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# Comparison of lean cellular manufacturing organization models: Multiple case study analysis

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## ABSTRACT

Cellular manufacturing represents a production system arrangement in which machines, tools, workers, and devices are grouped to produce a single product or a group of products with similar production requirements. By implementing cellular manufacturing, it is possible to significantly influence the elimination of the seven types of Lean waste: transport, inventory, unnecessary motion, waiting, overproduction, overprocessing, and defects. There are various models of a cellular manufacturing organization, and some of the most widely used and studied include the Toyota Sewing System, Bucket Brigades, Working Balance, and Rabbit Chase. This paper aims to present different types of lean cellular manufacturing organizations. By reviewing the literature, the advantages and disadvantages of individual types of cellular manufacturing will be systematized. In the practical part of the paper, the theoretical assumptions will be confirmed, and the impact and robustness of individual types of cellular manufacturing will be explored in different situations. Simulations were performed in real conditions on real products to demonstrate the efficiency of individual types of cellular manufacturing organizations depending on the duration of technological operations. The goal was also to examine the robustness of individual types of cellular organization in case of the absence of certain operators or insufficiently trained operators. The criteria used to compare different cellular models were productivity, non-conformance, WIP inventory, time to deliver the first correct piece, and flow time. Simulations were performed for the Toyota Sewing System, Bucket Brigade, Working Balance, and Rabbit Chase cellular manufacturing concepts. The simulation results indicate significant differences in the performance of individual concepts, where the difference in some criteria can reach up to 100%.

**Keywords**: Lean production, Cellular manufacturing, Hands-on simulations, Productivity, Toyota Sewing System, Bucket Brigades, Working Balance, Rabbit Case.

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## 1. Introduction

The cellular manufacturing organization is nowadays widely used in industry. Some authors divide this manufacturing organization according to the movement of the worker into walking worker (WW) organization and fixed worker (FW) organization [1]. The research on WW assembly systems is relatively young with not so many case studies regarding these topics [1]. According to this, WW is a recent concept that includes models like Working Balance (WB), Toyota Sewing System (TSS), Bucket Brigades (BB), and Rabbit Chase (RC).

The most commonly used type is Working balance (WB) in which the workload between operators is split equally. Each operator gets a different number of operations whose duration times when summed up are equal. This is impossible to achieve in most cases so usually production line is organized in a way of splitting the roles between operators so that the summed times of assigned operations are very close to one another. This usual approach has this major disadvantage and implanting other models known in the literature can often lead to better productivity than the WB model. In the literature, other models like TSS, BB, and RC are not analyzed and explained to a sufficient extent. There are not many studies regarding the topic of advantages and disadvantages of different models depending on type of the work. Great potential and need for comparative studies and simulations are hidden in specific questions such as productivity and quality output of the production line when one operator is missing, when the new operator starts working, when the number of operators is bigger than it is necessary etc. Studies in the literature mainly focus on mathematical models and numerical simulations of different lean cellular organizational models including some of these situations [2-4], but the imperfection of these simulations is that they cannot explain some effects that are not yet quantified. These effects are social loafing, learning curves, forgetting curves, the influence of tiredness, etc. The hands-on simulations performed in this work consider all these aspects to the possible extent and a conclusion regarding this is drawn and presented according to performed simulations.

## 2. Models of lean cellular manufacturing organization

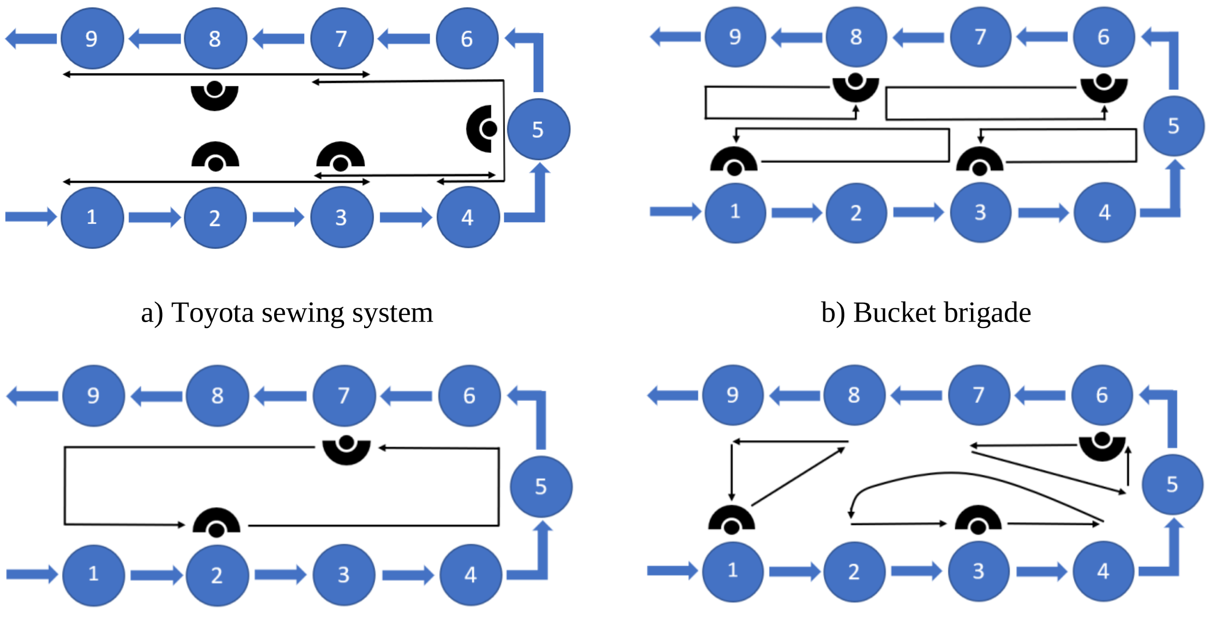
The cellular organization of production can be implemented based on any of the models used in the world today. The most commonly used models of cellular production are the Toyota Sewing System, Working Balance, Rabbit Chase, and Bucket Brigades. To select a model for implementation in the production process, it is necessary to know how each model works, and then what are the advantages and disadvantages of each model.

### 2.1. The functioning principles of different models

According to Black et al. [5] the TSS is a cellular production model which uses multifunctional workers in the cell that involves three to five workers operating 10 to 15 machines to produce a finished product or to prepare the product for further processing. It is known by this name because it was originally used to manufacture automobile seat covers for Toyota Motor Corporation [6]. This model is characterized by the arrangement of more workstations than operators who must be trained to perform different operations. Operators can be in a standing or sitting position and move from one workstation to another to complete operations. They move in a counter-clockwise direction and each performs several different operations, indicating that their location is not fixed. All operators work as a team and are fully responsible for production and quality. While working as a team, they take full responsibility for some operations while sharing responsibility with other operators in overlapping positions. This overlapping can occur at one or more operations. The last or more operations of one operator can be starting operations of the next one. This gives this model the ability to balance well and self-balance. Figure 1. shows examples of four different models of U shape production lines. For TSS, the situation with four operators is shown. The first operator performs operations of workstations 1, 2, and 3, the second workstations 3 and 4, the third workstations 4, 5, 6, and 7, and the last 7, 8, and 9. The overlapping workstations where the operators share responsibility are 3, 4, and 7.

