Process optimisation using collaborative robots - comparative case study

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Abstract: Human Robot Collaboration is seen as a significant feature of Industry 4.0 implementation. Collaborative robots (cobots) are supposed to deliver superior process performance, which was so far achieved through the application of Lean Manufacturing techniques. The following case study, built around the assembly process of a pneumatic cylinder, tends to analyse not only the actual benefits of cobot implementation, but also the success factors, in conjunction with Lean Manufacturing usage. Finally, this paper suggests a draft method towards the successful integration of cobot.

Keywords: collaborative robot, lean manufacturing, process improvement, integration method

1. INTRODUCTION

For the past few years, there has been an emerging shift to the '4th industrial revolution', also called 'Industry 4.0', a term first used by the German government. In the structured literature reviews (Liao et al., 2017), (Maghazei and Netland, 2017), (Moeuf et al., 2018), robotics is listed as one of the technologies participating in this 4th industrial revolution. A collaborative robot - named cobot, is a robot which has been specifically designed to work simultaneously and safely with humans - without safety cages/fencing - in shared workspaces. The objective is to improve the operations by delegating tasks to the cobot, and let the human operator carry out the tasks that cannot be handled by the cobot (Petruck et al., 2018). Based on a German survey (Bauer et al., 2016), the top-3 reasons to choose to implement cobots are: 1-operational efficiency, 2-innovation and 3-ergonomics.

Concurrently, Lean Manufacturing has so far been recognised as a leading model to achieve a sustainable operations improvement, relying on limited investments and therefore a controlled level of automation.

Both similarities and contradictions can be seen between Industry 4.0 and Lean Manufacturing models. They both seek a higher efficiency in operations, and consider human as a key asset in this improvement process. Nevertheless, Industry 4.0 can be seen as 'technology centered', whereas Lean Manufacturing is rather methodology orientated for performance enhancement. At conceptual level, several potential interaction scenarios between those two models 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) (Satoglu et al., 2018) (Kolberg and Zühlke, 2015). Such scenarios are still mainly theoretical and the use cases mostly described as 'to be' situations, offer little view for practitioners on how to shift from their current operations towards the integration of 4.0 technologies.

Through a case study, we suggest contributing to filling this gap by trying to answer the two following questions:

- How to assess the benefits of collaborative robot with figures?
- Are there any success factors in relationship with Lean Manufacturing?

2. CONDITION OF RESEARCH

2.1 Case study

A case study was built around a simplified manual assembly process of a pneumatic cylinder, see fig .1. This case offers some different types of tasks to be carried out, with different levels of complexity, see fig. 2. In order to mimic the integration process of a cobot into an existing production environment, it was decided to build first a fully manual process on which tentative optimisation loops will be implemented. The purpose is to compare different optimisation strategies and highlight potential success factors.

We selected Universal Robot^{TM} UR5 cobot, for the ease of use and the availability of online self-training material (*Universal Robots academy*).

2.2 Initial Setup

In order to minimise the impact of operators' experience during the comparison process, 2 separate teams - A and B - were gathered, with limited communication opportunities. They were composed of some 4th and 5th year students

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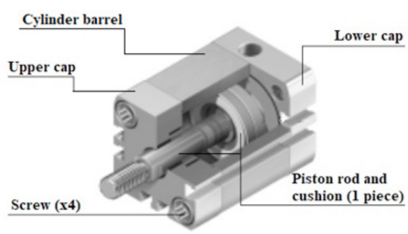

