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The Impact of Learning Factories on Teaching Lean Principles in an Assembly Environment

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Abstract. Learning factories are realistic manufacturing environments built for education; many universities have recently introduced learning factories in engineering programs to tackle real industrial problems; however, statistical studies on its effectiveness are still scarce. This paper presents a statistical study on the impact of learning factories on the students’ learning process, when teaching the lean manufacturing concepts in an assembly environment. The analysis is carried out through the Lean Manufacturing Lab at KTH, a learning factory supporting the traditional educational activities. In the lab, the students assemble a product on an assembly line; during three rounds, they identify problems on the line, apply the appropriate lean tools to overcome the problems, and try to achieve a higher productivity. The study is based on the analysis of the times recorded during the sessions of the lab. A questionnaire submitted to the students after the course evaluates the level of knowledge of lean production principles that the students achieved. The results are twofold: the improvement of the assembly times through the implementation of the lean tools and the positive effect of a hands-on experience on the students’ understanding of the lean principles, highlighted by the answers to the questionnaire. The main contributions are that applying the lean tools on an assembly line improves the productivity even with inexperienced operators, implementing a learning factory is effective in enhancing the learning process, and, lastly, that a first-hand experience applying the lean tools in a real assembly environment is an added value to the students’ education.

Keywords: Learning factory \cdot Lean manufacturing \cdot Lean principles \cdot Assembly \cdot Education

1 Introduction

The term Learning Factory (LF) identifies a system that integrates elements of education in a realistic production environment [1], thus implementing the
“factory-to-classroom” concept [2]. The teaching-learning process is moved closer to real manufacturing problems through emulation of a simplified shop-floor [3], so that learners can be tested in concrete industrial conditions while practicing with hands-on activities [2]. LFs support the experiential learning process [3] as defined by Kolb’s theory [4]: a concrete experience helps in realizing the knowledge transfer, according to a cycle in which the students (a) actively engage in a practical task; (b) observe, reflect, and discussed the activity with their peers; (c) abstract conceptualization (analysis) and generalize the events suggesting improvements (conclusions); (d) try to put knowledge into practice, thus making sure that the information is retained. A LF represents an approach that embraces the theory of experiential learning; engineering students’ learning process requires experience in laboratories to facilitate their understanding of the theoretical concepts learnt during regular classroom activity [5]. This makes LF a suitable learning activity to be embedded in engineering programs.

Lean Manufacturing (LM) is a philosophy intended to systematically reduce waste – i.e., non-value-added activities – in the entire product’s value stream, while promoting continuous improvement [6,7]. Such philosophy articulates in five basic principles: (i) identify the value from customer’s perspective; (ii) map the value stream to include only value adding processes; (iii) create continuous flow; (iv) establish pull system; (v) strive for perfection by continuously improve the company’s processes [8]. Several lean tools have been developed to implement these principles, such as Value Stream Mapping (VSM), Kanban/Pull production, 5S, and production smoothing [8,9]. Such approach promotes active involvement of workers that iteratively question and solve problems related to their tasks, thus acquiring knowledge from being engaged first-hand in the problem solving activity – “learning by doing” [10]. In view of the above, LFs appear to be a suitable teaching and learning activity for LM education and training of engineers. Numerous LFs have been built in recent years in academic facilities, institutes, and companies [11] as experience-based methodology improves the learners’ knowledge of lean principles while transferring the skills necessary for a real implementation [12].

This paper analyzes the impact of LF on the students’ learning process, when teaching the LM concepts in an assembly environment. The LM Lab (LML) developed at the Royal Institute of Technology in Stockholm (henceforth KTH) is taken as a case study. The analysis shows that applying lean tools on an assembly line improves productivity even with novice operators, that using a LF effectively enhance the learning process, and that a first-hand experience applying the lean tools in a real assembly environment is an added value to the students’ education.

The paper is structured as follows: Sect. 2 presents a brief overview of related literature, Sect. 3 describe the setup for the LML activity and how the analysis is performed, Sect. 4 presents the results of the analysis that are then discussed in Sect. 6.
Several studies report the potential and benefits of simulation games for LM training and education [13]. Such simulation games create a hands-on learning and training environment for better engagement of the learners, promoting a deeper understanding of the lean principles [13, 14]. Simulation games environment for training LM highly engage participants in realistic industrial situations, where they are asked to solve the encountered problem [14]: as a result, the participants gain a good and practical understanding of LM principles and tools and show the interest to play and learn even further [15].