In Figure 1. an example of the BB model is also shown. This model originates from the firefighting terminology used for the organization of human chain transport. Firefighters devised this model to organize people in a chain at a distance of one meter from each other and pass each other buckets of water or empty buckets that needed to be filled [7]. It also represents the behavior of ants in nature. When ants find a large amount of food in nature, they organize the transport of that food in a way of taking a small piece of it and walking in the direction of their nest. When the ant which is carrying some amount of food from the food source to the nest meets another ant walking in opposite direction to the food, the carrying ant passes the food to it and then it starts to walk to the food source again. The ant which received food walks back the in direction of the nest and passes food to the next ant it meets [8]. This organization model includes three basic phases, namely: taking over the workpiece from the previous operator, processing the workpiece along the line, and handing over the workpiece to the next operator. Each worker carries out the work from one station to another until he meets the next worker, then, he hands over the workpiece to the next operator and returns to take a job from his predecessor [9]. According to Roser [7] it is necessary to fulfill one of several prerequisites for a successful organization with this model:

- Short cycle times – reduction of waiting time due to the handover of the workpiece and avoidance of a complex handover process.
- Manual line flow – there must be a clear and identical sequence of steps for all pieces passing through the system, and processes should be manual, independent of machines.
- More operations than operators – operators perform different operations to balance the line.
- All operators trained for all operations – as operators move between different workstations, all should be trained for each operation (more precisely, only the first operator needs to know the first operation, and the last operator needs to know the last operation, but all the operators need to know operations between the first and last one).
- Nearby workstations – the further the workstations are, the more difficult it is to manage the BB.
- Uneven load – Bucket Brigade is a very suitable model for balancing uneven load.
- Bottleneck at the beginning – the first operation should be the slowest, and each subsequent operation should be faster.
- No buffer – buffers in combination with Bucket Brigades can lead to inefficient waiting times.




a) Toyota sewing system    b) Bucket brigade

c) Rabbit chase    d) Working balance

Figure 1. Operating models for U shape production line

RC is an organizational model for a manual production line, and it differs from other models because each operator does each of the operations, and there is no handover of the workpiece to the next operator [10]. In Figure 1 the situation with two operators is shown. Each of them moves with a workpiece from the beginning to the end of the production line, moving from one location to another to perform all required tasks [11]. When the process is finished, they take another piece and start over. The name comes from the fact that the faster operator pushes the slower one, which can be a problem because the speed of the system is limited by the speed of the slower operator. The theoretical number of operators can be as many as there are workstations. It is suggested that the number of operators should be less than the number of workstations because non-balanced work would lead to an increase in waiting losses. One operator would need to wait for the operator in front to finish his current operation so the previous one can start that operation.

Figure 1 bottom right corner shows the WB model. It is explained as a traditional cellular manufacturing model. The model in the figure is implemented with 3 operators. In this model, the load distribution is equal for all operators and they are assigned with similar total processing time operations. In this situation, operators are assigned with workstations and operations for which they are fully responsible.

In the literature, some authors are using the name Baton Touch (BT) for this organization model [7]. It is important to distinguish these two terminological expressions. Name WB is used when the assigned operations for the operator are in the sequence according to the workstation or operation number. For example, the first operator is performing operations 1, 2, and 3, the second one 4, 5, the third one 6, etc. The work distribution is not taking into account the possibility of allowing one operator to perform operations from the opposite side of the U-shape production line. The BT is used when operators are organized concerning total processing time but operations do not need to be in the sequence. The first operator can perform the first two and last operations, it is allowed to move from one side to another of the U-shape production line. Figure 1 is showing BT in the section where WB is presented but since the work balance or total processing time is the main request, the name WB is used in the further text uniting both of these expressions into one.

### 2.2. Theoretical assumption and literature review

Each of the models of the cellular organization of production has its advantages and disadvantages that should be analyzed to answer the questions of which model to implement in which situation, which model behaves better in which situation, and when which model will give the best results. In the literature, the most analyzed models for WW are WB and BB. In the research of Bartholdi et al. [12] BB is analytically studied on discrete workstations with stochastic times assuming the speed of each worker depends on only the worker. Wang et. al [13] expanded this study with the additional fact that the speed of the worker is not only affected by the worker itself but by the station and the job. The worker's speed may change with the job.

From the [12,13] one advantage of BB models which stands out is self-balancing. A line balancing will emerge spontaneously without the need for traditional industrial engineering technologies. Also, the simplicity of the BB makes it easy to implement and it often leads to the biggest productivity. Lim et. al. [14] when analyzing the performance of BB with hands-off times show that cellular BB is especially effective for a small team with work velocities close to walking velocities. It is more effective if each worker spends a short time per hands-off.

Armbruster et. al. [15] conclude that the advantage of BB is its very robust self-organizing principle. It self-organizes from optimal split workload assignment for all workers to optimally stable positions of the workers through switching rule and it allows workers to trade places. Alves [10] agrees with this adding that the disadvantage can be classifying operators based only on measure: their velocity, neglecting other measures. In addition to this, one more disadvantage is the delay that could occur when the operator takes over the product from his pre-processor.

Heizer and Render [16] single out as advantages of WB the achievement of a constant and continuous flow of production, elimination of excessive production losses, improvement of planning accuracy, encouraging the development of standardized work instructions to improve quality and efficiency, and setting goals for production in real-time, while accurately showing operators where they work and when they should complete their tasks. The authors also mention the disadvantage that this model is only useful for simple cells and may lead to inappropriate process design.

Alves [10] mentions the advantages of TSS as the allocation of operations to the operators is not fixed and they are not restricted to a work zone. It encourages autonomy and work responsibility promoting self-organization. The important thing which Alves [10] points out is that when the operator gets to the operation or the machine and the machine is blocked by the next operator, they put the workpiece in the decoupler between the workstations. Some authors like John et. al [17], are not considering the existence of decouplers which can be a negative characteristic of this model because it is what creates buffering between workstations since other operators have to wait for a slow operator. In addition, different operators are responsible for the first and last operation and there is no benefit of having the same operator controlling the input and output of the cell. Conway et al. [18] state that the purpose of storage space for workpiece in progress (WIP) is to provide the degree of independent action between workstations and explain that buffers were more necessary in balanced lines because in bottleneck systems the faster operators or machines tend to act like buffers.

Roser [7] points out several positive and negative sides of implementing the RC model. The RC model is simple to set up and manage, it has low stock quantities, fast delivery time, and clear responsibility that leads to better quality. The mentioned disadvantages by the author are that the slowest operator limits the speed of the system (as with most other models), possible mental pressure on the slower operator due to everyone else waiting for him, significant operator travel – each piece requires the operator to walk the entire line (but similar to many other models where workers walk), each operator must know how to perform all operations from the beginning, and training new operators can be difficult.

Besides these advantages and disadvantages of different models, some other theoretical assumptions also need to be tested. Filling the line when starting production for products with longer production times will lead to significant waiting losses. This drawback is the least pronounced in the RC model, more pronounced in the BB and the TSS, and the biggest losses will be in the WB model. In the case of an operation stoppage or equipment failure at one of the workstations, the line downstream of the stoppage operation will be emptied. In front of the operation where the stoppage occurred, there will be an accumulation of stocks. This situation will lead to line imbalance and queue loss. The biggest losses will be in the WB, then on the TSS and the BB, and the smallest losses will be in the RC model. According to this, the hypothesis which has to be proven is that different models perform differently in real case study situations for diverse product complexity.

## 3. Hands-on simulations of different models of cellular manufacturing organization

To make a comparison of different models of cellular production organization in the Lean Learning Factory laboratory (see Figure 2) at the Faculty of Mechanical engineering in Sarajevo, several hands-on simulations were performed by the students of the faculty. The experiment is organized by the students and supervised by the authors and the inexperience of the students leads to some expected problems similar to real industry conditions which are presented in this chapter. Each of the simulations was performed on different products and with different organization models, and based on the obtained results, a conclusion was drawn about the applicability of different models in different situations.

Figure 2. U shape production line in Lean Learning Factory laboratory where simulations were performed (Faculty of Mechanical engineering Sarajevo)

### 3.1. Hands-on simulation of the pen assembly line

The first simulation simulated the process of assembly of the pen in the organization of a U-shaped cell. The process consisted of 9 operations performed at 9 workstations. Figure 3 shows the ballpoint pen that was the subject of the simulation, as well as the appearance of its components.

The process simulation operations are as follows:

- Assembling the housing and the thrust part - workstation 1.
- Insertion of the working mechanism - workstation 2.
- Inserting ink cartridges - workstation 3.
- Setting the spring - workstation 4.
- Screwing the lid - workstation 5.
- Placing rubber grip - workstation 6.
- Bar code printing (the name of the pen color was printed on the bar code label) - workstation 7.
- Bar code setting - workstation 8.
- Quality control (visual control and control of the correctness of the mechanism and barcode) - workstation 9.

