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Research Article

Lean techniques application towards efficient collaborative robot integration: an experimental study

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Abstract

Paper aims: Highlight the practical implications of coupling collaborative robots with lean manufacturing techniques and understand mutual contributions towards enhanced operational performance.

Originality: Usage of an experimental approach, focusing on lean techniques as a differentiating skill to implement efficiently collaborative robots in a production representative environment.

Research method: Experimental case study, based on the gradual implementation of a collaborative robot within a manual assembly process in order to design a collaborative process.

Main findings: Guidelines for transition from manual to collaborative process, incorporating incremental improvement loops – and related skills – enabling enhanced performance.

Implications for theory and practice: Identification of a set of lean techniques contributing positively to collaborative robots' usage, incorporated in a step by step operator driven implementation process.

Keywords

Collaborative robot. Lean techniques. Process improvement. Integration method. Experimental approach.

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1. Introduction

Industry 4.0 is largely presented as a leverage for increased operational efficiency, focusing on value added augmentation and increased process transparency, enabled by as set of innovative technologies. Lean manufacturing techniques have also pursued the same objectives for several decades. Lean techniques, though, rather promote method and organisation improvement to remove waste from their manufacturing processes. Nevertheless, both approaches consider human resource as key asset. Possible interactions between those two models have already been explored in the literature (Kolberg & Zühlke, 2015; Satoglu et al., 2018), and several potential scenarios have emerged, ranging from: 'Industry 4.0 will make lean obsolete' to 'industry 4.0 is a support for lean manufacturing', including also 'lean manufacturing is a prerequisite for Industry 4.0', or 'industry 4.0 is an extension for lean manufacturing' (Dombrowski et al., 2017). Such scenarios are still mainly theoretical, and the use cases mostly described as 'to be' situations, offering little views for practitioners on how to shift from their current operations towards the integration of 4.0 technologies. Beyond the conceptual discussion, the authors aim at clarifying the practical implications. Thus, the experiment reported in this paper intends to offer a concrete view on the coupling opportunities between Industry 4.0 technology and lean techniques, and how to measure their output in terms of performance.

In structured literature reviews (Liao et al., 2017; Maghazei & Netland, 2017; Moeuf et al., 2018), robotics is listed as one of the technologies participating in this fourth industrial revolution. A collaborative robot, named cobot, is a robot specifically designed to work simultaneously and safely with humans in shared workspaces (without safety cages/fencing). This opens new ways to design processes, involving both human and such robots, with increased possibilities for task allocations due to smoother interaction (Petruck et al., 2018). Based on a German survey (Bauer et al., 2016), the top-3 considerations when implementing human-robot collaboration process are: 1-operational efficiency, 2-innovation and 3-ergonomics. From a methodological approach, lean manufacturing has been so far recognized as a leading approach to achieve operational efficiency, relying on a controlled level of automation, which leads to the possibility to perform incremental process improvements (also named kaizen), as an activity driven by operational workforce (Imai, 1986). It may then be relevant to investigate how this incremental improvement can persist with new technology introduction, and the role played by operating workforce in this situation.

Focusing on collaborative robotics, the authors will develop a process to try to answer the following question:

- Which lean techniques may support collaborative robot implementation, and how the acquired skills influence the resulting process efficiency?

This paper is structured as follows: Section 2 details the conditions of experiment: the chosen product and process, selected performance indicators, workers capabilities, the testing sequence and finally data collection and analysis methods. Section 3 presents the actual results from our experimentation. This paper ends by a conclusion and consideration for further work in Section 4.

2. Framing of experiments

2.1. Process and product consideration

In order to answer the above-mentioned question, we have to design an experiment environment considering manufacturing process and cobot capabilities, product characteristics, and the capabilities of the people participating to the experiment. Once these are fixed, performance measurement will have to be defined, as long as a sequence that will enable measuring the differentiating effect of the targeted skills and techniques.

The selected process should enable both collaborative robotics and lean techniques to be included in a relevant way. The specificity of cobots being their ability to be used in a working environment shared with operators, and their limitations being payload and speed (under collaborative work conditions), the chosen process may then contain a majority of assembly operations, that can also be performed by an operator. Concerning lean techniques, their benefits are generated through incremental improvements of existing practices. Therefore, the selected process should be simple enough to allow a significant number of repetitions to happen through the experiments. Nevertheless, it should also contain a certain level of complexity, and offer several possible assembly sequences in order to give room for improvement. We will then try to setup an assembly process where most operations may be performed either by cobot or by operator, whose work content should be in the region of 1 minute (to allow higher number of repetitions). In addition, a single operator workstation is considered for simplicity purposes. **The selected cobot** and its initial setting should comply with the characteristics mentioned above and safety requirements. The UR5 model from *Universal Robots* was chosen at this early stage for the accessibility of its programming interface (no coding required), and the collaborative speed was set to a constant value of 250 mm/s, according to ISO 10218-1 recommendation (International Organization for Standardization, 2011).

Reflecting similar requirements to **the selected product** and its subcomponents, their dimensions and shapes should comply with cobot handling capabilities, preferably without extensive programming skills or development of ad-hoc effectors since this is not the target of this work. Considering manual operations, dexterity should not be a discriminant factor. Thus, the nature of the assembly operations should remain simple, hence with a limited number of deformable subcomponents. This also offers the advantage of rapidly achieving repeatable measurement of operation times, once again independent from operator's dexterity.

It was also decided that the manufacturing experiment would only concern a single product. Although this is not in line with foreseen application of Industry 4.0 (aimed at mass customization), this choice significantly simplifies setup of experiments and comparison between different solutions.

Subjects running the experiment have to be representative of process engineering population, for the skill acquisition stage to be realistic. Therefore, students from 4th year of master's degree of mechanical engineering have been appointed to run the experiments, since such graduates are the main provider of resources for the manufacturing industry area.

2.2. Performance indicator selection

When it comes to operational performance in manufacturing processes, there are indeed several performance indicators. The purpose of this stage is to select one that is likely to reflect the changes induced by the successive experiments. Shah and Ward (2003) have defined six main indicators measuring to production operation performance, covering quality, cost and lead time area. Considering the framing of this work, we may keep only the manufacturing cycle time (CT) reduction as a performance indicator of the designed process.