Traditional teaching methods do not provide the desired improvement in the acquisition of knowledge and development of necessary skills to apply LM principles and tools. One study shows the importance of different teaching processes by implementing 5S methodology in the preparation of a laboratory environment, emphasizing the role of applying lean principles already in higher education institutes [16].

Employing “learning by doing” methods demonstrates to facilitate the acquisition of the concepts related to LM and to be effective in developing the skills for LM successful implementation. Therefore, in recent years several academic institutes and companies have promoted the construction of LF facilities [11]. The “Lean School” at the University of Valladolid (Spain) is the result of a
pedagogical project in collaboration with Renault Consulting [12], while Karlstad University (Sweden) designed and built their own lean factory on site [13]: both studies describe how the LF involves students in the emulated production environment, by being asked to improve the efficiency of the production line applying LM tools. The LF creates the suitable conditions for students to practically engage in different situations by applying the concepts and the tools presented in class. The students gain hands-on experience on the proposed experimental set-up, showing a better take in of the concepts with respect to those who have not taken the lab. From a pedagogical perspective, this means that courses and training programs that include a LF approach aim at fulfilling higher educational objectives than regular lectures. Looking at the Bloom’s taxonomy model for the cognitive domain – a classification of the level of understanding based on six different types of knowledge (remembering, understanding, applying, analyzing, evaluating, and creating) [17] – the LF through the “learning by doing” approach allows to step from basic cognitive objectives, i.e., remembering or understanding, to more complex ones, i.e., applying and analyzing.

3 Methods

3.1 Lean Lab Description

The LML is a learning activity based on the concept of the LF. The laboratory simulates a realistic manufacturing environment, whose main goal is to involve the students to develop solutions applying appropriate lean tools (Table 1). The LML consists of an assembly line with 6 workstations (Fig. 1a). The assembled product has a simple temple structure composed of several blocks and labels that differ from each other (Fig. 1b), thus requiring the operators to change tools between operations.

The LML is structured in 3 rounds, each of them lasting 12 min. The rounds are designed to show a step-wise improvement of the line applying LM tools. The first round is set in a disorganized way to highlight the waste in the whole assembly process. At the end of this round, the students engage in a group discussion aimed at identifying problems and suggesting relevant lean tools to solve them. The second round starts with the students implementing the suggested LM tools and then it is run with the proposed improvements in place. Another group discussion raises the problems still occurring. Additional LM tools are evaluated and suggested for implementation in the third round. The last round consists of major improvements to the previous setup, e.g., reduced number of stations, use of conveyor belt for transportation, use of product kits and advanced tools.

The students are actively involved in the LML as the production line needs (a) operators, performing the assembly operations at the workstations, (b) logistics, handling the transportation of components and WIP, (c) observers, measuring the cycle time at each station and inspect the problems on the line.

In every round, at each station the operators assemble a specific sub assembly, part of the final product. The observers measure the time to complete one sub
Table 1. Lean tools covered in the LML

<table>
<thead>
<tr>
<th>Tool</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5S</td>
<td>5S is a simple tool for organizing your workplace in a clean, efficient and safe manner to enhance productivity, visual management and to ensure the introduction of standardized working. 5S stands for: Sort, Set, Shine, Standardise and Sustain</td>
</tr>
<tr>
<td>Pull production</td>
<td>Pull production is based on customer demand. The production is triggered by a demand signal from a subsequent process. The production signal is sent upstream</td>
</tr>
<tr>
<td>Kanban</td>
<td>Kanban is a simple method to pass demand signals between processes. It is a signal to refill it with a specific number of parts or send back a card with detailed information about the part location</td>
</tr>
<tr>
<td>One piece flow</td>
<td>It is an ideal state of the operations where production works on one product at a time. It can be achieved by calculating a takt time, introduce pull system with one piece flow, ensure a feasible layout for one piece flow. “Make one, move one”</td>
</tr>
<tr>
<td>Line balancing</td>
<td>It aims at eliminating overburden to people and equipment, level out the workload of all manufacturing processes. To match production rate and takt time. Quantity of workers, work and machines assigned to each task should be re-balanced to meet optimal production rate</td>
</tr>
<tr>
<td>Built-in quality</td>
<td>Every operator is an inspector and works to fix problems at the station before passing them on. If defects do get passed on, they are detected quickly and problem can be immediately diagnosed and corrected</td>
</tr>
<tr>
<td>Takt time</td>
<td>It sets the pace of production aligning it with the customer demand. The aim of Takt is to detect deviations. If a product has not left the production flow when the takt time is out, it is a signal that there is waste in the process</td>
</tr>
</tbody>
</table>

assembly (cycle time) at each station, for every sub assembly they complete. The eventual waiting time between one product and the following is not considered. After each round, the students switch stations and occupation, moving from production operators to logistics and observers, so that they cannot develop skills and memorize the sequence of required operations to complete a sub-assembly. In the first round, the assembly operations run slower and are less likely to complete their assemblies since no LM tool has yet been applied; during round 2 the LML already comprises many improvements that facilitate the operators in their task; round 3 is the best possible set-up for the LML; however, it should be noted that – due to reasons of time and availability of the facility – less time is spent performing the activity and recording completion times in round 3 than in the other two rounds.