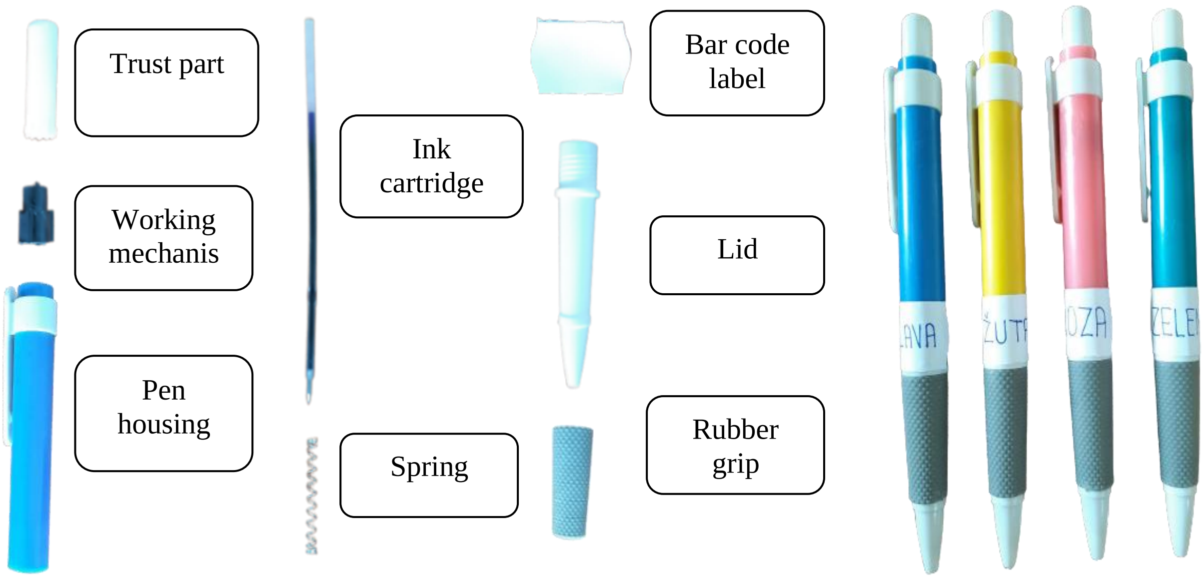



Figure 3. Pen together with its parts which assembly process is analyzed

The simulation participants were familiarized with the process before the start of the simulation, and then individually mounted the parts along the established line, while the duration of each operation was measured, including the time needed to move between workstations. Based on the measurement times, learning curves were formed for each of the operators. The learning curves are shown in Figure 4.

Each of the operators achieved a different level of training, and considering the starting times, the conclusion is that each one started with different knowledge and abilities, which can largely be related to situations in real production. It often happens that operators without work experience in similar jobs are employed in production, but also very often newly employed operators are those who are already experienced in these jobs. Therefore, it can be said that operators 1 and 2 already had more certain knowledge and abilities compared to operators 3 and 4. The first three operators, when assembling the twentieth pen, reduced the time by approx. 33% compared to the assembly time of the first pen, while the fourth operator reduced the same by 58%.

Variations in times were most often caused by difficult manipulation of small parts of the pen such as working mechanisms, springs, and barcodes. For further experiments and simulations, the same procedure is done until a satisfactory horizontal learning curve is obtained.

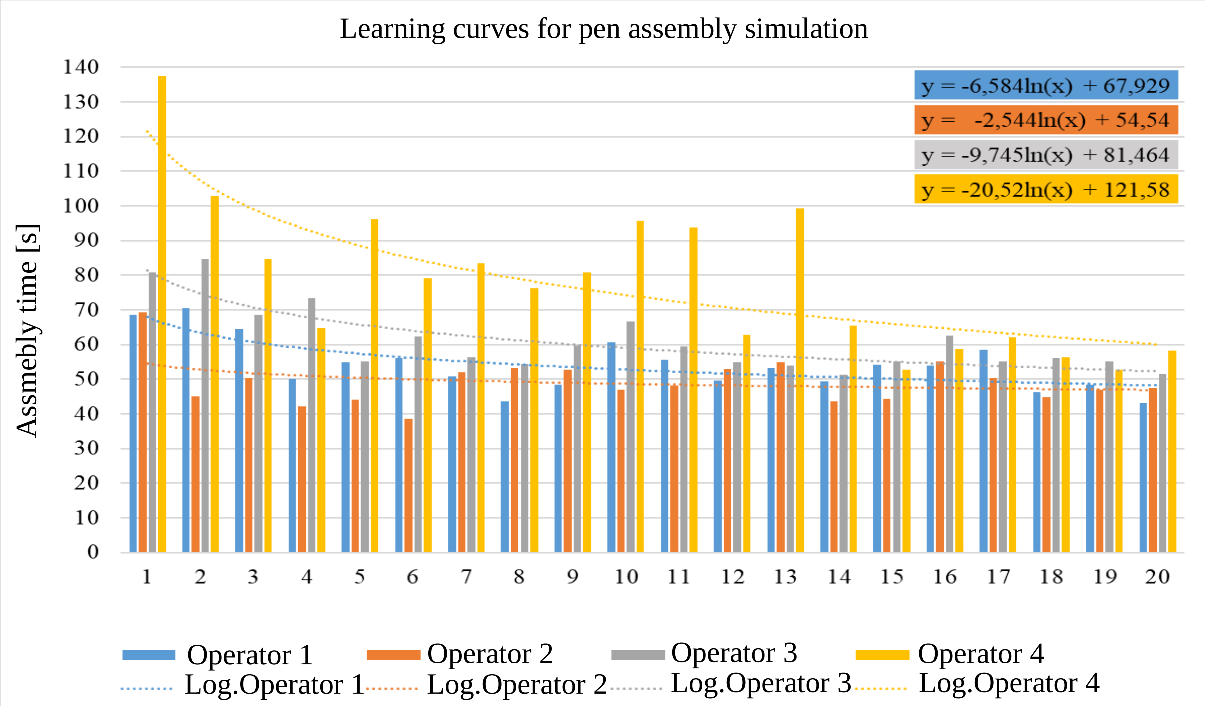



Figure 4. Learning curves of the pen assembly process

After the operators were trained, they reassembled the pens, and the times for each operation were measured, including the time required to move between workstations. The times recorded corresponded largely to the times achieved during training. Considering that the operators are trained and that the commitment coefficient is 1 (100%), the final times for each operation are standardized. The graph of average times for each operation is shown in Figure 5.

The total time for mounting one pen is standardized at 49.4 seconds. Operation 8, bar code placement, took the longest, averaging 9.3 seconds. This time represents the expected cycle time. Based on this, the delivery of 6.45 pens per minute is expected. Given that one operator can deliver 1.21 pens per minute, this indicates the need for 6 operators. However, for the simulations of the practical part of this work, work with 4 operators was chosen. Therefore, the new expected delivery becomes 4.84 pens per minute.

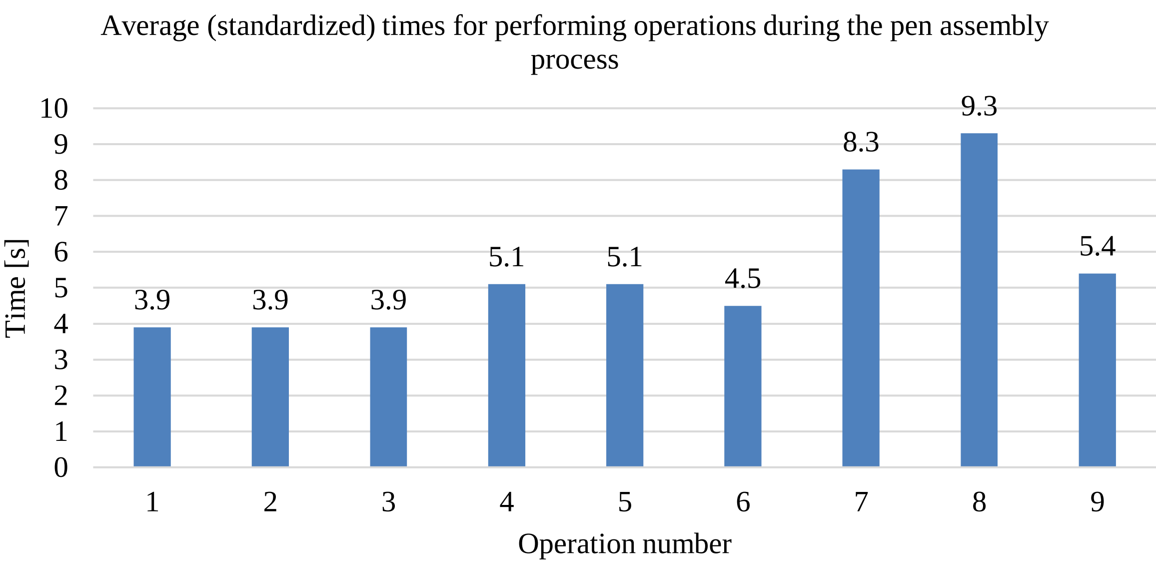



Figure 5. Average times for performing operations during the pen assembly process

The simulation of the Toyota Sewing System model was performed for 2 cases: a twenty-minute simulation with 4 trained operators and a five-minute simulation with 3 trained and 1 untrained operator. In Figure 6 top left corner the layout of operations assigned to individual operators for TSS is shown.