Fig. 1. Pneumatic cylinder description - from manufacturer's catalogue

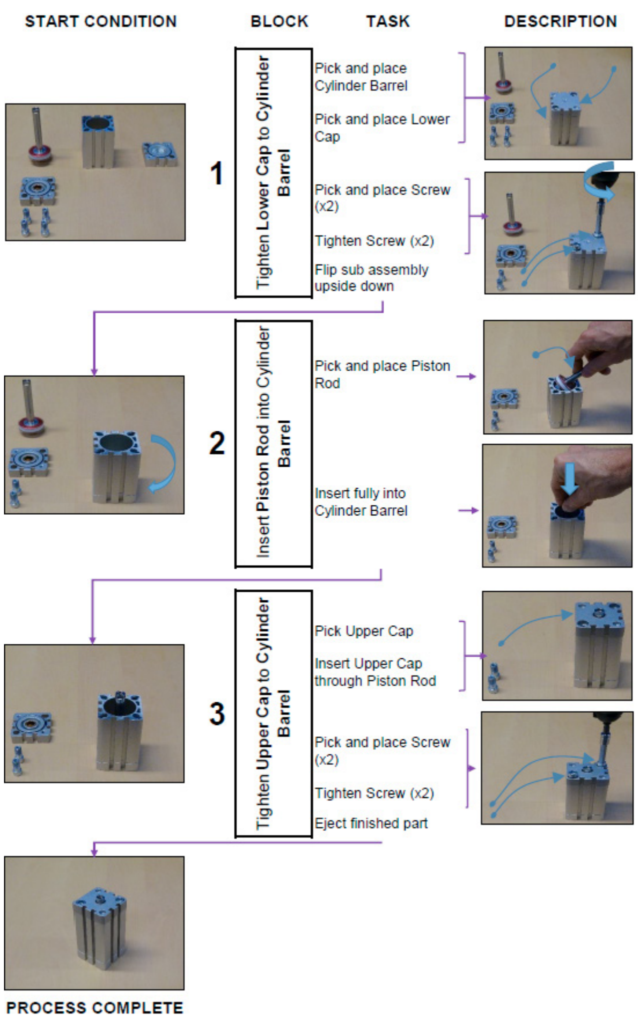

Fig. 2. Pneumatic cylinder assembly sequence

in Mechanical Engineering from two separate campuses: ECAM Lyon (Team A) and Arts et Métiers Lille (Team B). It was checked that they had no knowledge on robot programming prior to this study.

Conditions of research with the successive process configurations are shown in fig. 3.

To ensure similar initial conditions, Team A developed a fully manual assembly process: M-1, which was replicated by Team B based on video analysis: M-1'. It was then checked Teams A and B achieved comparable Cycle Time (CT) on their respective processes, this is confirmation stage C1. From this point, both teams were given the same

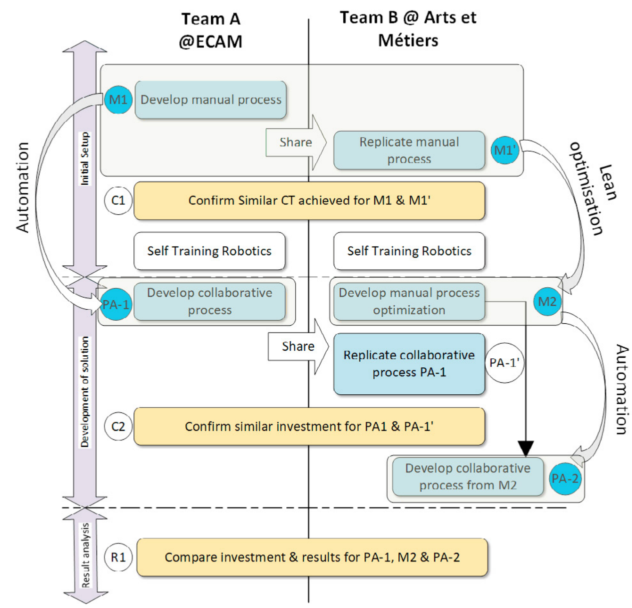

Fig. 3. The conditions of research

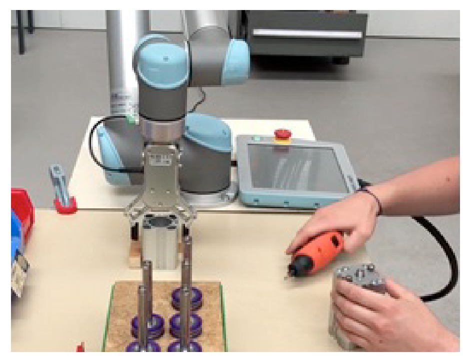

Fig. 4. Collaborative solution

training opportunity through *Universal Robots Academy* - an online tutorial for UR cobots.