3.2 Analysis

Throughput Time. The time to fully assemble a single product consists of the sum of the times for said product to be assembled at each station (1 to 6) – we call this “line throughput time”. The throughput time of every completed product for every iteration of the LML is recorded, even the ones that exceed the 12 min mark: we give additional time to complete the assembly, but we label these cycles as “overdue”. We divide the throughput times of each completed assembly by round (round 1-2-3) and compare them to the target time of 12 min, to see how many are “on time” and how many are “overdue”. Then, we check the three rounds assembly
time populations for normality by looking at the normal probability plot and performing a Shapiro-Wilk test. We also plot a box plot with the three populations to have a first insight into how far apart and different they look.

We test separately round 1 against round 2, and round 2 against round 3 to check if the differences are statistically significant, using a t-test with two samples and unequal variances; we want to check if there is evidence that applying the lean tools through the rounds of the LML helps reducing the throughput time for the product. Since strong indications of non-normality should not be ignored and the performance of the t-test can be affected, we choose to perform a non-parametric Mann-Whitney U test on the same hypothesis.

After course completion, the student show correct learning pattern and are thus considered for a second stage of investigation of their perceived impact of the LF.

**Population.** The course has a total of 88 enrolled students who do the lean lab activity. All the students are enrolled at KTH and are following a Master’s program in production engineering: they have a background in manufacturing and learn the concepts of LM and the lean tools of Table 1 during the course before the lab takes place; the majority does not have previous hands-on experience in assembly activities and is not trained to perform such tasks, so they can be considered as novice operators for the assembly operations they perform in the lab.

Due to different availability, the students autonomously form groups of 8 to 10 participants for the sessions, where they can individually work at the various stations, collect time data or note what upgrades could be made on the line.

Since not all the students that take part in the laboratory participate in the questionnaire, we calculate the margin of error – or confidence interval – for the answers, using the inverse equation for calculating a significant sample size [18]:

\[
n_0 = \frac{Z^2 \cdot p \cdot q}{e^2},
\]

where \(n_0\) is the adjusted sample size, \(Z\) is the critical value of the Normal distribution at \(\alpha/2\) (where \(\alpha = 0.05\) for a confidence level of 95%, and the critical value is 1.96), \(e\) is the margin of error or confidence interval, \(p\) is the estimated sample proportion, and \(q = (1 - p)\). We use the adjusted sample size because our population is small: a Finite Population Correction is applied to Eq. 1 [19]:

\[
n = \frac{n_0}{1 + \frac{(n_0 - 1)}{N}},
\]

where \(n\) is the actual sample size, \(N\) is the population size and \(n_0\) is the adjusted sample size.

**Questionnaire.** After the students complete all the rounds of the laboratory, we submit a questionnaire to collect their opinions about the experience as a whole and its usefulness to understand and learn the LM principles. Also, we want to understand whether the LF experience successfully engage the students more than a standard set of lectures on the topic, and if it would be valuable to add more hands-on activities in similar courses.
After collecting the responses, we conduct a $\chi^2(4, N = 25)$ test to examine the significance of the students picks in the questionnaire – i.e., if the answer that the students select more frequently significantly represents the group’s general preference.

4 Results

Throughput Time. Table 2 shows how many products the students complete in each round and how many of them are “on time”, along with the percentage of “on time” completion. During round 1 they complete the least number of assemblies, because of the implied difficulties in the LML set-up: this is reflected in the percentage of assemblies completed “on time”, which is 0%. The number increases during round 2, as well as the percentage of product completed within the 12 min mark. In round 3, despite completing all assemblies before 12 min, the total number of products is lower because we allocate less time to this round – compared to the other two – due to restrictions in time and availability of the facility.

<table>
<thead>
<tr>
<th>Round</th>
<th>N of completed products</th>
<th>N of “on time” products</th>
<th>Percentage of “on time” products</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>18</td>
<td>69%</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>24</td>
<td>100%</td>
</tr>
</tbody>
</table>

We record the throughput times for all completed assemblies separately during the three rounds, and Table 3 shows the average, standard deviation and variance values for the three populations.