2.3. Sequence of experiments

In order to be able to identify any differentiating effect of acquired skills, the participants have been split in two teams. One being a control group (Team A), who will receive no lean related training, the other one being the target group (Team B), who will benefit from appropriate training through the successive steps of a collaborative process construction (See Figure 1). The four steps are detailed below, starting with development of a manual process as common starting base for experiment (step 1). Then, after being trained on CT reduction techniques

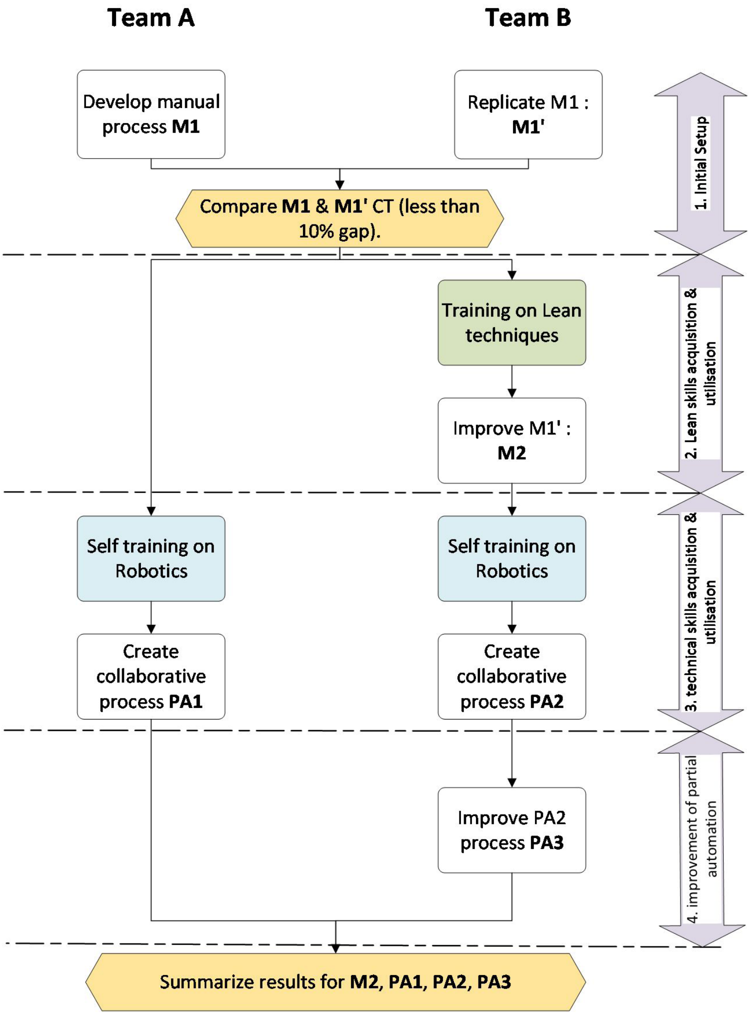

Figure 1. Conditions of research.

and man / machine separation, target team will try to remove waste from this initial process, according to the lean principle that no re-organization of operations should take place on an inefficient process (step 2). Once this is achieved, both teams will be trained on cobot programming and start collaborative process creation (step 3). Finally, the target team will have the opportunity to improve further the collaborative process to verify how kaizen techniques apply on a human robot environment (step 4).

Step 1. Initial Setup.

- **Purpose:** Create a manual process (M1) for part assembly as a common base for robot introduction, develop knowledge on the assembly operations.

- **Method:** Team A developed process M1, deciding on operation sequencing, and workstation layout. It was then replicated by Team B (process M1') based on video recordings.

- **Validation:** Comparison of each process CT. Process are deemed similar when their respective CT show less than 10% discrepancy.

Step 2. Lean skills acquisition & utilisation.

- **Purpose:** Develop skills in lean techniques towards their application in collaborative process development (step 3).

- **Method:** Team B was trained in this field through a 2 hours course. It was decided to operate a selection within the 21 lean practices identified by Shah & Ward (2003), in order to keep only the ones relevant to the case study, i.e. single station and focus on CT reduction. Therefore, only the techniques related to CT reduction through waste elimination and process balancing were considered. With regards to cobot usage, the bases of lean automation principle were taught: necessity of 'man and machine separation' (jidoka), i.e. operator should not be observing machine work (Marchwinski & Shook, 2003).

- **Validation:** At the end of the training stage, Team B is given the opportunity to exercise their skill on the manual process M1', to confirm their ability to implement kaizen. In addition, as part of a lean approach, this period is an opportunity to remove waste from the manual process prior to cobot introduction.

Step 3. Technical skills acquisition and utilisation.

- **Purpose:** Develop necessary skill for cobot usage (both teams), and observe whether the lean techniques acquired by team B in step 2 make a tangible difference on the collaborative process CT achievement compared to team A.

- **Method:** In order to build practical know-how on cobot introduction in assembly process, both teams have been given the opportunity of self-training online with Universal Robots Academy ® for 4 hours. At the end of this session, all students should be capable of programming the both desired robot trajectory and effector activation. Then, each team has opportunity to decide on how to introduce cobot into their manual process in order to reduce CT. It is also checked that the development times for each team are comparable.

- **Validation:** by comparison of CT achieved by each team, as per explain in Initial Setup.

Step 4. Improvement of partial automation.

- **Purpose:** Assess the possibility of pursuing the kaizen activities after cobot introduction into the process.

- **Method:** Opportunity was left to Team B to reduce the CT of the collaborative process they had developed, without any further guidance. Development time was recorded to verify it was consistent with the previous steps.

- **Validation:** by measurement of CT achieved by team B.

2.4. Result measurement and assessment methods.

2.4.1. Result measurement

The review conclusion by Maghazei & Netland (2017) suggested examining the research along with the characteristics of the Advanced Manufacturing Technologies (AMT) in terms of: the evaluation of the technology before implementation, the implementation phase, the outcomes (operational, organizational, strategic, and social) and the contextual variables that can have an influence. So, we divide a cobotics project into 3 successive phases as described in Figure 2. A cobotics project is to deploy some cobots in manufacturing or logistics activities, either working jointly with humans or standing alone. In order to assess the investment, or 'cost' related to a solution, the sum of 'Engineering' and 'Implementing' times spent by students is measured along the development process. The sum is named 'Development Time' (DT). This may correspond to the resource effort spent by the process engineering and shop floor resources to optimize an existing process in an industrial environment.

Since the aim of the study is to highlight the efficiency of the integration of collaborative robotics, the performance output cannot be considered alone. Thus, DT is recorded and compared for each process to ensure they represent similar amount of resource usage. Each process involving manual operations has natural fluctuation for each of its cycle. Thus, in order to obtain reliable and comparable measurements at each step, each production run has been broken down into elementary operations through video analysis. For each elementary operation, minimal repeatable value achieved through a minimum of 5 cycles withour abnormamity was saved for calculation of CT (Videos of each process are available at the following URL: https://www.youtube.com/playlist?list=PLEUzN_0cAg_lSzqMKHTwfzxxjpSOhJDTj). This work is visualized by using Standard Work Combination Table (SWCT) – a lean tool that highlights the manual and automated operation, and their interaction under a timeline format.

