s and 45s task time**

5. conclusion

In this thesis, several simulation-based experiments were carried out on serial assembly lines composed by five, fifteen and twenty-five stations with and without buffers. From the simulations done with the five workstations line, it has been found that if the CV of work behaviour is large, the system cycle time is more affected, than in any other lower CV level, also noticeable is that, the influence of CV on system cycle time is linear, which means that this kind of influence is predictable. In such situation, waiting time and blocking time percent of each worker with different position is different. Waiting time percent is increasing along the assembly line position, blocking time percent is decreasing. The quantity of the waiting and blocking percent is also influenced by CV. Thus, CV of worker behaviour should be seriously take into account. Simulating assembly line composed of a higher number of stations than five has helped to confirm the results of 5 workstations related to CV. From the influence of line length increasing (15 and 25 workstations cases) analysis it can be concluded that if the line length increases, the cycle time is more affected. Moreover, the common point of 3 different line length cases is the sum of waiting and blocking time percent is almost equal along the whole position for each line.

As for the impact that buffers have to assembly lines in terms of cycle time and WIP, Longer the line, more the line needs high level of total buffer capacity to minimize cycle time Decision about optimal buffer size should be based on line length, cost of buffer, the improvement of cycle time. Task time variation have no impact on buffer, blocking and waiting time but influence cycle time.

In conclusion, the worker task time variability can have large impacts on the output performance of manually operated systems, and should be taken into account when modelling and managing tightly coupled systems. Having variation in the workers performances will inescapably affect the system performance. Consequently, it is recommended when performing simulations of systems which are manually operated, to consider CV level, possible line length, optimal buffer size, in order to have a more realistic output.

References