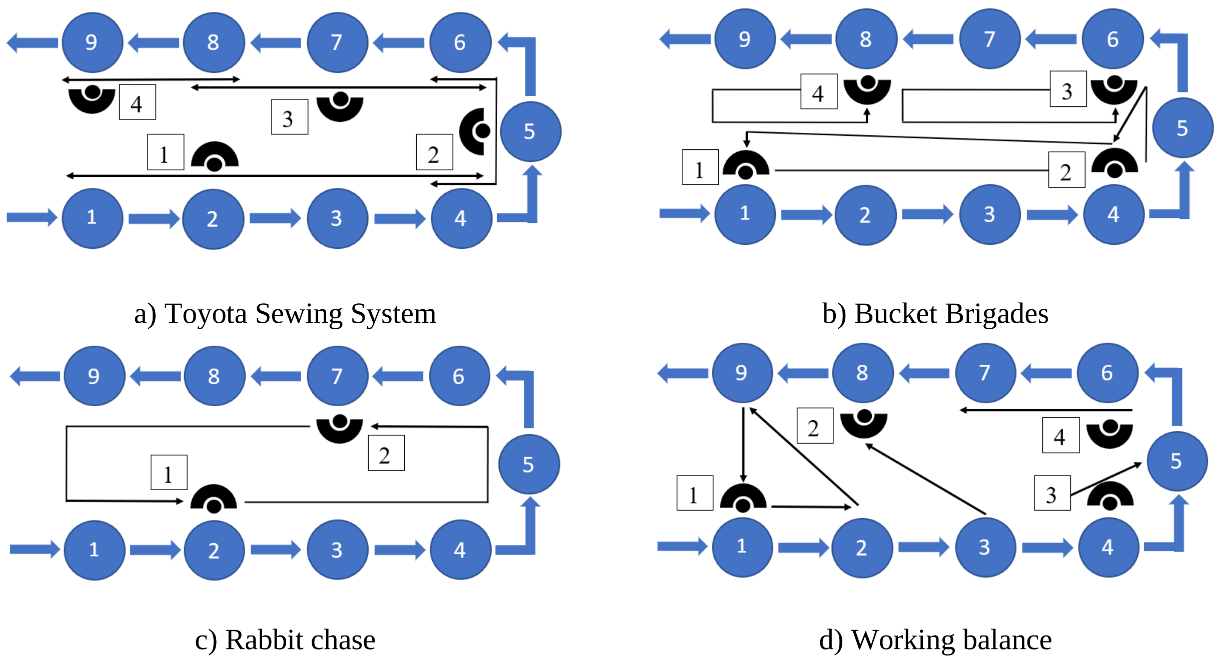



Figure 6. Distribution of operations between operators during pen assembly simulation for different models of organizations

The simulation of the BB model was performed for 3 cases, where 4 operators participated in the first two, and 3 operators in the third (the case of the absence of one of the operators). In the first case, the fastest operator is also the leader, while in the second case, this role is assigned to the slowest operator. The simulations of these two cases lasted 20 minutes each, while the third case was simulated for 5 minutes. In Figure 6 the initial layout of the operator during the simulation of the BB model is also shown. During the simulations of this model, buffers were not used, and the process of handing over the workpiece was not a problem, because the operations are mostly short-term and simple. Teamwork comes to the fore in this model, waiting times are minimized, and the process is fluid, but also dynamic with a lot of movement between workstations.

During the simulation of the RC model, the operators were divided into two groups, so that each group consisted of one faster and one slower operator. The way this model is organized is also shown in Figure 6 in the lower left corner.

The simulation of the Working Balance model was performed in 2 cases: a twenty-minute simulation with 4 trained operators and a five-minute simulation with 4 operators, one of which is untrained (the case of operator replacement due to absence). In Figure 6 the layout of operations as assigned to operators is shown. The schedule is made according to the measured times. According to the ideal layout, each of the operators should be assigned operations with a total duration of 12.345 seconds. However, this was impossible, so the layout of operations was created so that the operations performed by the first two operators take 13.2 seconds each, the operations performed by the third operator (the slowest) 10.2 seconds, and the operations performed by the fourth operator 12.8 seconds. According to all the above, the projected productivity is 93.5%.

Table 1. shows the summarized results of all simulations performed on the pen assembly. It shows different indicators of the model's performance. The analyzed indicators are productivity, WIP creation, and delivery of the signal product. It is important to mention that when calculating productivity, WIP is also included respecting the stage at which it is noticed. It is calculated in finished products so it can be also used in productivity calculation.

Table 1. Results of pen assembly simulations

| Model | TSS | | BB | | | RC | | WB | |
|---|---|---|---|---|---|---|---|---|---|
| Note | Four operators | | Four operators | | | Two operators | | Four operators | |
| | All trained | One not trained | Led by fastest | Led by slowest | Three operators | Group1 | Group2 | All trained | One not trained |
| Simulation time (min) | 20 | 5 | 20 | 20 | 5 | 10 | 10 | 20 | 5 |
| Finish products (pcs) | 70 | 19 | **80** | 81 | 16 | 18 | 21 | 59 | 11 |
| Defect pieces (pcs) | 3 | **0** | 2 | 2 | 2 | 2 | **0** | 3 | 1 |
| WIP at the end of simulation (pcs) | 13 | 2 | 2 | 4 | 3 | **0** | 1 | 11 | 5 |
| WIP in finished products at the end of the simulation (pcs) | 9,32 | 0,78 | 1,04 | 2,09 | 1,93 | **0,00** | 0,89 | 5,48 | 3,44 |
| Delivery time of the signal product (s) | 170 | 63 | 45 | 58 | **39** | 46 | 49 | 90 | 112 |
| Productivity (pcs/min) | 0,99 | 0,99 | 1,01 | **1,04** | **1,20** | 0,60 | 0,73 | 1,07 | 0,96 |

The simulation results of productivity show that in the case of using the BB model, it is better to organize the process so that it is led by the slowest operator. Although teamwork is best expressed in this model, it was noticed that the slowest operator does the work faster because he is under pressure. This is an individual matter, which does not depend on the model but on the operator. However, it is important to note that even in the case when the process is led by the fastest operator, the productivity is not significantly lower.

If the defective pieces are analyzed, there were no defective pieces in even 1 out of 2 simulations of the RC model. This is of course expected. RC is a model in which each operator has full responsibility for the complete product because he processes it along the entire line. That is why an expected increase in the attention of operators and the prevention of defective pieces. There were no defective pieces even in the simulation of the TSS model in the case when one of the operators was replaced by an untrained operator. However given that the mentioned simulation lasted 5 minutes, the relevance of such a result is questionable. If the process is impossible to organize according to the RC model (too many operations/workstations, ...), and defective pieces are the most important characteristic, then in this case it is best to use the BB model, regardless of whether the process is run by the fastest or the slowest operator.

The shortest delivery time of the signal product is achieved during simulations of the BB model with three operators. When considering BB, the delivery time of the signal product does not depend only on the speed of the operator, but on the organization of the process. Comparing the situation with three operators with those with four, it is better to use the BB model with one less operator.

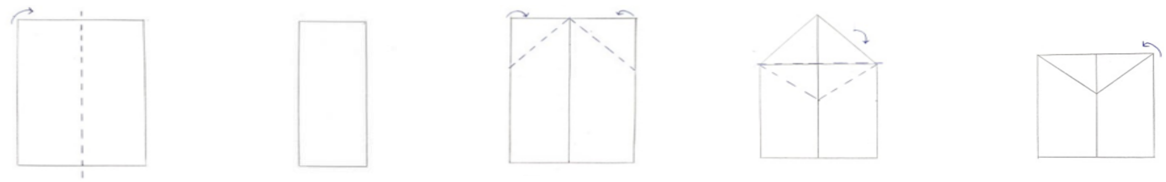
Productivity results are one of the most important indicators of the production process. Comparing different productivity results it can be seen that once again BB with three operators gives the best results proving that the WB is not the best option to use in the production process besides it is most often used in practice.