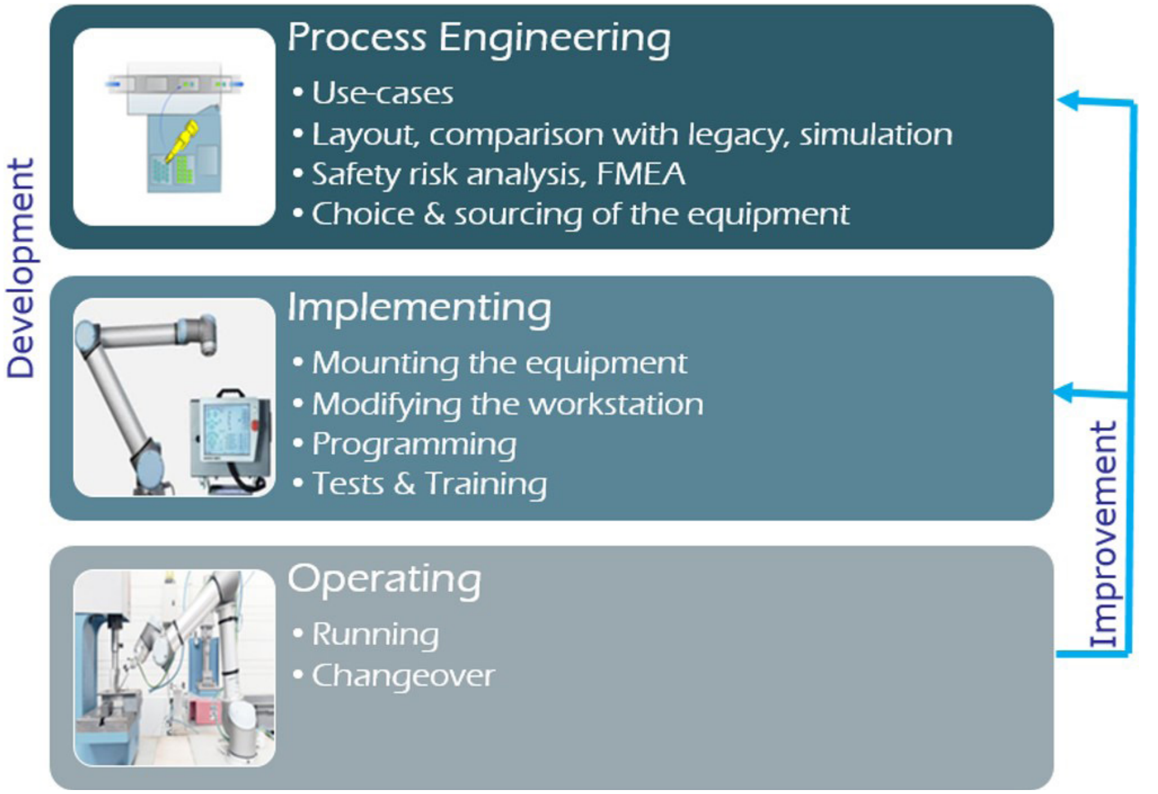

Figure 2. The three phases of cobotics project.

2.4.2 Assessment of experiment results

Performing partial automation of a manual process may be seen as a line-balancing problem of two operators, one of them being the cobot. The resulting cycle time will correspond to the work content of most heavily loaded operator. A theoretical optimum cycle time could be achieved (CT_{ideal}), based on equal workload between operator and cobot (Figure 3), i.e. no waiting time on each side. At this stage, we may consider that any manual operation is transferable to the cobot, nevertheless we could already observe that there is difference in pace between operator and cobot for the execution of the same task. This **pace ratio** (later referred as 'k') can be determined by comparing the transferred time (amount of manual operations removed from operator workload) and cobot working time (resulting cobot workload to carry out those operations). Using k to predict cobot workload implies that transferred operations are of the same nature, which will be verified in the experiment conducted in this case study. We also defined a **transfer ratio** (later referred as 'R'), representing the amount of task allocated to the cobot, equal to **transferred time** compared to the corresponding manual process CT (R=0: fully manual, R=1: fully automated).

Given CT1 is the initial cycle time of the full manual process.

$$CToperator = CT1 \times (1 - R) \tag{1}$$

$$CTcobot = k \times CT1 \times R \tag{2}$$

Best balancing is achieved for $CToperator = CTcobot$, i.e.