2.3 Development of solution

Team A immediately started the engineering stage of collaborative solution: PA-1, whereas Team B was given the opportunity to study and propose some improvements prior to the start of the integration of the collaborative solution: M-2. The purpose of this intermediate step is twofold:

I. With limited time available, can we obtain, through the regular continuous improvement tools, some comparable benefits to collaborative automation?

II. Prevent Team B from developing some similar types of collaborative solutions to team A's.

As a second control item – C2, Team B was asked to replicate the solution PA-1 from Team A, to confirm that the skills acquired during the self-training stage were comparable. This is process PA-1'. See fig. 4.

Finally, Team B was asked to develop their own collaborative process: PA-2. Videos of each process are available at the following URL (youtube): `http://yt.vu/p/PLEUzN_OcAg_lSzqMKHTwfzxxjpSOhJDTj`

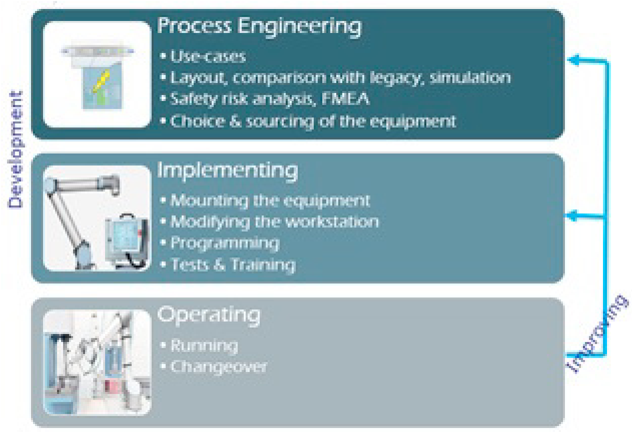

Fig. 5. The 3 phases of cobotics development

2.4 Result analysis

The review conclusion by (Maghazei and Netland, 2017) suggested examining the research alongside with the characteristics of the Advanced Manufacturing Technologies (AMT) in terms of: the technology evaluation before implementation, the implementation phase, the outcomes (operational, organisational, strategic, and social) and the contextual variables that can have an influence. Therefore we divide a cobotics project into 3 successive phases as described in fig. 5. 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 the students will be measured through the development process. The sum will be called 'Development Time' (DT). This may correspond to the resource effort spent by the process engineering and shop floor resources to optimise an existing process in an industrial environment. The performance output will be measured by the reduction of the average Total Cycle Time (controlling standard deviation remains comparable to the initial). It will be called ΔCT. Since the aim of the study is to highlight the efficiency of the integration of collaborative robotics, the performance output cannot be considered alone, even though it is itself a significant parameter. Thus, we propose to visualise each solution with Development Time vs ΔCT, and compare them.

2.5 Analysis tool

Each production run has been video recorded for analysis. The blocks and the tasks of the observed process were broken down into task elements in order to capture and quantify the detailed impacts of each solution. This work is visualised by using Standard Work Combination Table (SWCT), a Lean Manufacturing tool that highlights the manual and automated tasks, and their interaction under a timeline format. SWCT for each manual and partially automated process can be found in Appendix A.1, A.2, A.3.

Table 1. Manual process confirmation C1

	Av. CT	σ(n=8)	Variation Coeff.
Team A (M1)	46.5s	6.1s	13%
Team B (M1')	47.2s	4s	9%

Table 2. Collaborative process confirmation C2

	Dvpt time	Av. CT	σ(n=4)	Variation Coeff.
Team A (PA-1)	14 hrs	53.5s	4.4s	8%
Team B (PA-1')	16 hrs	52.5s	3.4s	6%