### 3.2. Hands-on simulation of the paper plane making process

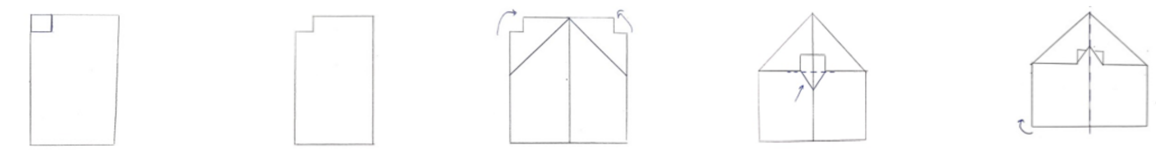
The second simulation performed is a paper plane making game. The simulation has 15 different operations which are performed on 8 workstations. Every two operations were performed at one workstation. The first two operations at the first workstation, the second two at the second workstation, and continuously to the last workstation eight where only operation 15 was performed. The operations are shown in Figure 7.

The steps of process simulation are as follows:

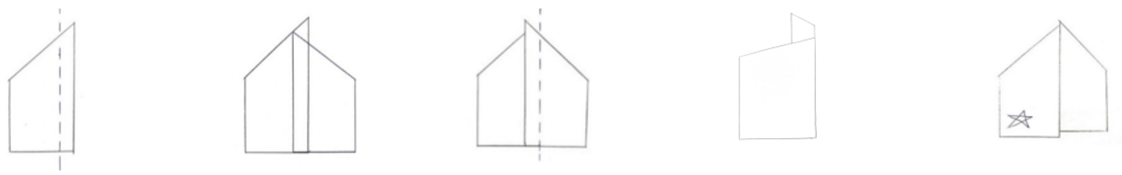
- Fold in half - workstation 1.
- Open paper - workstation 1.
- Fold two corners to the center - workstation 2.
- Fold point down - workstation 2.
- Fold paper in half - workstation 3.
- Cut or tear square from the corner - workstation 3.
- Open paper - workstation 4.
- Fold corners down to the center - workstation 4.
- Fold the original corner up to cut slot -workstation 5.
- Fold paper in half – workstation 5.
- Fold half of the paper along the line to form wing-workstation 6.
- Turn paper over - workstation 6.
- Fold along the line to form the second wing - workstation 7.
- Bend back wings a bit to create air-whether vehicle - workstation 7.
- Drawing star to the correct position using star model - workstation 8.



1. Fold in half | 2. Open paper | 3. Fold two corners to center | 4. Fold the point down | 5. Fold the paper in half



6. Cut or tear a square from the corner | 7. Open paper | 8. Fold corners down to the center | 9. Fold the original corner up to cut slot | 10. Fold the paper in half



11. Fold half of the paper along the line to form a wing | 12. Turn paper over | 13. Fold along the line to form the second wing | 14. Bend back wings a bit to create an air-whether vehicle | 15. Drawing star to the correct position using a star model

Figure 7. Operations of the paper plane making process

The simulation group is organized according to the average times for performing each of the operations shown in Figure 8. These times are obtained while training the operators for different operations. All operators were trained for all operations until a satisfactory horizontal learning curve was achieved and the times were calculated as the average of all operators for every specific operation. The total time for producing one paper plane is 56,3 s. Figure 8 shows that the bottleneck of the simulation is operation 15 or drawing the star to the correct position using the star model. This is expected tact time of 13,71 s. According to this, the delivery of 4,38 paper planes per minute is expected. However, simulation was performed with a number of operators ranging from 2 to 5.

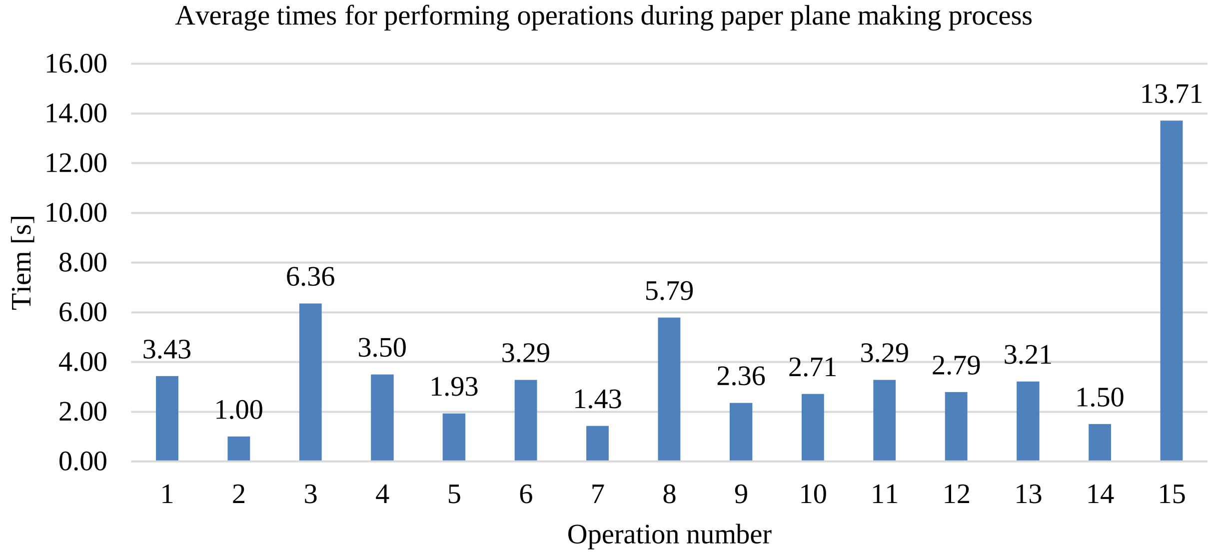



Figure 8. Average times for performing operations during the paper plane making process

The simulation group performed a simulation of TSS, BB, and WB with 5 operators. In addition to that, the simulation of RC is done with 2 operators, and one more BB is performed with 3 operators. Group organization is shown in Figure 9. It represents different models of organization with workstations from 1 to 8. For TSS operator 1 was performing operations from 1 to 4 (workstations 1 and 2), operator 2 operations from 3 to 8 (workstations 2,3 and 4), operator 3 operations from 7 to 12 (workstations 4,5 and 6), operator 4 operations from 11 to 15 (workstations 6,7 and 8), and the last operator operation from 13 to 15 (workstations 7 and 8). Overlapping workstations are 2,4,6,7 and 8. For WB operator 1 was performing operations 1, 2, and 15, operator 2 operations 3 and 4, operator 3 operations 5,6 and 7, operator 4 operations 8,9 and 10, and last operator operations from 11 to 14. The starting configuration of BB is shown in the figure but after a couple of minutes of simulation, the assembly line led to self-balancing. And finally, RC was performed with two operators who showed the best operating skills. The additional BB simulation with 3 operators is not shown in the figure, since it is organized in the same way as with four, and when the simulation is in progress starting configuration will be rearranged.

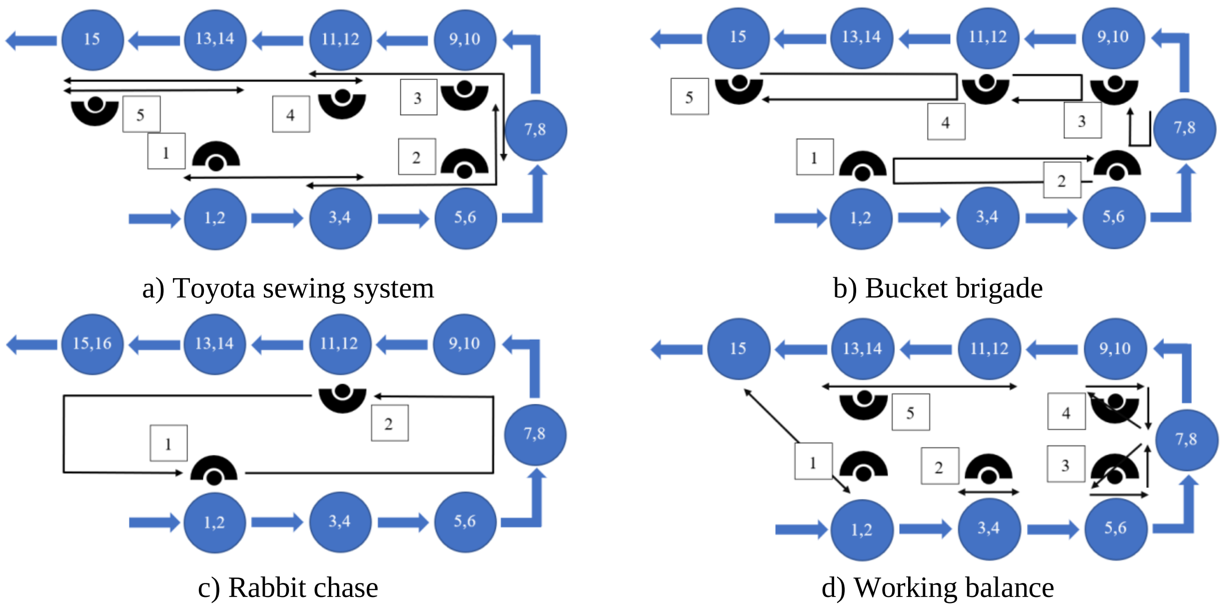



Figure 9. Distribution of operations during paper plane production simulation for different models of organization

The results of these simulations are presented in Table 2. The same indicators were analyzed as for the pen assembly simulation. The only difference between these simulations is that with a paper plane different set-up of the production line is applied. For the simulation of TSS, BB, and WB with 5 operators, the production line was filled with WIP. Every operation had already placed WIP on it. In the case of BB with 3 operators, the assembly line had WIP prepared on operations 1, 8, and 14, and in the case of RC, operations 1 and 8 had WIP prepared. This is the reason why Table 2 has WIP in finished products at the beginning and at the end of the simulation presented. Due to this, the effect of the pre-filled production line is analyzed.