$$CT1 \times (1 - R) = k \times CT1 \times R <=> R = \frac{1}{1+k} \tag{3}$$

The corresponding cycle time is then: $CT_{ideal} = \dfrac{CT1}{1+\frac{1}{k}}$

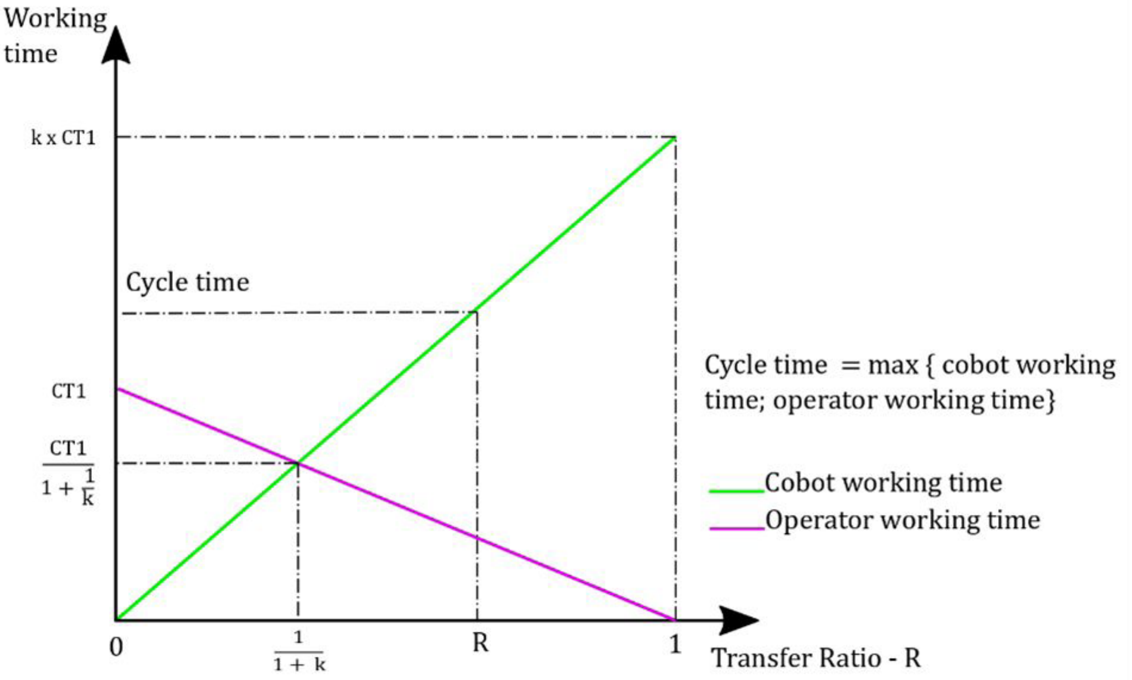

Figure 3. Cycle time achievement based on transfer ratio.

Along with the pace ratio, transfer ratio and transfer time, we propose to use two additional terms to describe this process, which are explained below:

- **Additional handling:** measures the quantity of work added to the operator's work content due to the introduction of a cobot. This may consist in cobot activation during the cycle execution, and hand movements in order to reach the fixed delivery position of the cobot from its pick and place operations.

- **Waiting time:** represents the total time during which the operator has to wait for the cobot to complete its task before to complete his own.

As described earlier, two techniques are available to reduce cycle, and can be used concurrently (Figure 4):

1. Transferring manual operation to cobot.

2. Applying continuous improvement techniques (kaizen) to manual operations to reduce their work content.

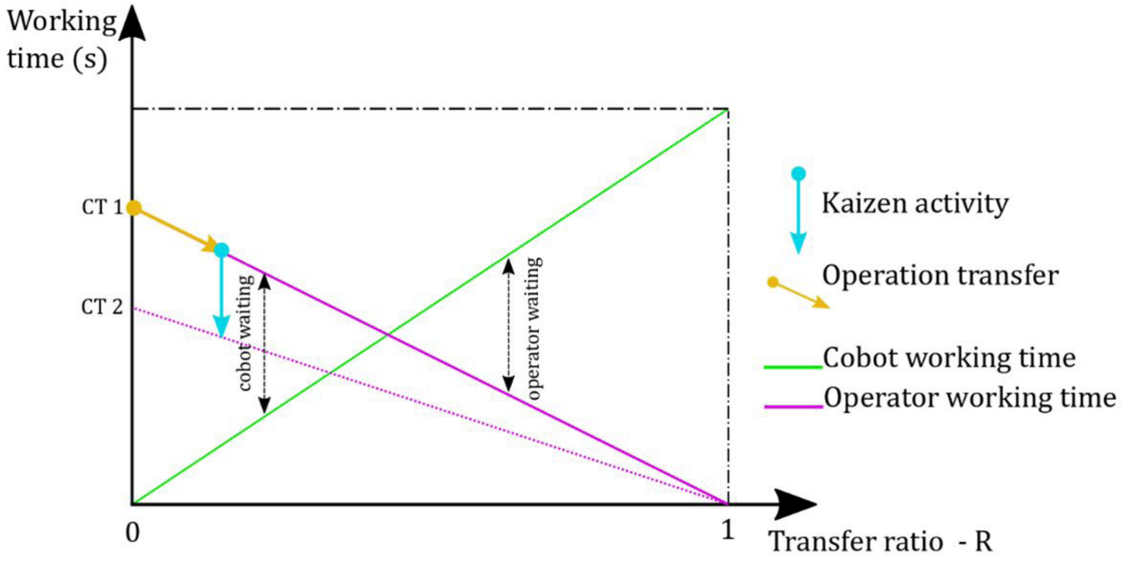

Figure 4. Operation transfer and kaizen impact on CT.

Additionally, there is no benefit to perform operation transfer beyond the point of equal workload of operator and cobot (corresponding to CT_{ideal}), since resulting CT will only increase and generate operator waiting time, thus making any further kaizen activity on manual operations worthless.

Nevertheless, operation transfer is limited by two factors:

- Remaining cobot waiting time is too small to transfer further manual operations,

  i.e. $Cobot\ waiting\ time \leq \mathrm{k} \times \min\{remaining\ manual\ operations\}$

- Remaining manual operations complexity in regards to team skills is too high to consider transfer towards cobot.

3. Experimental application

3.1. Case study selection

Following considerations from section 2, we selected a pneumatic cylinder, as described in Figure 5. The work content for the manual assembly of its eight sub-components as presented in Figure 6 was measured at 46.5

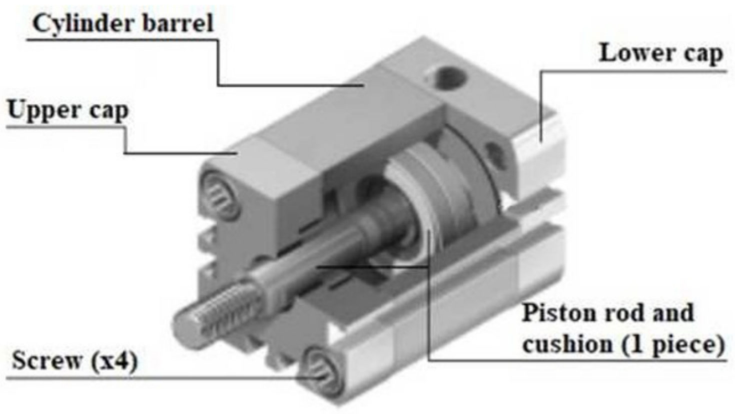

Figure 5. Pneumatic cylinder (from manufacturer's catalogue).

