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# LAYOUT EVALUATION WITH THE INDUSTRY 4.0 APPROACH FOR A MANUFACTURING LABORATORY

Rodriguez, L.; Loyo, J. & Silva, U.
Department of Systems, Division of Basic Sciences and Engineering, Autonomous Metropolitan University Azcapotzalco, Av. San Pablo 180, Col. Reynosa Tamaulipas, Mexico City (CDMX), Mexico
E-Mail: lwra@azc.uam.mx, lqj@azc.uam.mx, ussr@azc.uam.mx

**Abstract**
In this study, the Systematic Layout Planning methodology was adapted with an Industry 4.0 approach (SLP-Ind. 4.0) to optimize the design of a Production Design Area in a Manufacturing Laboratory. To validate the proposed SLP-Ind. 4.0, a "representative" product assembly process involving a ladder-shaped structure made of five Lego® bricks was evaluated. Four layout alternatives were evaluated, one considering the process manually and another three incorporating automated equipment such as a cobot (Collaborative Robot), a vision system, and at least one conveyor belt. Experiments and simulations of the process were obtained indicators through simulation such as cycle time, the line efficiency and production capacity. The results demonstrate that the optimal alternative improves the efficiency of the manufactured parts by 16.84 % compared to the manual process. In addition, the selected option has desirable characteristics such as modularity, flexibility, and adequate human-machine interaction. Therefore, with the use of SLP-Ind. 4.0 it is easier to obtain adaptable layouts to the variations of the production processes, ensuring a versatile manufacturing environment.
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**Key Words:** SLP, Layout Planning, Design, Industry 4.0, Cycle Time, Simulation

## 1. INTRODUCTION

Systematic Layout Planning (SLP) is a methodology used to design or improve the layout of facilities, such as factories, warehouses, offices, and workspaces. The primary goal of SLP is to optimize the spatial arrangement of various components within a facility to enhance efficiency, productivity, and operational strategy while minimizing material flow and costs [1, 2]. The SLP method can now be enriched by incorporating simulation programs, known as "simulation-based approach framework", to thoroughly evaluate various layouts scenarios in a cost-effective and efficient manner [3]. The advantage of implementing simulation has been demonstrated through several studies, obtaining for example better decision making [4] and achieving notable reductions in cycle times of up to 64 % [5]. Additionally, the impact of material flow has been investigated considering delivery times and the proximity of workstations [6, 7]. As well as the impact of maintenance operations that interrupt the flow of material and information [8]. Other studies on the layouts of facilities are related to the interrelations of the activities and the added value in the process [9-12]. The analysis of critical factors such as the distance that the raw material must travel, processing time, operating costs [13], material handling [11, 14], and the measurement of the number of steps using the AnyLogic® program [15].

Comparisons have also been made between the SLP and the multi-plant design proposal, to determine the effect on distance travelled for a group of product families [16]. Studies have been complemented with lean manufacturing tools such as value stream mapping (VSM) with the aim of optimizing the flow of the entire system, the distance between machines, material frequency, and capacity [17]. Or in increasing the added value of the operations carried out, reducing assembly times, as well as cost savings [18-20]. Another approach considered in some investigations is the inclusion of QFD (quality function deployment) to achieve a design according to customer perception, which allows for generating alternative layouts [21]. As well as the use of decision trees to select the material handling system based on the production parameters evaluated in the FlexSim® simulation environment [22].

All these studies allow us to analyse the layouts in a more detailed and specific way to some problems, however, the analysis and inclusion of the new Industry 4.0 technologies have not been widely explored. The main objective of this work was to adapt the SLP with an Industry 4.0 approach (SLP-Ind. 4.0) for the layout of the Production Design Area, within the Manufacturing Laboratory (ML) with an Industry 4.0 approach of the Metropolitan Autonomous University, campus Azcapotzalco, in Mexico City, Mexico.