Table 2. Results of paper plane making simulations

| Model | TSS | BB | | RC | WB |
|---|---|---|---|---|---|
| Number of operators | 5 | 5 | 3 | 2 | 5 |
| Simulation time (min) | 7 | 7 | 7 | 7 | 7 |
| Finish products (pcs) | 35 | **38** | 21 | 13 | 29 |
| Defect pieces (pcs) | 3 | 7 | 1 | 1 | **15** |
| WIP at the end of simulation (pcs) | 5 | 4 | 3 | 2 | **10** |
| WIP in finished products at the beginning of the simulation (pcs) | 6,73 | 6,73 | 1,47 | 0,61 | 6,73 |
| WIP in finished products at the end of the simulation (pcs) | 1,97 | 2,04 | 1,16 | 1,00 | 4,59 |
| Delivery time of the signal product (s) | 100 | 52 | 57 | 94 | 114 |
| Productivity (pcs/min) | 0,86 | 0,95 | **0,99** | 0,96 | 0,77 |

All simulations were performed for 7 minutes resulting in different performance indicator values. Looking at finished products, BB with 5 operators gave the best results of 38 pieces, followed by TSS, WB, BB with 3 operators, and RC, respectively.

Analyzing the results of defective pieces produced, it is noticed that WB has many more defective pieces compared with other simulations. This is explained with two facts. First, WB was the first simulation performed and the group was not well organized and prepared, and second, the group had a bad star model for operation 15. These two reasons led to an increased number of defective pieces.

It is expected that RC can have a maximal 2 WIP, BB 5, and 3 with respect to the number of operators. RC has 2 WIP since the simulation stopped while both operators were working on their pieces. The same situation is with BB with 3 operators. In BB with 5 operators, the last one finished his piece at the moment when the simulation stopped, and that explains WIP is equal to 4, not 5 as expected. TSS and WB are creating WIP according to how well the production line is balanced. Based on this, WB has 10 WIP at the end of the simulation and this confirms the impossibility of perfectly balancing WB in most cases. This resulted in the biggest number of WIP created.

When calculating the productivity, finished products together with WIP at the simulation end subtracted by WIP at the beginning of the simulation concerning the length of simulation multiplied by the number of operators is used. This took into account production line pre-fill. According to this, all simulations show greater productivity compared with WB. The best result is noticed in BB with three operators. RC shows slightly better results compared with BB with 5 operators since RC is performed with the two best and fastest operators.

### 3.3. Hands-on simulation of the torch assembly line

The last performed simulation was torch assembly. Following previous simulations, it was also performed in the U-shape production line. It had eight operations shown in Figure 10 distributed on 5 workstations. The first and the last operations were performed on the first and last workstations, and further every two following operations were distributed per workstation.

The steps of process simulation are as follows:

- Fit the rounded part of the metal ring downwards - workstation 1.
- Inserting the bulb - workstation 2.
- Screwing the torch contactor onto the bulb holder - workstation 2.
- Inserting the glass inside the previously prepared part - workstation 3.
- Screwing the bulb from operation three with the part from the previous operation - workstation 3.
- Putting an elastic band of the appropriate color on the body of the torch - workstation 4.
- Inserting batteries properly - workstation 4.
- Assembling parts of the corresponding color - workstation 5.

Figure 10. Operations for torch assembly simulation

Torch assembly simulation was performed by two groups. Participants in both groups first got through the learning process until satisfactory horizontal learning curves were obtained. Times were measured for each operation and operator, and after that, average times for performing operations during pen assembly were calculated. The times are shown in Figure 11. According to this, the total time for producing one torch is 20,21 s. In Figure 11 can be seen that tact time is equal to the longest operation and that is operation 1 lasting 4,12 s. Due to this, the expected delivery is 14,56 torches per minute.

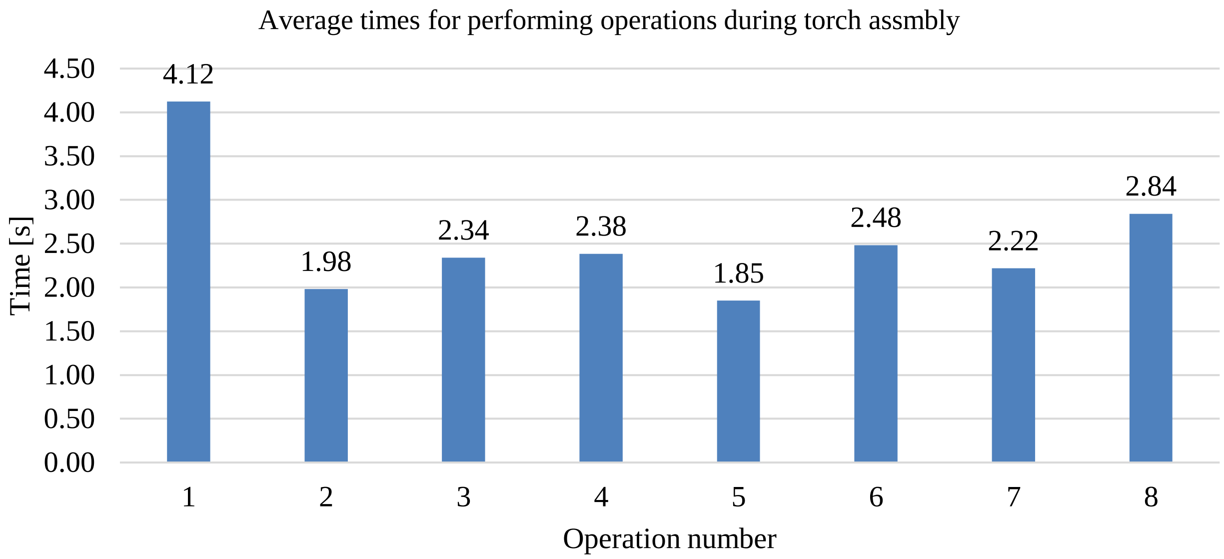
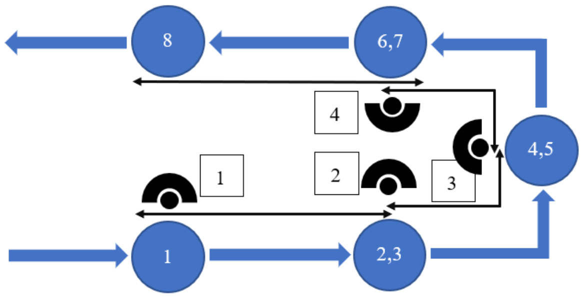
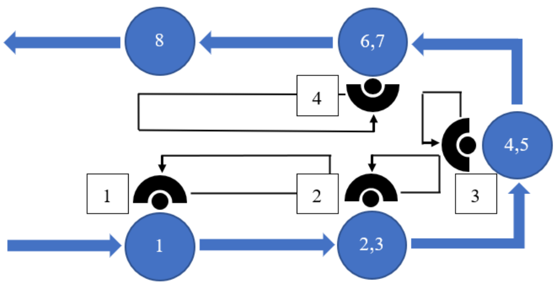



Figure 11. Average times for performing operations during torch assembly simulation

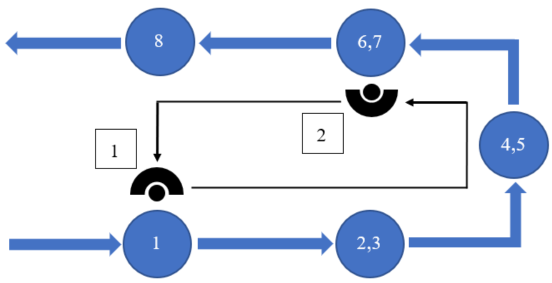
Simulations were performed for TSS, BB, and WB for 4 operators, BB for 3 and 2 operators, and RC for 2 operators. The stated configuration of simulations with 4 operators is shown in Figure 12. In TSS, operator 1 was performing operations 1, 2, and 3, operator 2 operations 2,3, and 4, operator 3 operations 4,5 and 6, and operator 4 operations 6, 7, and 8. Indicating that overlapping operations were 2, 4, and 6. The starting configuration of BB with 4 operators is shown in the upper right corner of Figure 12 and after some time passed, this starting arrangement was self-balanced. The figure also shows RC with 2 operators and WB with 4 arranged in a way so that each operator has the length of operatories equal to or close to 5,3 s.