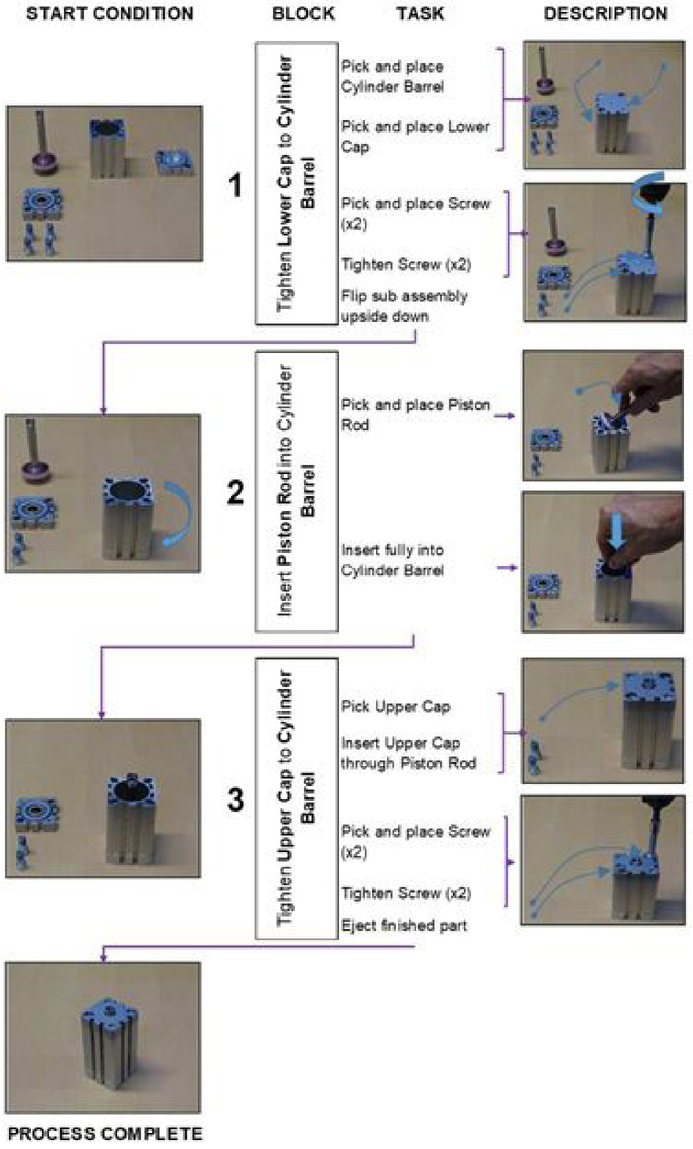

Figure 6. Pneumatic cylinder assembly sequence.

seconds. Operations involved in this process are mainly part setting and tightening, and the only deformable part is the 'piston rod and cushion', with its soft plastic gasket. The cubic shape of most sub components should also make them easy to pick by cobot effector.

3.2. Experimental results

Step 1. Initial setup.

The results of initial confirmation of manual processes M-1 (see Figure 7) and M-1' show comparable achievement for both teams (Table 1). Operator motion speed was also compared between teams to avoid any bias.

Block	N°	Task element	Duration (s) Operator Work	Operator Wait	Robot Work	Robot Wait
1	1	pick and place cylinder barrel	1,6			
	2	pick and place lower cap	1,3			
	3	pick screw x2	1,5			
	4	place screw x 2	2,3			
	5	pick and set screw gun	2,5			
	6	tighten screw 1	5,5			
	7	screw gun transfer	1			
	8	tighten screw 2	5,5			
2	9	turn cylinder barrel upside down (& return gun to home position)	1,2			
	10	pick and place piston rod	1,7			
	11	insert piston rod	1,6			
3	12	pick upper cap	1,5			
	13	install upper cap on rod & barrel	1			
	14	pick screw x2	1,5			
	15	place screw x 2	1,8			
	16	pick and set screwgun	1,7			
	17	tighten screw 1	5,5			
	18	screw gun transfer	1			
	19	tighten screw 2	5,5			
	20	eject part (& return gun to home position)	1,3			

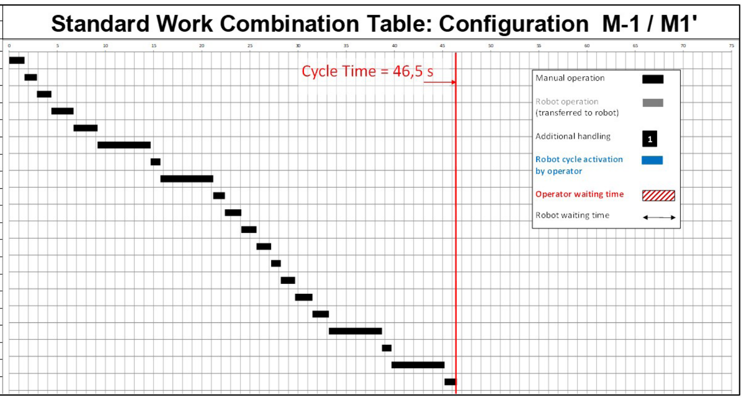

Figure 7. SWCT for process M1/M1'.

Table 1. Manual process confirmation.

	CT (s)
Team A (M1)	46.5
Team B (M1')	47.2

Step 2. Training on lean techniques.

Team B was proposed to use their acquired lean techniques to improve M1 cycle time through elimination of unnecessary gestures. A 2 seconds CT reduction could be achieved, through reduction of motion and simultaneous use of both hands to perform sub assembly operations as detailed in Figure 8.

Step 3. Technical skills acquisition and utilisation.

After the self-training session, both teams could operate their cobot for the tasks involved in the assembly process. They were then invited to improve the CT of their respective manual processes (M1 & M2) by introduction of cobot.

Team A, in spite of a higher development time (see Table 2), could not improve M1 CT, as visualized in Figure 9. The main contributors of this degradation are the additional handling operations due to multiple activation of cobot during the cycle, and the generation of operator waiting time (see Figure 10).

Team B could reduce M2 cycle time by 2 sec. (see Figure 11), with comparable transferred time to team A, but could minimize the quantity of additional handling with one interaction with cobot per cycle, and avoid operator's waiting time (see Figure 12). They also managed to reproduce the kaizen from M2 into the collaborative process (see operation 13 & 14, in Figure 11).

Step 4. Improvement of partial automation.