This laboratory is used for students to develop their practices in automated production systems. Inside its facilities, three research professors supervise daily activities, while a group of twelve social service students work from 8 am to 8 pm. Additionally, student groups of up to 30 members periodically attend to learn about the equipment and carry out laboratory practices. The objective of this laboratory is to develop production processes with Industry 4.0 technology, which allows the complexity of real industrial processes to be replicated on a scale. For the development of the layouts proposals, the collaborative man-machine environment, the equipment, and the flow of activities of the process oriented towards customization were considered, according to the requirements of the assembly sequence and inspection points.

## 2. METODOLOGY

The conventional SLP methodology consists of the 10 steps [23] described in Fig. 1 a, which in the present study were adapted to be applicable to an Industry 4.0 model (SLP-Ind. 4.0) taking into account the characteristics of socio cyber-physical work systems [24], as seen in Fig. 1 b. For its development, interactive design [25], design planning, and simulation [26] were used, as well as the modularity and flexibility of the system so that it is easily reconfigurable to other processes [27, 28], and the methodology was reduced from 10 to 6 steps.

The initial step of SLP-Ind. 4.0 “Information” involves gathering information about the process analysis, like the conventional SLP. Additionally, an analysis of the material flow within the layouts alternatives is conducted. The SLP steps “Activity relationships” and “Activity Relationship Chart (ARC)” are merged into SLP-Ind. 4.0 Step 2, referred to as “Modularity and flexibility”, which focuses on establishing the interconnections between stations while considering the global architecture of the productive system [5]. Similarly, steps 4 and 5 of the conventional SLP are consolidated into SLP-Ind. 4.0 step 3, termed “Space requirement”. This step involves reviewing the requirements of processing stations, raw material supply, process inventory, and finished product storage. The estimation of the workspace requirements is calculated using Eq. (1).

$$MSPACE = BMS + OS + MS + WIP \tag{1}$$

where *MSPACE* is the Machine/Element Space. *BMS* is the Basic Machine Space. *OS* is the Operator Space considering 90 cm on each side of the operator. *MS* is the Maintenance Space considering 60 cm around the machine. *WIP* is the Work in Process space. All these parameters in square meters.

SLP-Ind. 4.0 step 4, “Space adjustment” which consolidates steps 6 and 7 of the conventional SLP. This step addresses the inherent process restrictions to ensure effective control and monitoring of the system. Step 5 “Assessment” combines steps 8 and 9 of the conventional SLP. The evaluation process incorporates the weighted factor methodology and system modelling, complemented by the simulation of workdays. Lastly, SLP-Ind. 4.0 incorporates step 6 “Implementation”, which aligns with step 10 of the conventional SLP. In this phase, the optimal alternative is implemented to assess its efficiency within an actual operational environment.