A visual representation of the time distributions is presented with the box-plot of Fig. 2, which shows that the three populations are quite distant from one another, and also highlights that they have unequal variances.

<table>
<thead>
<tr>
<th>Round</th>
<th>Average line throughput time [s]</th>
<th>Standard deviation [s]</th>
<th>Variance [$s^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1195.67</td>
<td>240.16</td>
<td>57678.79</td>
</tr>
<tr>
<td>2</td>
<td>669.96</td>
<td>93.18</td>
<td>8681.88</td>
</tr>
<tr>
<td>3</td>
<td>393.71</td>
<td>54.39</td>
<td>2957.87</td>
</tr>
</tbody>
</table>

Since doubts regarding the normality of the distributions arise through visual representations such as histograms and normal probability plots (not reported
here), we perform Shapiro-Wilk tests. They do not show evidence of non-normality for round 1 ($W = 0.934, p = .45$) and round 3 ($W = 0.93, p = .09$), but they highlight that round 2 is significantly non-normal ($W = 0.90, p < .02$).

Fig. 2. Box-plot of the three rounds time distribution

Given the large difference in variance between the three rounds, we apply a t-test with two samples and unequal variances to test if such differences are significant (separately for round 1 against round 2 and for round 2 against round 3). The line throughput times recorded during the first round of the lab ($M = 1195.67$ s, $SD = 240.16$ s) compared to the times recorded during the second round ($M = 669.96$ s, $SD = 93.18$ s) demonstrate to be significantly higher, $t(13) = 7.33, p < .01$; likewise for the times of the second round ($M = 669.96$ s, $SD = 93.18$ s) compared to the times of the third ($M = 393.71$ s, $SD = 54.39$ s): $t(41) = 12.92, p < .01$.

Furthermore, given that the evidence of non-normality of round 2 might affect the performance and power of the t-test, we also perform a non-parametric test, namely the Mann-Whitney U test; it is generally less powerful than its parametric equivalent, but its value is not hindered by non-normality. Thus, a positive result might confirm the implications of the t-test. The median line throughput time in rounds 1 and 2 are 1232 and 681 s; the distributions in the two groups differ significantly (Mann-Whitney $U = 0.0$, $n_1 = 12$, $n_2 = 26$, $p < .01$ two-tailed); likewise, median line throughput time in rounds 2 and 3 are 681 and 377 s; the distributions in the two groups differ significantly (Mann-Whitney $U = 8.0$, $n_2 = 26$, $n_3 = 24$, $p < .01$ two-tailed).

The t-test and the Mann-Whitney U test results are the same, so we can conclude that they are reliable: given the box-plot information and these results, we can confirm that the time for assembling a complete product with the setup from round 1 is significantly higher than with the setup from round 2, and
Table 4. Confidence interval from sample size

<table>
<thead>
<tr>
<th></th>
<th>Population size (# of students attending the lab)</th>
<th>88</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (1 - \alpha) )</td>
<td>Confidence level</td>
<td>95%</td>
</tr>
<tr>
<td>( Z )</td>
<td>Critical value</td>
<td>1.96</td>
</tr>
<tr>
<td>( n )</td>
<td>Actual sample size (# of students taking the questionnaire)</td>
<td>25</td>
</tr>
<tr>
<td>( n_0 )</td>
<td>Adjusted sample size</td>
<td>34.52</td>
</tr>
<tr>
<td>( p )</td>
<td>Likely sample proportion</td>
<td>50%</td>
</tr>
<tr>
<td>( e )</td>
<td>Margin of error</td>
<td>16.68</td>
</tr>
</tbody>
</table>

consequently that the setup of round 3 makes the operation significantly quicker than round 2.

The time layout is in line with the expected outcome and thus a correct learning process to raise the expected learning outcomes of the course; this is the base for the second part of the analysis.

**Population.** Only 25 students out of the 88 enrolled in the laboratory activity participated in the submitted questionnaire, so we evaluate if the sample size significantly represents the answers from the whole group of students, as explained in Sect. 3.

Data and results of the margin of error calculation are presented in Table 4. The 95% confidence interval (CI) level is a very common choice for any standard application, the values of \( N \) \((N = 88)\) and \( n \) \((n = 25)\) are known, while the value of \( n_0 \) derives from Eqs. 1 and 2; the value of \( p \) is set based on what the expected answers are: in this case the result is unknown, and the most conservative value of 50% is selected.