Team B was offered the opportunity to reduce further the CT of their collaborative process PA-2, with no guidance on the method to be used (operation transfer or kaizen on manual operation). An additional reduction

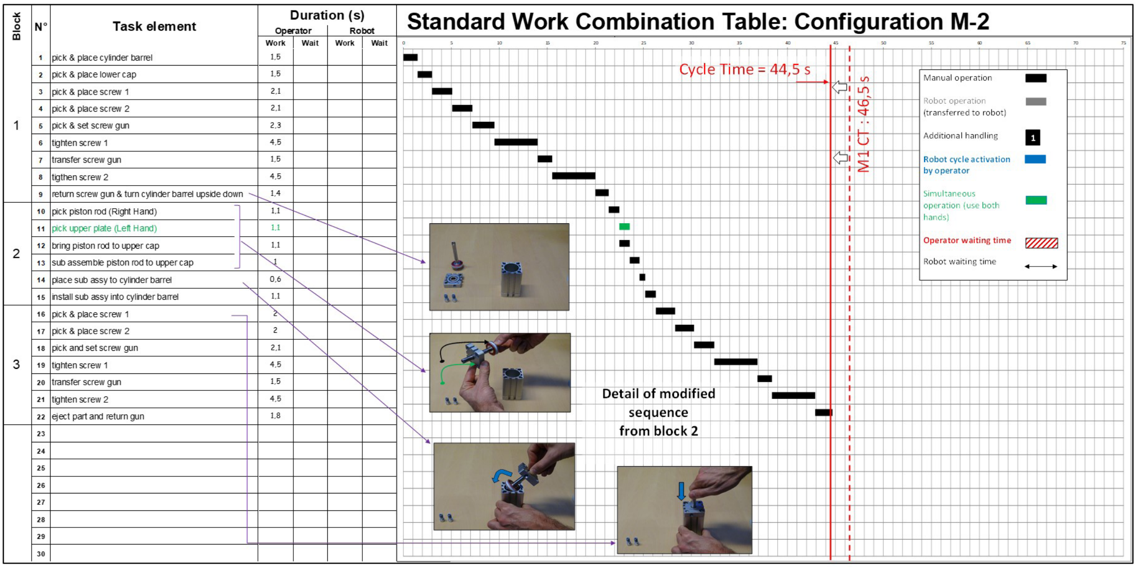

Figure 8. SWCT for process M2.

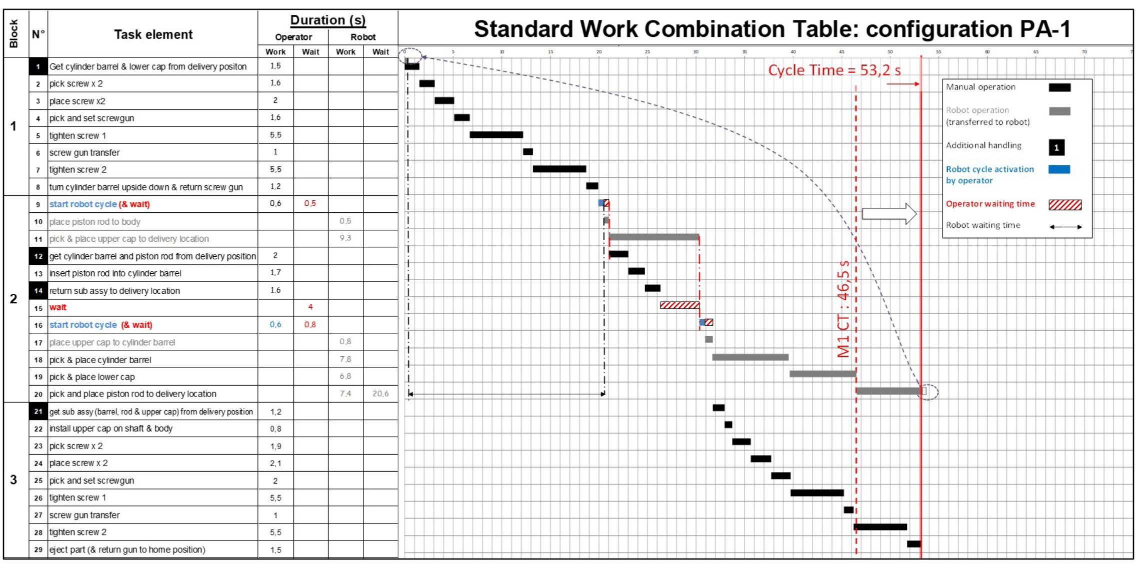

Figure 9. SWCT for process PA-1.

Table 2. Summary results.

	Team	Dvpt time (hours)	CT (s)	Operator		Transferred time (s)	Transfer ratio – R	Robot		Pace ratio – k
				work (s)	wait (s)			work (s)	Wait (s)	
M1	A	-	46.5	46.5	N/A*	N/A*	N/A*	N/A*	N/A*	N/A*
PA-1	A	14	53.2	47.9	5.3	5.4	0.12	32.6	20.6	6.04
M2	B	5	44.5	44.5	N/A*	N/A*	N/A*	N/A*	N/A*	N/A*
PA-2	B	5	42.1	42.1	N/A*	5	0.11	28.8	13.3	5.76
PA-3	B	5	40.0	40.0	N/A*	5	N/A*	28.8	11.2	N/A*

*Not Applicable.

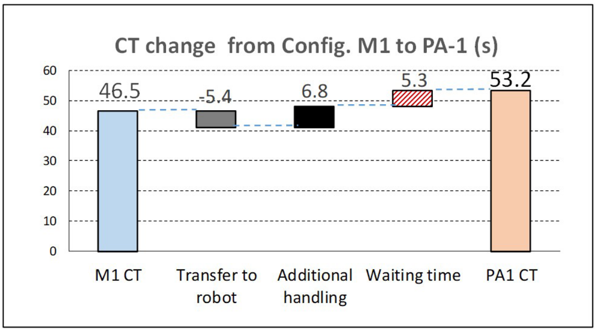

Figure 10. Team A's collaborative solution result.

Block	N°	Task element	Duration (s) Operator Work	Operator Wait	Robot Work	Robot Wait
1	1	get cylinder barrel & lower cap from delivery position	1,4			
	2	pick & place screw 1	2,6			
	3	pick & place screw 2	2,5			
	4	pick & set screw gun	1,7			
	5	tighten screw 1	4,5			
	6	transfer screw gun	1,5			
	7	tigthen screw 2	4,5			
	8	return screwgun to home position	1,6			
2	9	get piston rod & upper cap sub assy (cycle start)	1,8			
	10	deliver piston rod & upper cap			0,3	
	11	pick & place cylinder barrel			7,7	
	12	pick & place lower cap			8,7	
	13	pick upper cap			4	
	14	sub assy upper cap to piston rod			3,5	
	15	place sub assy to delivery position			4,6	13,3
	16	place sub assy to cylinder barrel	1,3			
	17	install sub assy into cylinder barrel	1,2			
3	18	pick & place screw 1	2			
	19	pick & place screw 2	1,5			
	20	pick and set screw gun	1,8			
	21	tighten screw 1	5			
	22	transfer screw gun	1,2			
	23	tighten screw 2	4,5			
	24	eject part and return screw gun	1,5			