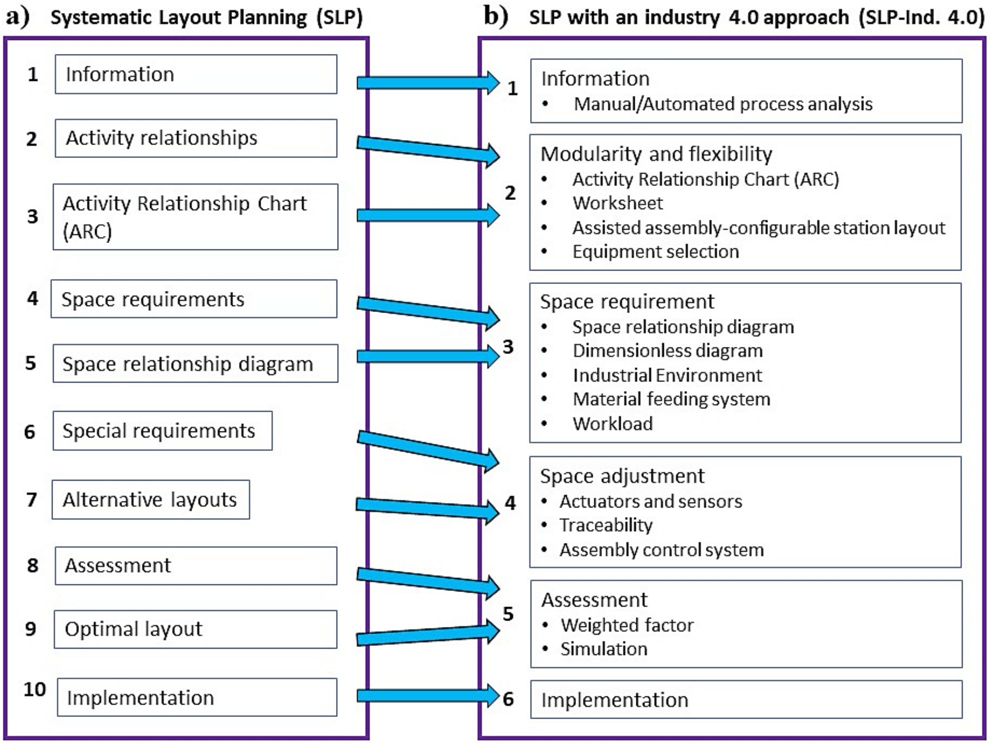



Figure 1: SLP Methodology: a) conventional and b) the proposed SLP-Ind 4.0.

This research was conducted in two main phases. The first phase involved the application of conventional SLP to determine the layout of all areas within the Manufacturing Laboratory (ML). In the second phase, the SLP-Ind. 4.0 approach was employed, specifically considering its implementation in a "representative productive process" and the Production Design Area.

During the initial phase, a comprehensive analysis was performed on the available 100 m$^2$ area. Various factors such as lighting, ergonomics, security, quantity, and human traffic were taken into account. The distributed areas included three offices, a meeting area, a kitchen, a store, eight design computers, three FDM printers, and the allocation of space for a Production Design Area. It is important to note that the bathroom area was not considered in this analysis as it had already been built outside of the laboratory. Three overall proposals were evaluated, and based on the results, it was determined that the layout option shown in Fig. 2 provided the optimal layout. This configuration allowed for a 30 m$^2$ space to be allocated specifically for the Production Design Area.

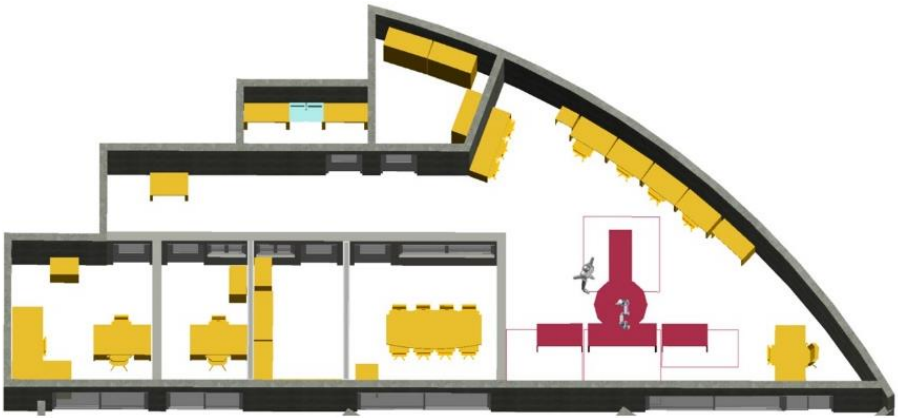


Figure 2: Layout of the Manufacturing Laboratory and of the Production Design Area highlighted with red frames.

In the second phase, the SLP-Ind. 4.0 method was employed to identify the optimal layout option for the Production Design Area, which constitutes a crucial component of both the Manufacturing Laboratory and this study. This area encompasses the raw material, assembly, inspection, finished product, and rejected product sections. Four layouts alternatives were evaluated with respect to their efficiency in facilitating the assembly process of an "representative" product.

The first alternative involves a manual process, while the remaining three alternatives incorporate automated equipment. These automated options utilize specific machinery, including a Cobot (Collaborative Robot) UR-3 from Universal Robots, equipped with a gripper model Robotiq 2 Finger, a Keyence CVX-300 vision system [29], and one or two conveyor belts, depending on the configuration.

The "representative" productive process analysed corresponds to the assembly of an educational product made up of 5 Lego® bricks of different colours (Fig. 3). The assembly entails forming a ladder shape, with a 2×4 brick serving as the base, followed by the placement of 1×4, 1×3, 1×2, and 1×1 bricks. Notably, a restriction was imposed to prevent the repetition of colours in successive pieces, with the requirement of aligning the pieces to the left while stacking them on top of the base piece. The production scenario considered an 8-hour shift, accounting for a deduction of 30 minutes for delays and waiting time, resulting in 7.5 hours of productive time.