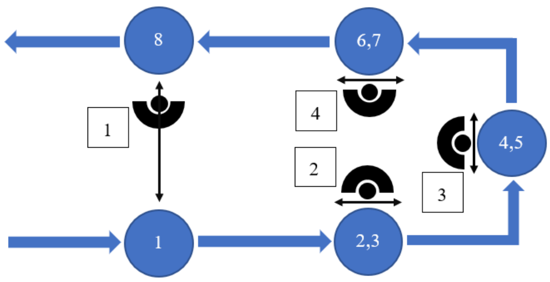

a) Toyota Sewing system




b) Bucket Brigades




c) Rabbit case




d) Working Balance

Figure 12. Distribution of operations between operators during torch assembly simulations for different models of organization

Table 3 shows the summarized results of all simulations performed on the torch assembly. The two groups performed the same simulations so results can be compared and analyzed. The difference from previous product assembly simulations, in the torch assembly process, defective pieces in the process were recorded. They were also calculated in productivity according to the same procedure performed for WIP in previous products. According to this, WIP and defective pieces in the process concerning the stage/operation at which they were noticed are calculated in finished products and used in productivity calculation. The production line was empty at the simulation start, so there was no WIP before the simulation took place. WIP at the end, together with finished products and defective pieces in the process resulted in productivity with respect to simulation time and number of operators.

Table 3. Results of torch assembly simulations

| Model | TSS | | BB | | | | | | RC | | | | WB | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Note: Number of operators | 4 | | 4 | | 3 | | 2 | | 2 | | 2 | | 4 | |
| Note: Groups | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Simulation time (min) | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| Finish products (pcs) | **36** | 31 | 34 | 32 | 35 | 31 | 31 | 24 | 21 | 22 | 27 | 25 | 23 | 26 |
| Defect pieces (pcs) | 3 | 2 | **10** | 5 | 7 | 3 | 5 | 3 | 7 | 4 | 6 | 2 | 2 | 3 |
| WIP at the end of simulation(pcs) | 3 | 4 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 2 | 1 | 7 | 2 |
| WIP in finished products (pcs) | 1,49 | 1,11 | 1,16 | 0,84 | 1,93 | 0,74 | 0,75 | 0,30 | 0,75 | 0,54 | 1,29 | 0,75 | 4,06 | 0,95 |
| Defective pieces in progress (pcs) | 1 | **15** | 1 | 6 | 0 | 3 | 1 | 4 | 0 | 4 | 0 | 3 | 5 | 4 |
| Defect pieces in progress in finished products (pcs) | 0,75 | 3,16 | 0,75 | 1,42 | 0,00 | 0,61 | 0,75 | 0,91 | 0,00 | 0,91 | 0,00 | 0,61 | 2,44 | 1,67 |
| Delivery time of the signal product (s) | 68,00 | 40,00 | 43,17 | 43,58 | 26,29 | 29,00 | 23,44 | 24,39 | 40,40 | 41,54 | 22,92 | 26,59 | 66,00 | 44,00 |
| Realization of production (pcs) | 38,24 | 35,27 | 35,91 | 34,26 | 36,93 | 32,35 | 32,50 | 25,22 | 21,75 | 23,45 | 28,29 | 26,36 | 29,50 | 28,63 |
| Average of the realization of productions (pcs) | 36,75 | | **35,08** | | **34,64** | | **28,86** | | 22,60 | | 27,32 | | 29,07 | |
| Productivity (pcs/min) | 1,37 | 1,26 | 1,28 | 1,22 | 1,76 | 1,54 | 2,32 | 1,80 | 1,55 | 1,67 | 2,02 | 1,88 | 1,05 | 1,02 |
| Productivity average (pcs/min) | **1,31** | | **1,25** | | **1,65** | | **2,06** | | **1,61** | | **1,95** | | **1,04** | |

Taking a look at Table 3, most finished products were achieved in the TSS simulation of Group 1 directly influencing productivity. Comparing this TSS simulation productivity with BB and WB with 4 operators, a couple of conclusions can be drawn. First, it is expected that WB will give the worst results which is confirmed both individually by comparing Groups 1 and 2 performances for different simulations, and as the average of the two groups for different simulations. Second, is expected that BB with four operators will give better productivity than TSS, but TSS led to better results. In TSS operators are dominantly distributed on the operations they are trained for sharing a relatively small number of operations with others, while in BB operators have to be well trained for every operation which in this case, they were not well prepared for other operations additional to those they usually do. This unlimited flexibility of BB can lead to breakage of the starting layout and workers can do operations they do not have much experience with.

The torch pieces prepared for assembly have pre-defected pieces and that explains why some simulations have increased the number of defective pieces which is the case for BB with four operators for Group 1, and also TSS simulation with 4 operators for Group 2 referring to defective pieces in the process.

BB with 3 and 2 operators and RC with 2 operators gave expected better results compared with WB. As the number of operators decreased, better operators were engaged in simulations, and those who showed weaker performance were left out, with this the full potential of every simulation came to the fore.

If the analysis of the results is only focused on BB with different numbers of operators one interesting effect is noticed. It is expected that with the number of operators working, the realization of production will also increase, and if the operators' number increases linearly production realization will also increase linearly. This is not the case with simulations of BB with 2,3 and 4 operators. Figure 13 shows the average realization of production of groups 1 and 2 for BB simulations in addition to the realization of production obtained for one operator working alone on the torch assembly. The non-linear behavior with the slope decreasing with the number of operators increasing can be explained by social loafing. It is defined as the reduction of individual effort when participating in a group [19]. This reduction in the literature is known as the Ringelmann effect. Many authors based their research on this effect according to the research of Moede [20] and it was thought that Ringelmann was the Moedes student. The work on social loafing was initiated by Ingman et. al. [21] who followed Moede [20]. Kravitz et. al. [22] found the real origin of this effect in the research of Ringelmann [23]. Ringelmann [23] discovers that individual group members tend to become less productive as the group size increases. This can be seen in the simulation of BB with a different number of operators shown in Figure 13. The figure shows an expected realization of production with the number of operators increasing and the Ringelmann effect noticed for obtained results for the realization of production. The two main reasons for this behavior that can be emphasized are loss of motivation and coordination problems.