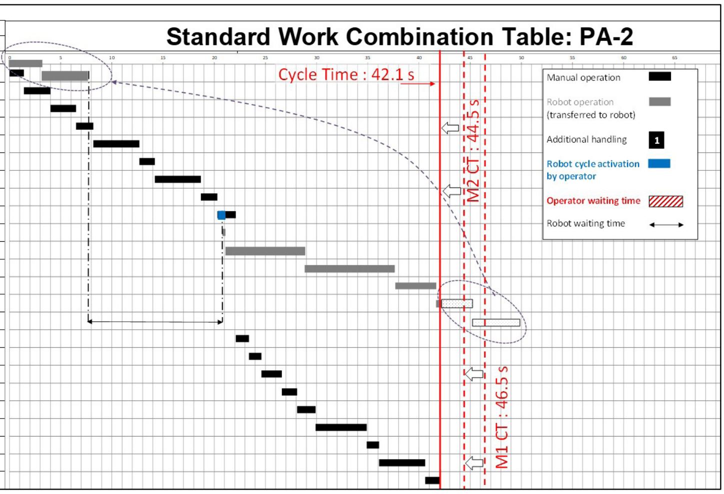

Figure 11. SWCT for process PA2.

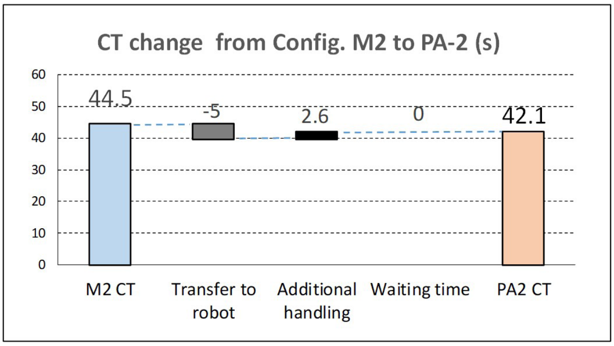

Figure 12. Team B's collaborative solution result.

of 2.1 sec. could be achieved, through kaizen on remaining manual operations, without altering the cobot operations (see Figure 13).

3.3. Discussion on experimental results

Firstly, the pace ratio (k) values were close enough for both teams, with an average value of k=5.9. The nature of the transferred operations was mostly of the same nature (pick and place), so logically the value for k was in the same range for both teams.

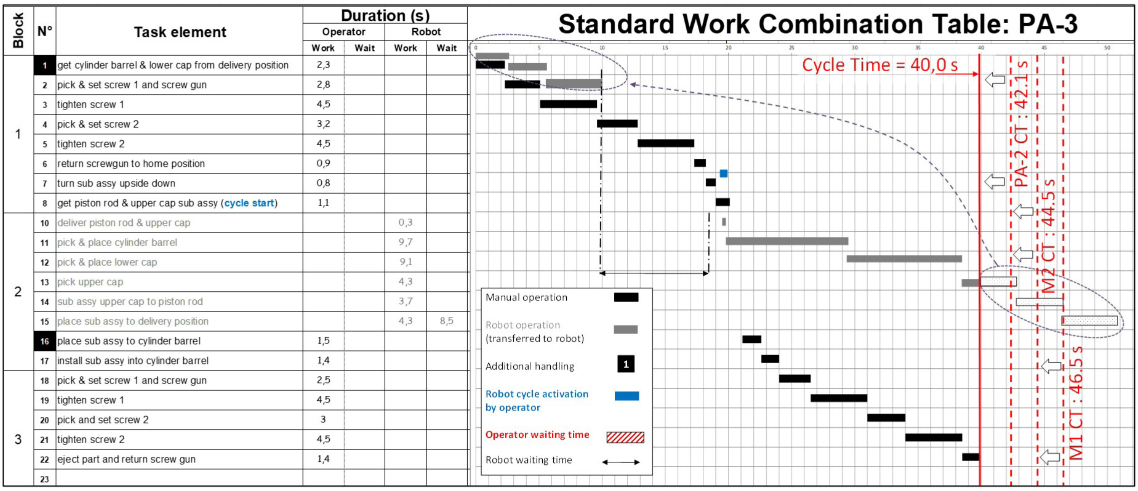

Figure 13. Team B improved collaborative solution.

Based on M1 cycle time and k (Table 2), we can determine $CT_{ideal:}$
CT1 = 46.5 seconds, and k= 5.9 based on average of Team A & B

$$CTideal = 46.5 \div \left(1 + \frac{1}{5.9}\right) = 39.8\ sec. \tag{4}$$

The associated transfer ratio value being:

$$R = \frac{1}{1+5.9} = 0.14 \tag{5}$$

- Comparison of collaborative solutions (PA-1 & PA-2)

Both processes showed similar values for R (see Table 2), below the threshold value of 0.14. Nevertheless, this resulted in significantly different performances for CT. It can be noticed that in the case of PA-1, the transferred time benefit has been totally cancelled by the additional handling time, since two cobot and operator interactions were necessary per each assembly cycle. On top, the sequencing of tasks allocated to cobot generated operator waiting time and further degraded cycle time.

Furthermore, team B carried the saving obtained by lean techniques (operations 10 to 13), into the collaborative process. They could achieve a single operator and cobot interaction, maintaining additional handling at a lower level. Additionally, applying lean principle of man and machine separation kept their focus on avoiding the operator to face idle time. Such strategy enabled to save further time on an already improved manual process. Therefore, we may recognize at this stage that lean techniques support efficient integration of collaborative robotics. In addition, the process of eliminating waste through motion reduction from manual operations (step 2) prior to cobot introduction (step 3) proves efficient when such operations are being transferred to cobot with increased impact on CT.

- Improvement strategy on collaborative process (PA-2 to PA-3)

As no guidance was given to team B for this improvement step, both operation transfer and manual operation kaizen strategies were available towards cycle time reduction. As a result, kaizen of manual operations was selected. Some team debriefing was carried out to understand the facts underlying their decision: with a cobot waiting time of 13.2 s, operation transfer strategy could have been applied to manual operations up to 2.2 sec. long, providing they would not generate additional handling time. This is the case for the insertion of piston and cap sub assembly insertion into barrel, referred as operation 16 and 17.

Due to the perceived complexity of this task, team B fed back that they rather decided to focus on kaizen, stating that the time spent in repeating assembly process to build PA-2 had provided hints for further kaizen - as additional usage of both hands, which they applied for PA-3. This confirmed the assumption for potential limitations in operation transfer towards cobot, and that some trade-offs between additional automation and application of lean techniques may be beneficial, as long as process permits it, i.e. operator keeps the highest workload.