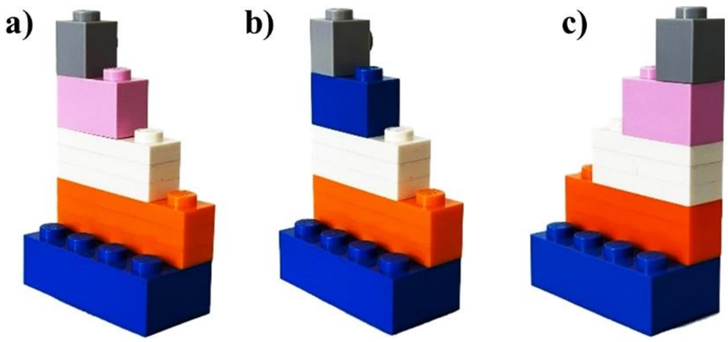
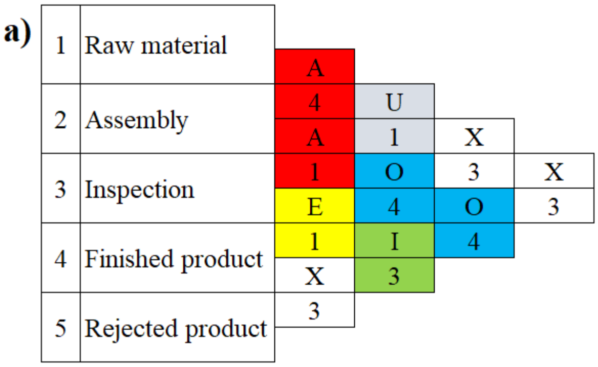



Figure 3: Representative product; a) within specifications, b) repeated colour, and c) wrong position defect.

## 3. RESULTS

Using the SLP-Ind. 4.0 approach, the Production Design Area was evaluated, and four layout alternatives were compared. The analysis produced results corresponding to each step of the developed methodology. Four operators participated in the manual process, three carried out the subassemblies, and the last of whom also verified the quality of the finished product. Additionally, a fourth operator supplied the raw material.

In the SLP-Ind. 4.0 step 2 "Modularity and flexibility", the use of automated equipment was contemplated, and other layout alternatives were established as possible solutions. Fig. 4 shows the Activity Relationship Chart (ARC) obtained, in which the main five sections of the system were analysed. The activity of raw material with assembly (Cobot) is the only element that is considered in a type A relationship. Similarly, there is a relationship X between the finished product and rejected product, in order to prevent the pieces from being mixed between the two areas.




b)

| No. | Reason |
|---|---|
| 1 | Better flow |
| 2 | Interconnected areas |
| 3 | Released product |
| 4 | Raw material supply |

Figure 4: Production design area workstations: a) Activity Relationship Chart (ARC), b) Reason codes.

Based on these findings, the three layout alternatives shown in Fig. 5 were proposed. The workstation consists of sections of Raw material (1), Assembly (2), Inspection (3), Finished product (4), and Rejected product (5).

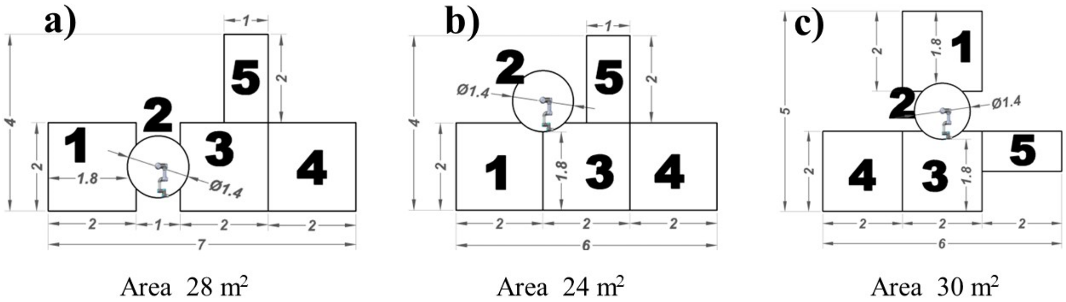



Figure 5: Layout alternatives using automated equipment for the Production Design Area.