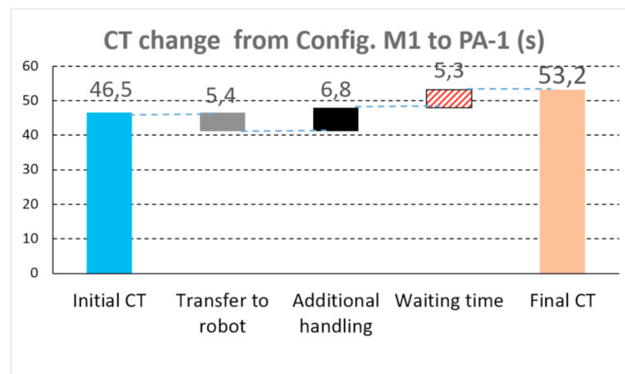

Fig. 6. Team A's result for PA-1 cycle time

3. RESULTS

3.1 Initial setup

The results table of initial confirmation of manual processes M-1 and M-1' show comparable achievement for both teams, see table 1. It was then decided to move to the next step and include a cobot for Team A - config. PA-1, while Team B would perform continuous improvement loop on the manual process : config. M-2.

As a second confirmation item, Team B replicated the team A's collaborative process regardless of their own improvements (config. PA-1'). The respective development times are then compared, see table 2.

Again, the results are comparable, and it was assumed that both teams acquired similar skill level in Robotics through their self-training stage.

3.2 Team A's collaborative process

No specific guidance was given to team A on how to integrate the cobot in the manual process, just only to try to transfer the operations towards the robot. Despite the cobot introduction, Cycle Time has not been improved overall. The main impacting factors were highlighted on fig. 6.

Transferred time to robot measures the amount of manual work that was removed from the operator's work content of the initial process. It is mainly the pick and place operations in this case study, as they are perceived as quickest to develop.

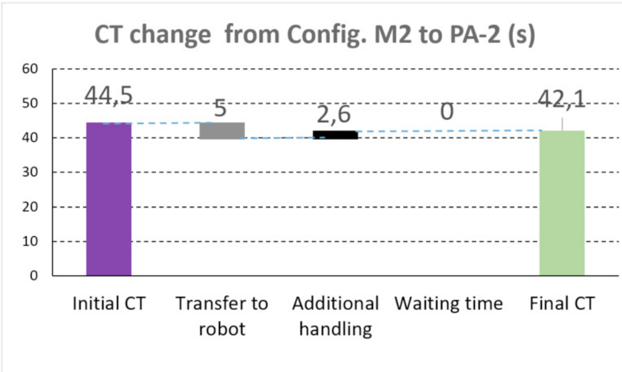

Fig. 7. Team B's result for PA-2 cycle time

Additional handling measures the quantity of work added to the operator's work content, due to the introduction of a cobot. In our case study, it mainly consists in the activation of the robot through a touch panel and the movements related to the fixed delivery position of the cobot from its pick and place operations. In Team A case, this time alone -7s- is higher than the transferred time (5.4s), hence already cancelling at this stage the benefit from the automation.

Waiting time represents the total time during which the operator has to wait for the cobot to complete her/his own task. Due to the duration and the sequencing of automated operations versus manual ones, a total operator waiting time of 5.3s has been created.

The details of both manual and collaborative processes can be found in Appendix A.1 and A.2, where those times captured through video analysis have been highlighted.

3.3 Team B's collaborative process

Prior to developing their processes, Team B had been given a 4 hour course on Lean techniques, covering the following items: standardised work creation and kaizen, operation time reduction, jidoka (man and machine separation). From this point onwards, students worked in autonomy until their processes were finalised.

Step 1: manual process improvement Team B achieved a CT of 44.5s, i.e. 2s reduction through the improvement on the combination of tasks and the sub component relocation to minimise the motion distances. This step's purpose is also to trigger some new ideas for automation (configuration M2).

Step 2: collaborative process creation After a development time of 5 hours, Team B did set-up a process 2.4s shorter than the initial one, see fig. 7

The *transferred* time is comparable to the config. PA1, but the *additional handling* time was maintained at a lower value thanks to the single activation of the cobot per total cycle (versus 2 for previous config. PA-1). Finally, Team B controlled the task sequencing between the operator and the cobot during the process development to avoid generating some operator *waiting time*. The detailed image of the manual and the collaborative processes can be found in Appendix.