- Implication of skills acquired on process design performance

Students from team A and B could also feedback freely on the skills they gained during this project. This activity may give insights on additional success factors at organizational level. Results described in Table 3 suggest that beyond expectable results for robotics related competencies, participants form Team B developed - through practice - a number of lean related skills after their initial training by supervising teacher. Interestingly, a set of soft skills including behavior have been mentioned, such as teamwork and accountability in connection with lean process management (Liker, 2005). Through this case study, it could be observed that performance improvement is achieved thanks to the combined usage of lean related and technology related skills (Figure 14).

Lean related skills have positive impact on the following stages:

a. Effective operation transfer: PA-2 vs PA-1 (avoid creation of operator waiting time).

b. Manual cycle time reduction (kaizen).

Technology related skills have positive impact on:

a. Achieving better operation transfer (R) value, closer to optimum.

Table 3. Skills acquisition.

		Team A	Team B
Hard skills		Trajectory optimisation	Trajectory optimisation
	Robotics	Programming	Programming
		Understanding cobot's ability	
	Process design	Layout optimisation	Layout optimisation
		Assembly task sequencing	Process video analysis
		Task allocation	Waiting time elimination
Soft skills		Time and priority management	Job and responsibility sharing
		Teamwork	Teamwork
			Accountability

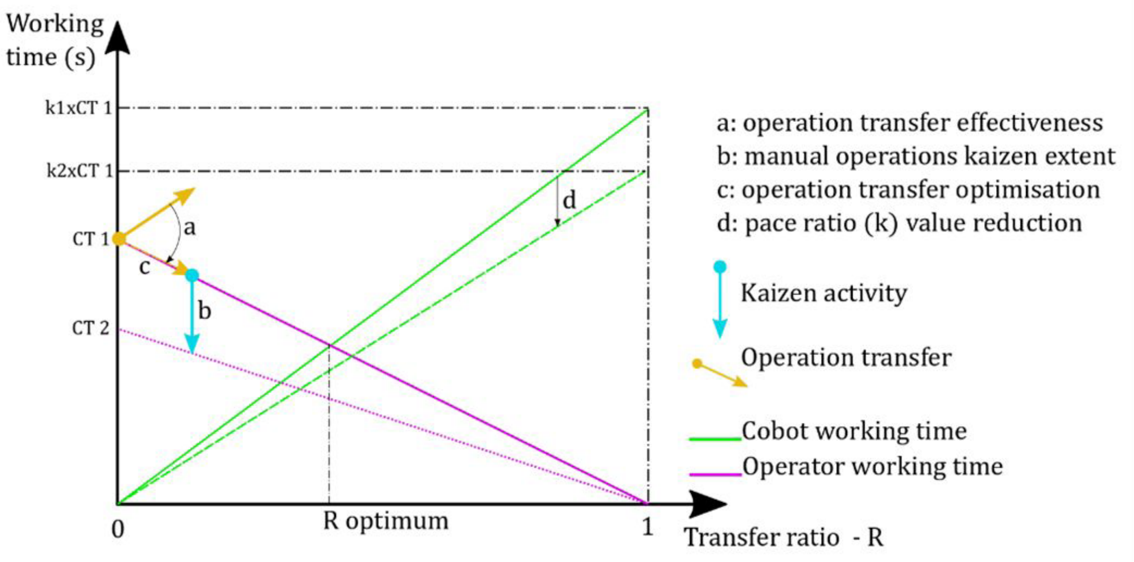

Figure 14. Skill influence on performance achievement.

Combination of lean and technology related skills:

a. Reduction of k (pace ratio) value.

Although it has not been formally tested during this case study, reaching improved value of the pace ratio (k), for a given type of operation, could participate to lower cobot workload, offering more task transfer opportunities, and lower CT_{ideal} values. By debriefing with students on their strategy, it was understood that cobot working time was purposely kept low for a given task, although no kaizen activity on this aspect was formally carried out. Moreover, process videos review highlight room for improvement in cobot trajectory in order to minimize pick and place operation times. We may assume such activity would require combination of both lean and technology skills (motion reduction principles and use of higher-level trajectory control functions).

4. Conclusion and further works

Industry 4.0 concept has now emerged for several years. This industrial revolution enables usage of new technologies, such as cobot, contributing to transform an environment previously managed according to lean manufacturing methods. In this paper, we aimed to define the success factors for efficient integration of cobots in conjunction with lean techniques. To do so, we made an experimental study: two teams of students had to develop the best operations sequence and content to assemble a pneumatic cylinder, using lean techniques and cobot. An experimental protocol has been proposed: how to design and perform the experiment to achieve significant results, and how to utilize these results to answer the research questions. From the initial process, 6.5 sec. could be saved (14% CT reduction): 2 are directly accountable to waste elimination in the manual process, but this kaizen, when replicated in the collaborative process creation stage (step 3), participated to the overall saving of 2.5 sec. of this solution. Later, the 2 sec. improvement on the collaborative process are also a direct application of waste elimination in manual operation, but the resulting saving they brought on the overall process is achieved through proper design of operator / robot separation (otherwise it could have simply generated additional operator waiting time). So even though improvement actions can be measured separately, the process and sequence used to implement them also has an effect on the overall performance obtained.

To conclude, lean related skills are key to determine the most appropriate allocation and sequence of operations. Technology related skills have positive impact on the effectiveness of cobot usage. Therefore, combination of lean and technology related skills has a greater impact on reduction of cycle time, than each set of skills applied separately.

An iterative method – showing similarities with kaizen cycle – has been identified and may give with simple empirical testing some insights to practitioners of the expectable CT improvement on a given process through usage of cobot.

Nevertheless, further loops of process improvements will be necessary to test its validity, along with the exploration on how far collaborative robots can enhance process efficiency, and whether additional skills may be required to unlock higher levels of performance. Such development may also open ways to consider operator skills development, but also the roles and responsibilities through a collaborative robotics integration, as a human centered process. The experimental determination of a pace ratio between operator and cobot (k), although not new in itself, may support decision making process for task allocation with better confidence on its applicability in real production environment. Nevertheless, additional work is necessary to determine k values for different types of operation in order to reach better prediction accuracy for $CT_{ideal.}$ Both teams had to perform some adaptions of their part containers to enable the locating and picking by the cobot. This will have some detrimental effects on both cubic efficiency and container exchange frequency, which will have to be measured and considered in the final efficiency gain balance, in order to give a more realistic image of production environment. In this case study, the limited work content and unicity of product gave some straightforward decision for task allocation to operator and cobot, as Industry 4.0 aims at mass customization. Further work should consider more complex assembly situations, especially including product variety, to understand whether this experimental task allocation and kaizen work frame remains valid under its current form.

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