In the context of alternative comparisons, it is important to note that alternative 1 represents the manual process. Alternative 2, as depicted in Fig. 5 a, was developed with a primary focus on optimizing the “flow of materials”. In this configuration, the assembly section (2) is positioned between the raw material stations (1) and inspection (3). In this arrangement, a cobot is employed, with an extended reach of 75 cm, to collect raw material pieces and assemble them at its designated station (2). The cobot repeats this operation five times before turning to the other side to leave the finished piece at the inspection station (3). The inspection station features a conveyor belt, where a vision system identifies the quality of each piece. If a piece is found to be defective, a piston mechanism redirects it to another conveyor belt, leading it to the rejected product station (5). On the other hand, if the piece passes the inspection, it continues along the conveyor belt towards the finished product station (4).

Fig. 5 b shows alternative 3 developed with a “Modularity and flexibility” approach. Like the previous alternative, the cobot interacts with the raw material station (1) and the inspection station (3). However, it is strategically positioned at the corner where these two areas converge, ensuring that its movement between stations does not exceed 60°. Additionally, alternative 3 includes a piston and two conveyor belts, serving the same function as in alternative 2.

Alternative 4, shown in Fig. 5 c, emphasizes “Items reduction”. In this scenario, once the cobot completes the assembly and leaves the finished part at the inspection station (3), the conveyor belt integrated with the vision system, is configured to move either to the right or left. This enables the transportation of the finished piece to the appropriate station, either the finished product (4) or rejected product (5) stations.

During the SLP-Ind. 4.0 process, specifically in step 3 “Space requirement” and step 4 “Space adjustment”, the spatial requirements for each system element and the necessary adjustments for corridors and areas were calculated. It is important to note that, in addition to the cobot area, all other areas have been expanded to contain the space needed for the system worker to move around and monitor the cycle of operation. To simplify the systems and analyse them under the same conditions, the areas for raw material (1), inspection (3), and finished product (4) were standardized at 4 $m^2$, while the rejected product area (5) was set at 2 $m^2$. The assembly area (2), corresponding to the cobot's operational space, forms a circular shape with a diameter of 1.4 m.

The Table I presents the calculated distances for alternative 4, focused on the "Items reduction". It was determined that frequently used materials should be positioned at 30 cm, taking into account the principles of man-machine collaboration. Additionally, the assembly space was defined by outlining the boundaries of the raw material containers within the table area, based on the cobot's range of movement and the sequence of required motions.

Table I: Dimensions of layout alternative No. 4.

| **No.** | **Space/section** | **Width** (m) | **Length** (m) | **Area** ($m^2$) | **Additional space** | **Quantity** | **Required area** ($m^2$) |
|---|---|---|---|---|---|---|---|
| Raw material section | | | | | | | |
| 1 | Raw material container | 0.10 | 0.40 | 0.04 | 0.36 | 5 | 2.0 |
| | Worktable for the location of the pieces | 1.80 | 2.00 | 3.60 | 0.90 | 1 | 4.50 |
| Aisles: 0.65 $m^2$ (10 %) Total: 6.50 $m^2$ | | | | | | | |
| Assembly section | | | | | | | |
| 2 | Assembly space | 0.20 | 0.20 | 0.04 | - | 0.60 | 0.64 |
| | Cobot | - | - | 1.54 | 2.00 | 1 | 3.54 |
| Aisles: 0.418 $m^2$ (10 %) Total: 4.18 $m^2$ | | | | | | | |
| Inspection section | | | | | | | |
| 3 | Conveyor belt | 1.40 | 0.30 | 0.42 | 1.80 | 1 | 2.22 |
| | Vision camera | 0.026 | 0.11 | 0.0029 | 1.80 | 1 | 1.8029 |
| Aisles: 0.40 $m^2$ (10 %) Total: 4.02 $m^2$ | | | | | | | |
| Finished product station | | | | | | | |
| 4 | Worktable for the location of the pieces | 2.00 | 2.00 | 4.00 | 0.90 | 1 | 4.90 |
| Aisles: 0.49 $m^2$ (10 %) Total: 4.90 $m^2$ | | | | | | | |
| Rejected product station | | | | | | | |
| 5 | Worktable for the location of the pieces | 2.00 | 1.00 | 2.00 | 0.90 | 1 | 2.90 |
| Aisles: 0.29 $m^2$ (10 %) Total: 2.90 $m^2$ | | | | | | | |