3.4 Summary results

In both team A and B cases, when incorporating cobot, the resulting robot working time was close to 6 times the corresponding manual work from the original process See table3. Although this first finding is based on a very limited number of trials, it may give an idea on opportunities entailed the cobot integration. Further work is required to better identify any correlations, including other types of operations than pick and place or simple assembly.

Nevertheless, based on both team strategies, an outline for a method appears, which could be sequenced as follows:

1. Run initial optimisation loop to avoid spending time automating some inefficient operations

2. Select the candidate tasks for the automation based on their complexity versus team skills: define target transfer time

3. Evaluate the subsequent cobot working time (consider transfer time x 6 for low complexity operations). Verify robot working time <(Initial CT − transfer time)

4. Simulate the process sequence and verify no generation of some operator waiting times

5. Implement the process. Stabilise the results

6. Check the resulting cobot waiting time

7. Run another loop from step 2., considering a target transfer time in accordance with the cobot waiting time identified in 6.

4. CONCLUSIONS

Cobot integration can have some positive impacts on operation performance, even with limited development time. In some industrial applications, this may support a Takt time change without having to add under-utilised human resources, or limit the usage of overtime (Gil-Vilda et al., 2017). To that extent, the collaborative robot may support flexibility of the Lean Manufacturing environment. This experiment also highlights Lean Manufacturing techniques – standardised work analysis, continuous improvement (Kaizen), Man and Machine separation – as some key success factors for effective introduction of cobots. Besides, students from Team A and B were given the opportunity to feedback freely on the skills they thought they gained during this project. This activity may give hints on additional success factors to be considered at organisational level. Results described in table 4 suggest that beyond expectable results for robotics related competencies, a number of Lean related skills have been acquired on top of guidance from supervising teacher. Interestingly, a set of soft skills including behaviour have been mentioned, such as teamwork and accountability, also in connexion with Lean process management (Liker, 2005).

5. LIMITATIONS AND FURTHER DEVELOPMENTS

An iterative method, showing similarities with Kaizen cycle – has been identified, but some further loops of process improvements will be necessary to test its validity, along with the exploration on how far collaborative robots can

Table 3. Result summary.

	Team	Dvpt time (*hours*)	CT (*s*)	Operator work (*s*)	Operator wait (*s*)	Transfer-red time (*s*)	Robot work (*s*)	Robot wait (*s*)
M1	A	-	46.5	46.5	N/A	N/A	N/A	N/A
PA-1	A	14	53.2	47.9	5.3	5.4	32.6	20.6
M2	B	5	44.5	44.5	N/A	N/A	N/A	N/A
PA-2	B	5	42.1	42.1	N/A	5	28.8	13.3

Table 4. Skills acquisition.

		Team A	Team B
Technical skills	Robotics	Trajectory optimisation Programming Understanding of robot's ability	Trajectory optimisation Programming
	Process design	Layout optimisation Assembly task sequencing Task allocation	Layout optimisation Process video analysis Waiting time elimination
Soft skills	Organisation	Time and priority managment	Job and responsability sharing
	Behaviour	Teamwork	Accountability Teamwork

enhance the process efficiency, and whether additional skills may be required to unlock higher levels of performance. Such development may also open research on operator skill development, as well as roles and responsibilities entailed by cobot integration as a human centred project.

Besides, both teams had to carry out some adaptations of their part containers to enable cobot to conduct pick and place tasks. This will have some detrimental effects on box design cost and 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 the production environment.

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6. ACKNOWLEDGEMENTS

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Appendix A. STANDARD WORK COMBINATION TABLES OF EACH PROCESS (SWCT)