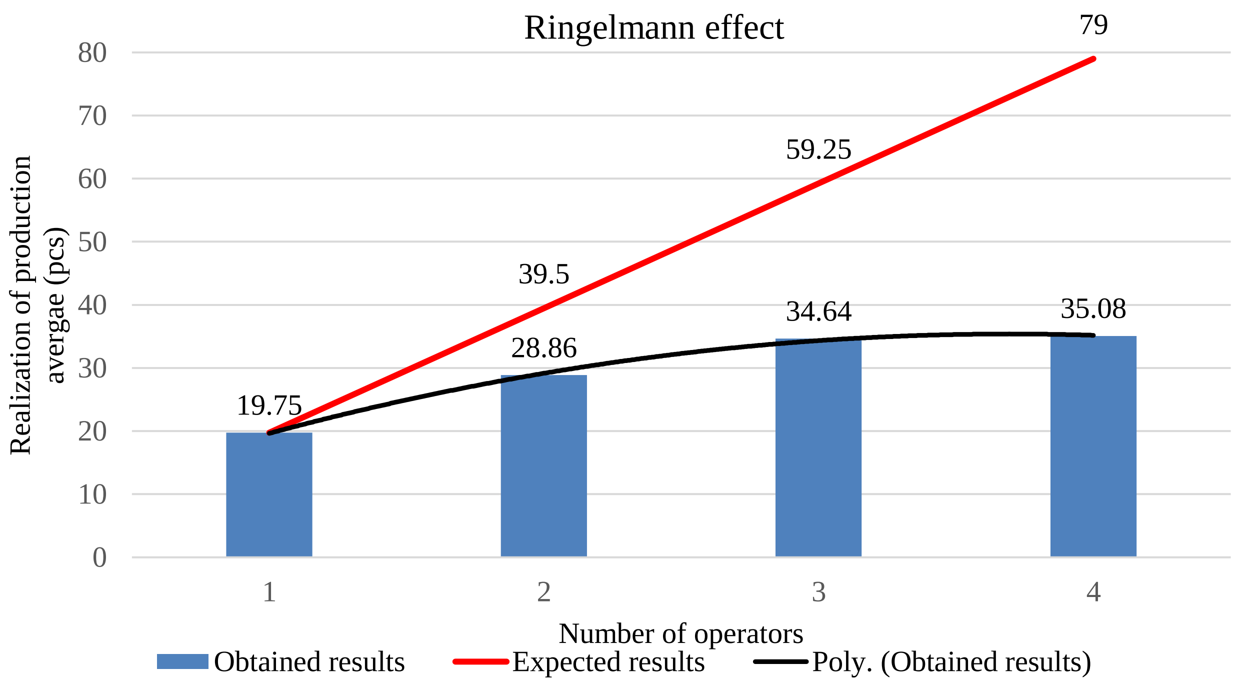



Figure 13. Ringelmann effect in BB

## 4. Discussion

According to the obtained results from all the case studies going from the simplest to the more complicated, the advantages and disadvantages of different lean cellular manufacturing models are presented in Table 4. It shows a summarised review with grading of how each model behaves in different situations from the lowest (+) to the biggest grade (++++).

Table 4. Summarized review of lean cellular manufacturing organization models

| Models | WB | TSS | BB | RC |
|---|---|---|---|---|
| WIP | + | ++ | +++ | ++++ |
| Balancing | + | +++ | ++++ | ++ |
| Polyvalence | ++++ | +++ | ++ | + |
| Teamwork | + | +++ | ++++ | + |
| Operator missing | + | ++ | ++++ | ++++ |
| Untrained operator | + | ++ | ++++ | + |
| Training new operator | + | ++ | +++ | + |
| Waiting loss | + | +++ | ++++ | + |
| Walking loss | ++++ | +++ | ++ | + |

Analyzing WIP creation between the models, in WB the amount of WIP created is the biggest, and due to that it has the lowest grade. In RC WIP creation has the best grade since the WIP number is equal to the number of operators, and TSS and BB are in-between respectively. WIP in WB is created due impossibility of perfectly balancing the line according to the time required to produce one product. In BB upper level of the WIP amount is equal to the number of operators while in TSS WIP can be created more due to insufficient balancing and bottlenecks.

BB shows the best results in balancing since it is a self-balancing model and it will balance after some time. TSS is below BB since the model has some limitations while balancing with the implementation of one, or more overlapping operations. WB is the hardest model to balance. In most cases, it is impossible to divide operations between operators so they have all the same working times. RC has the disadvantage of the faster operator being slowed down by the slower one, but it is expected that the slower one will speed up due to pressure introduced by the faster one.

When analyzing polyvalence, WB gives the best results since it can be used in many different situations. It is followed by TSS, BB, and RC respectively. These types have some limitations when implemented according to many different parameters.

In WB all operators are doing only operations they are trained for, and in RC all operations are performed by all operators. This indicates that there is no teamwork in these two models. TSS has some implemented teamwork because of overlapping positions. And the best teamwork is shown in the BB model. The operators are constantly in contact with one another, passing the workpiece between them.

In a situation where one operator is missing the RC and BB can give the best results because the operators are trained for all operations and they can compensate the missing operators without any problems. In WB operators do not have to be trained for all operations, just operations they are working on. This creates a problem when one operator is missing because the present operators do not have the knowledge to perform the operations of the missing one. The time is required to teach existing operators to overtake the mentioned operations. TSS has slightly better potential to compensate for the missing operator.

Introducing an untrained operator and training the new one will create the worst impact on the WB and RC, since the operator has to be trained for specific operations, in the case of WB, and for all operations in the case of RC. For these two situations, TSS will give better results, because more experienced operators will help the new one with overlapping positions. Untrained operators and implementing new operators for the BB model have different weights. Training a new operator requires time since he has to learn all operations, and introducing an untrained operator will not create a major disturbance while performing the BB model because other operators will compensate for his incapabilities.

Considering waiting losses, the WB and RC show the worst results because of already mentioned problems of WB balancing and RC's faster operator waiting for the slower. BB has the lowest waiting time since the workplaces are continuously handed over to the next operator. Waiting losses can occur in TSS due to bad balancing.

One of the trait indicators where WB gives the best results is walking loss. In WB operators have the least amount of movement, while in TSS, BB and RC have more amount of movement respectively. In TSS operators have to move less than in BB where operators are constantly moving back and forth along the production line, and in the case of RC, operators have to move over the entire production line producing the most walking losses.

## 5. Conclusion

There are not so many sources in the literature and in practical studies in which production line organization is studied through all models of lean cellular manufacturing organization. Most literature findings focused on BB and WB models. They are not focusing on situations with different operators' numbers, when a new operator is introduced, when the length of the operations is different, how different models react to untrained operators, etc. The performed study analyzed these situations comparing results of different models implemented on three different products, from the simplest to the more complicated.

The simulations are performed on the pen, paper planes, and electric torches with all four lean cellular manufacturing models (WB, BB, TSS, and RC). In the models, different situations were analyzed. Some of them are pre-filling the production line with WIP, analyzing products with a low possibility of creating defective pieces, taking into account defective pieces in the process, and implementing quality control in the assembly process.

The simulations showed that even though WB is mostly used in industry today, it consistently gives worse results considering productivity than other self-balancing models of lean cellular manufacturing organizations. Some difference in productivity was as high as 100%. BB with 2 operators gave double the productivity of WB in torch assembly simulation, and in the simulation of pens and paper planes results were also better for other models than WB.

In all simulations, RC resulted in better performance analyzing productivity compared to WB and TSS, but worse results than some BB simulations. The disadvantage of RC that makes it worse than BB is that it will lead to waiting losses because one or some operators are slower than others. This can also cause physiological pressure on slower operators inducing them to speed up. Also is expected that BB is a better model of the organization compared to TSS, but in some situations when the system collapses, TSS will give better results.

The most difficult thing is to create a division of work and organize production in the WB and TSS model, a somewhat easier task is to organize it in BB, and the simplest in RC. Regarding the robustness of the model in the case of the absence of one worker, organizing production is the most difficult in WB and TSS, but it is easier in BB and the simplest in RC. This flexibility implies that operators are trained for all operations when it comes to RC or for most operations when it comes to BB, which in some practical situations is impossible to achieve because it requires a wide range of operator competencies.

It is concluded that BB gives the best performances regarding balancing, teamwork, the situation when one operator is missing, when introducing an untrained operator, and regarding waiting losses. It is a self-balancing model and the balancing performance of this model is the highest, but it has to fulfill many requirements to achieve its full potential, such as short cycle times, nearby workstations, all operators trained for all operations, etc. Teamwork especially stands out in this model since operators are constantly handing over workpieces between them. This is also noticed in waiting losses, by handing over the workpieces to the next operator these losses are eliminated. When introducing a new operator, other operators will compensate for his incapabilities not causing problems in the production line.

While performing torch assembly simulations for the BB organizational model with a different number of operators one interesting effect was noticed, the Ringelmann effect. This behaviour is explained as social loafing which represents a reduction of individual effort when participating in a group. It is expected that the realization of production will increase linearly with a number of operators increasing linearly which was not the case indicating the presence of this effect. It is usually caused by motivation loss and coordination problems.

The main limitations of this paper stem from the following facts: the simulations were done in laboratory conditions, the simulations were performed on relatively simple products, and more reliable conclusions if the simulations were done for a longer period, fatigue, motivation, and effort could have influenced the results of the simulations

This creates opportunities for future research to overcome these limitations with a focus set specifically on some of the different situations presented in this work such as only situations when one operator is missing, only introducing an untrained operator, waiting losses, walking losses, etc. Also, different models can be compared using some multicriteria decision-making methods. Besides this, research can focus on the Ringelmann effect in the production process with different models and with more performed simulations.

**Declaration of competing interest**

The authors declare that they have no any known financial or non-financial competing interests in any material discussed in this paper.

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