In Step 5 "Assessment" of SLP-Ind. 4.0, the weighted factors methodology was employed to assess alternatives 2 to 4. Table II displays the results of evaluating 10 factors that are highly relevant to the development of alternatives within the Industry 4.0 approach. The evaluation scale ranges from 1 (very poor) to 100 (excellent). It is evident that the selected proposal corresponds to alternative 4, achieving a total of 79 points. This demonstrates an advantage of 8 and 4.5 points over alternatives 2 and 3, respectively. The selected alternative offers a cost-effective solution by using a single conveyor, which not only ensures proper segregation between the reject station and the finished product, but also mitigates errors from overlapping materials. This design feature significantly improves the flexibility of the approach, allowing for optimal placement of items.

Table II: Evaluation of alternatives 2 to 4 using weighted factors.

| No. | Criteria | Weight | Assessment | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Alternative 2 | Weighted score 2 | Alternative 3 | Weighted score 3 | Alternative 4 | Weighted score 4 |
| 1 | Possibility of future facility expansion | 0.10 | 80 | 8 | 80 | 8 | 80 | 8 |
| 2 | Cost savings to implement layout | 0.10 | 80 | 8 | 80 | 8 | 80 | 8 |
| 3 | Improved space utilization | 0.15 | 60 | 9 | 70 | 10.5 | 80 | 12 |
| 4 | Layout flexibility | 0.10 | 70 | 7 | 70 | 7 | 80 | 8 |
| 5 | Safety considerations | 0.05 | 80 | 4 | 80 | 4 | 80 | 4 |
| 6 | Storage efficiency | 0.10 | 70 | 7 | 70 | 7 | 70 | 7 |
| 7 | Flexibility | 0.20 | 70 | 14 | 70 | 14 | 80 | 16 |
| 8 | Penalties | 0.10 | 60 | 5 | 80 | 8 | 80 | 8 |
| 9 | Adaptability | 0.05 | 80 | 4 | 80 | 4 | 80 | 4 |
| 10 | Efficiency of Assembly Travel | 0.05 | 80 | 4 | 80 | 4 | 80 | 4 |
| | **Total** | **1.00** | | **71** | | **74.5** | | **79** |

Additionally, alternatives 2 to 4 were modelled and simulated using FlexSim® program. Firstly, the available resources, task performers, transportation, and stores were identified to establish the variables for representation. Once the model was defined, simulations were carried out to observe the scenario's behaviour for the selected alternative. A summary of the Key Performance Indicators (KPIs) obtained is presented in Table III, and a comparison was made with the experimental results from alternative 1.

According to the results, the best design option was alternative 4. Therefore, this alternative was implemented in step 6 of the SLP-Ind. 4.0, experimentally analysing three shifts of 7.5 hours each, on three consecutive days, also showing the corresponding average results in Table III.

Table III: KPIs for the four layout alternatives.