**Questionnaire.** Figure 3 shows the answer to the questionnaire. The majority of them highlights that the students found the lean lab experience to be useful and satisfactory, and that it helps in learning the LM principles.

Table 5 shows the results for the \( \chi^2(4, N = 25) \) test for each question: the majority pass the test with p-value lower than \( \alpha = 0.05 \), except two (questions 3.4 and 3.6), as highlighted in the table.

5 Discussion

The aim of our study is to verify the significance of implementing LM tools on a experimental assembly line in terms of number of products completed on time and in terms of line throughput times and to assess how much this lesson is effectively learned by our students participating to the LML. Results seem to confirm the usefulness of LM tools and that the experimental setup is appreciated and increase students’ perception of lean tools.

**LM Tools for Improved Productivity.** The results show an increase in the number of assemblies that are completed within the 12 min mark, going from
Fig. 3. Distribution of students’ answers in the questionnaire

Table 5. $\chi^2(4, N = 25)$ test results (* indicates a p-value > .05)
0% to 100% through the three rounds; the average throughput shows a decrease in times, with round 3 averaging results almost four times shorter than round 1. The t-test and the Mann-Whitney U test confirm the previous results, showing high significance in the differences between the time populations of the three rounds. This means that the implemented tools actually serve their purpose of easing the operators' jobs and making an assembly line as lean as possible, enhancing the productivity.

It is worth noting that the productivity increases even when inexperienced operators perform the required operations, thus showing that the improvement is not due to the ability of a particular worker, instead it depends solely on the efficacy of the lean tools. Companies deploying an assembly line should carefully consider applying those tools because they have beneficial effects that reverberates to the productivity of the line.

As mentioned, less time is spent with round 3 set-up, thus only 24 completed products; allocating the same amount of time to all rounds would mean being able to compare total numbers of completed assemblies as well as percentages, to have a more complete picture of the assembly process under different set-up combinations.

Enhanced Learning Process Through LF. The LML serves as a hands-on experience to give students at KTH Production Engineering Department a different approach to learning manufacturing concepts and specifically lean production. The knowledge transfer occurs in a practical set-up, where the learner is immersed in a recreated production environment, and can test the previously acquired concepts of lean manufacturing and the efficacy of applying those tools.

The students partake in a well designed laboratory that makes them analyze and solve the problems on the line and assess the efficacy of lean tools by applying them in a realistic manufacturing environment. Seeing the assembly times steadily decrease from one round to the other allows them to comprehend how the application of lean manufacturing principles influences production. Given this valuable experience, they increase their level of educational objectives in the cognitive hierarchy of Bloom's taxonomy: from just a knowledge and comprehension level that comes from learning in the classroom, they go to an application and even analysis level, which gives them potential to become better learners and better professionals. A practical approach to teaching is commonly believed to be a good way of keeping the students engaged in the learning process and gives them a way to get a deeper understanding of what is taught during standard lectures.

The answers from the submitted questionnaire confirm that our students appreciate the hands-on experience and that they are very satisfied with the activity, they also think it is useful to improve their learning process: including more similar activities in other courses where a lab could be implemented could be a useful teaching approach. Finally, the students believe that this lab is helpful for learning and remembering most main concepts of LM and specifically the LM tools, since they can see them applied in reality and analyze how they prove beneficial during production; however, for two of the lean tools – namely
built-in quality and continuous improvement – no evidence is given from the questionnaire that the lab activity helps with the learning process.

6 Conclusions

In this paper we analyze the impact of LF, to teach LM concepts in assembly, on the students’ learning process; the aim of the lab is to let the students experience the efficacy of the lean tools first-hand, how those tools reduce the assembly times, assess the good lab design and achieve specific higher level educational learning objectives. The LML at KTH is taken as a case study. This activity produces an increase in students’ understanding of the lean tools and their ability to indicate, analyze and deploy actual improvements on a real assembly line. The application of such tools show how they affect assembly times and productivity, thus highlighting how they can be exploited to promote efficiency and increase the output of companies.

The work hereby presented, and the collected data come from the very first iteration of the experimental setup of the course, and all the answers contained in the questionnaire come from a sample of the total number of students that attended the LML, thus this study does not compare results with previous studies and has a wide CI when analyzing the answers. Future work includes collecting more data from future iteration of the course, to analyze a wider sample of the population, to reduce the CI and better capture the significance of the students’ experience, and to compare the results over the years. Moreover, the participation to the questionnaire will be made mandatory for all students taking part in the course.

References


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