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			

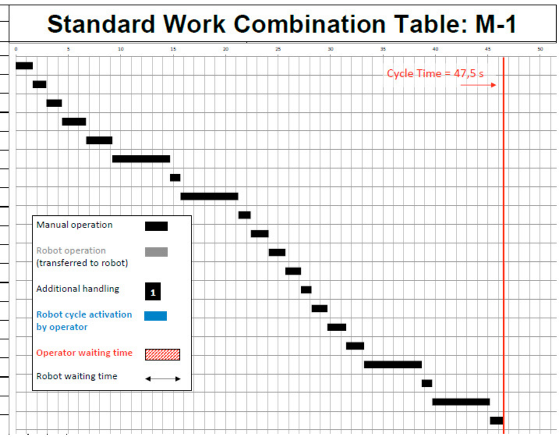

Fig. A.1. SWCT for process M1

Block	N°	Task element	Duration (s) Operator Work	Operator Wait	Robot Work	Robot Wait
1	1	Get cylinder barrel & lower cap from delivery positon	1,5			
	2	pick screw x 2	1,6			
	3	place screw x2	2			
	4	pick and set screwgun	1,6			
	5	tighten screw 1	5,5			
	6	screw gun transfer	1			
	7	tighten screw 2	5,5			
	8	turn cylinder barrel upside down & return screw gun	1,2			
2	9	start robot cycle (& wait)	0,6	0,5		
	10	place piston rod to body			0,5	
	11	pick & place upper cap to delivery location			9,3	
	12	get cylinder barrel and piston rod from delivery position	2			
	13	insert piston rod into cylinder barrel	1,7			
	14	return sub assy to delivery location	1,6			
	15	wait		4		
	16	start robot cycle (& wait)	0,6	0,8		
	17	place upper cap to cylinder barrel			0,8	
	18	pick & place cylinder barrel			7,8	
	19	pick & place lower cap			6,8	
	20	pick and place piston rod to delivery location			7,4	20,6
3	21	get sub assy (barrel, rod & upper cap) from delivery position	1,2			
	22	install upper cap on shaft & body	0,8			
	23	pick screw x 2	1,9			
	24	place screw x 2	2,1			
	25	pick and set screwgun	2			
	26	tighten screw 1	5,5			
	27	screw gun transfer	1			
	28	tighten screw 2	5,5			
	29	eject part (& return gun to home position)	1,5			
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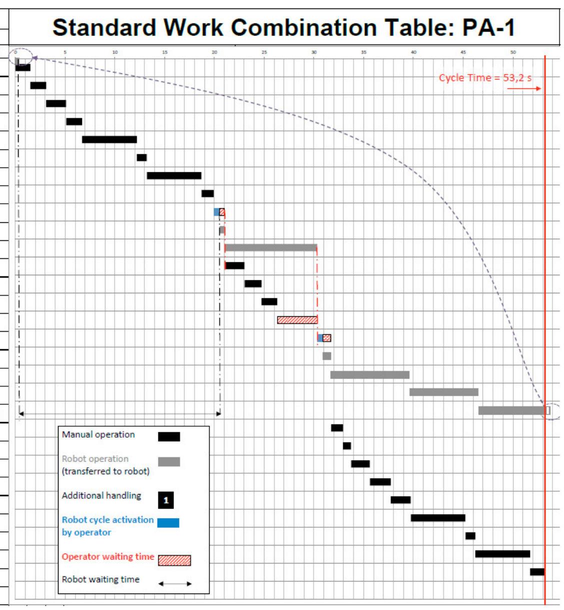

Fig. A.2. SWCT for process PA-1

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			

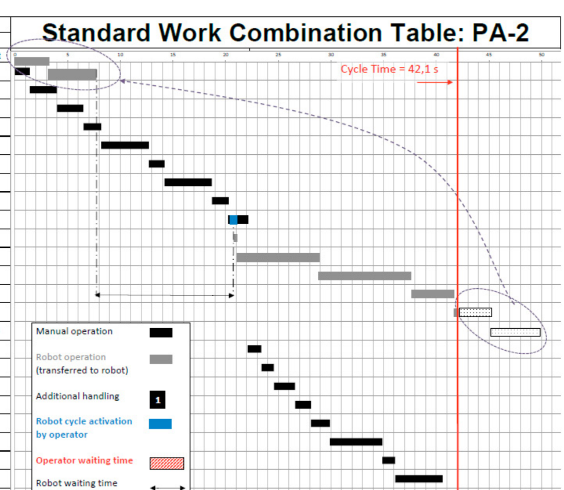

Fig. A.3. SWCT for process PA-2