| KPI | Alternative 1 (exp) | Alternative 2 (simulation) | Alternative 3 (simulation) | Alternative 4 (simulation) | Alternative 4 (exp) |
|---|---|---|---|---|---|
| Leisure time | 2,198 s | 297 s | 1,198 s | 1,247 s | 1,240 s |
| Cycle time | 9.7 s | 24.51 s | 33.72 s | 22.64 s | 22.65 s |
| Positioning time | 23,211 s | 25,214 s | 26,951 s | 25,168 s | 25,200 s |
| Setting time | 1547 s | 1,028 s | 657 s | 1,022 s | 997 s |
| Available time | 18,900 s | 27,772 s | 28, 143 s | 27,778 s | 27,758 s |
| Operating time | 26,574 s | 26,574 s | 27,847 s | 26,531 s | 26, 532 s |
| Theoretical production | 3,000 pcs | 1,234 pcs | 1,251 pcs | 1,235 pcs | 1,235 pcs |
| Actual production | 2,783 pcs | 1,194 pcs | 864 pcs | 1,224 pcs | 1,222 pcs |
| Availability | 76.92 % | 95.69 % | 98.95 % | 95.51 % | 94.89 % |
| Throughput | 100.00 % | 96.73 % | 69.07 % | 99.14 % | 98.90 % |
| Quality | 98.32 % | 98.26 % | 98.20 % | 99.00 % | 99.00 % |
| Efficiency | 76.92 % | 91.01 % | 67.16 % | 92.99 % | 92.29 % |

Fig. 6 illustrates the simulation conducted for alternative 4, focusing on the “Items reduction” approach. Similarly, Fig. 7 shows the actual and final layout of the system.

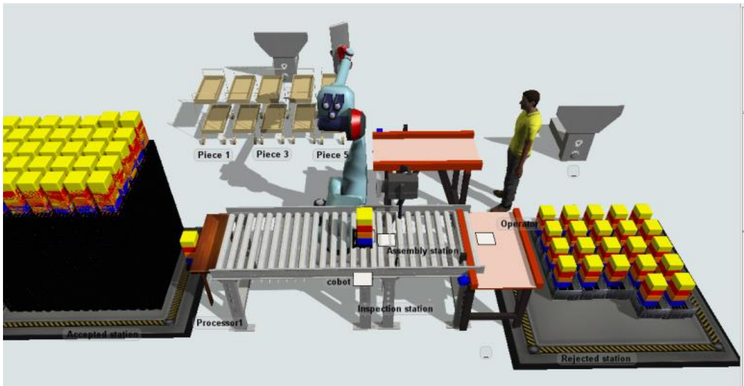



Figure 6: Simulation in FlexSim® of the layout of alternative 4.

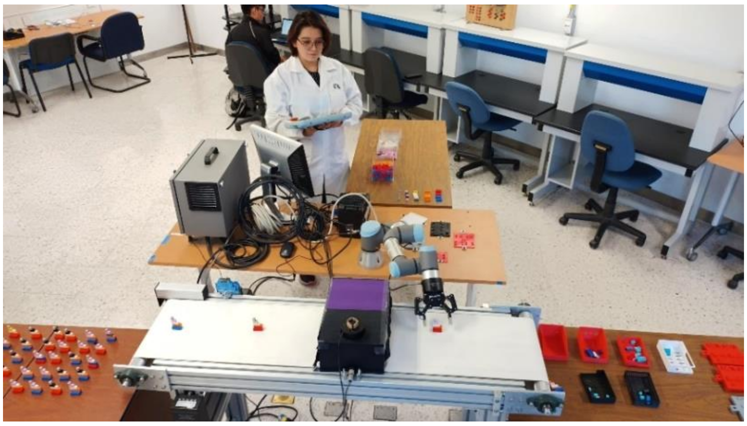


Figure 7: Actual layout of alternative 4.

## 4. DISCUSSIONS

To assess the reliability of the SLP-Ind. 4.0 proposed, four design alternatives were analysed regarding their efficiency to manufacture a "representative" product. Which corresponds to the assembly of 5 Lego® bricks in the shape of a ladder. This selection was based on the product's simplicity and the widespread availability of its components worldwide, enabling easy replication and verification of results in other laboratories. Furthermore, this production process allows the measurement of common KPIs applicable to other manufacturing processes, as presented in Table III. It becomes feasible to monitor the number of defective parts and optimize the overall process.

It was obtained that the best layout option was the fourth alternative “Items reduction”. This was mainly because the cobot not only assembles the parts, but also transports them between workstations. Similarly, the quality inspection system was used not only for finished products, but also for inventories in process and for raw materials. For this fourth alternative, the cycle time establishes the production rate from when the raw material enters until the finished product is obtained. This cycle time amounts to 22.64 seconds, taking into account not only the assembly time but also the travel time of the product on the conveyor belt.

The simulation and experimentation carried out in this study were based on a single 7.5-hour work shift. However, the automated process has the potential to operate continuously throughout the day using three work shifts, resulting in an effective production time of 22.5 hours. Each shift allows 30 minutes for cleaning, inspection, and reorganization activities. Considering this extended operating scenario, a production capacity of 1,227 pieces per day, equivalent to 54 pieces per hour, can be achieved. Under this assumption, the efficiency of the assembly process amounts to 92.35 %. This efficiency includes 89.5 % attributed to the fastening of the finished product parts and 7.33 % due to the assembly process itself. The remaining 3.17 % corresponds to wasted time related to the transfer of raw materials from the container to the assembly station.

An aspect not analysed in this study is the automation to store finished products or supply raw materials, which could be done with the same cobot or with an additional one. In the case of using a single cobot, the assembly line could be reconfigured in a "U" shape, allowing the cobot to be used in the storage or replacement of materials when the designated spaces reach their maximum capacity. Additionally, if the cobot were used in the raw material supply process, it would ensure that the pieces are in the desired sequence of shape and colours since in the process analysed in this study the operator supplies the pieces.

## 5. CONCLUSIONS

In this study, a modified version of the conventional SLP methodology was introduced, referred to as SLP-Ind. 4.0, which consists of six distinct steps tailored to the Industry 4.0 context. The effectiveness of this adapted methodology was validated by utilizing it to identify the optimal layout within the Production Design Area of the Manufacturing Laboratory at UAM AZC.

The proposed SLP-Ind. 4.0 methodology integrates the conventional SLP method with the advancements of Industry 4.0 systems. This developed approach incorporates the crucial aspect of "Modularity and flexibility," enabling the identification of interoperability requirements between automated equipment in a streamlined manner. The aim is to achieve seamless interconnectivity, effective communication, and enhanced control over the productive system. Moreover, by leveraging vision systems, the methodology enables the acquisition and processing of digital signals, facilitating the identification of crucial process parameters. This flexibility empowers operators to reconfigure the system as needed. Consequently, it becomes feasible to establish adaptable flow layouts tailored to specific assembly and inspection points. Furthermore, the SLP-Ind. 4.0 methodology encompasses the development of a system model and its simulation to analyse system behaviour. In this study, the FlexSim® program was utilized, facilitating the establishment of pertinent performance indicators based on the analysis of the selected layout alternative.

The main difference between the SLP-Ind. 4.0 developed and the conventional SLP method lies in its emphasis on integration and modularity for the purpose of selecting technological devices within an Industry 4.0 approach. This integration and modularity include the system architecture and the flexibility of the workstations, focused on the customization of the process and the integration of the worker as a process manager and not only as an operator. This emphasizes the importance of providing the operator with proper and prior training to effectively assume this managerial role.

The study proposed and evaluated four layout alternatives for the Production Design Area, taking into account the conditions of a representative production process and the facility. These alternatives involved different design approaches, including “Manual production”, “Material flow”, “Modularity and flexibility”, and “Items reduction”. These design strategies are highly versatile and can be easily adapted to other labs or manufacturing facilities.

The fourth alternative, “Items reduction” was the optimal choice due to its notable attributes. This alternative had an efficiency rate of 92.99 %, a processing time of 22.64 seconds and a defect percentage of 1.8 %. This corroborates the efficiency of automated processes since the cobot has a precision of 0.03 mm in its movements and assemblies, reducing the occurrence of joint openings commonly associated with manual operations. In addition, the fourth alternative stood out as the most cost-effective and efficient implementation proposal. Because it only required the implementation of a cobot, a vision system for product inspection, and a conveyor belt, which minimized the use of resources and maximized productivity.

Finally, it was confirmed that the automation of production processes enables the substitution of repetitive tasks traditionally performed by manual operators. This shift liberates both the system and operators to focus on activities that truly enhance the process, such as optimizing product flow, reevaluating layout strategies, and exploring novel approaches that ensure quality standards are met. By eliminating repetitive tasks, automation allows stakeholders to focus their efforts on value-added activities, fostering innovation and continuous improvement within the system.

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