Tampere University of Technology
Department of Mechanical Engineering and Industrial Systems
MEI-56006 Production Automation Planning

PRODUCT AUTOMATION PLANNING

Project work 2018: Final report

Group ABB OT160

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1. INTRODUCTION

This report answers the group assignment given on the course Production Automation Planning, in Tampere University of Technology. The report consists of planning an automated assembly system for a product known as ABB OT160 (Figure 1). The product is a 3-pole, front operated, base mounted switch-disconnector, and its structure is composed mainly of plastic material with some metallic parts to provide its electrical functions.

The annual production volume desired for this product is circa 500000 units and the production is set to operate five days a week in three shifts. Other ABB products, for example robots, should be used in the automated product assembly system, if possible. Each production phase must be quality-checked automatically.

In phase one of the assignment, a design for assembly (DFA) analysis of the product is made. The analysis consists of an assembly graph and a table identifying the different parts of the product, the problems in their assemblability and suggestions to improve them. Additionally, a calculation of the estimated assembly time is made. As a result, an introduction to the new and re-designed case product is made.

Figure 1. *ABB OT160 assembled*

2. DESIGN FOR ASSEMBLY

As a first step, the product was fully disassembled, and the parts were analyzed in terms of their purpose, and the possibility of automated assembly.

2.1 Part analysis and problem identification

All parts were studied individually. The parts were named, and their purposes were defined. The possible problems with automated assembly were identified and noted along with options to improve the design. A functional (A/B) analysis was made according to the chart shown in figure 2 for the parts. This analysis defined if the parts were deemed necessary (A) or unnecessary (B).

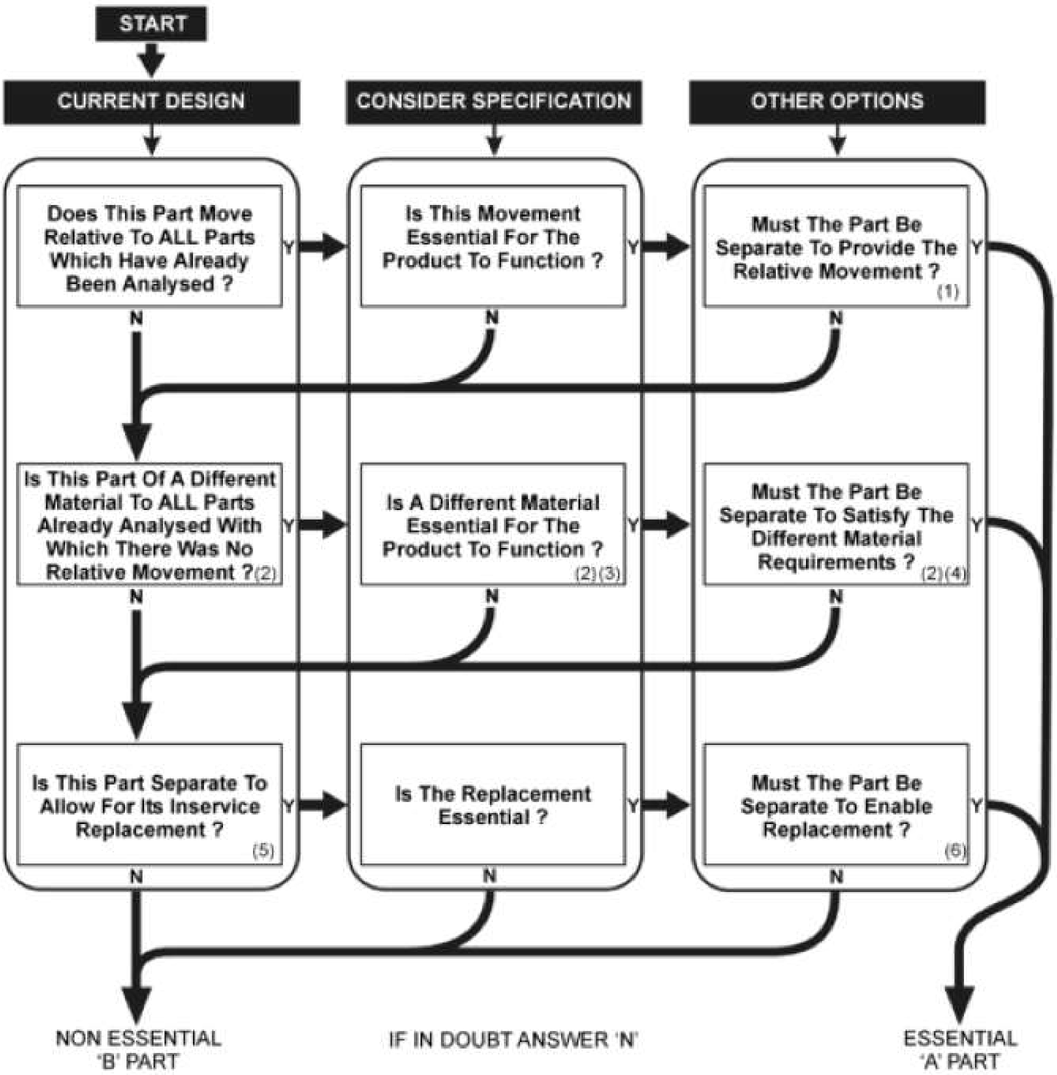
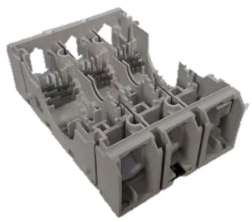
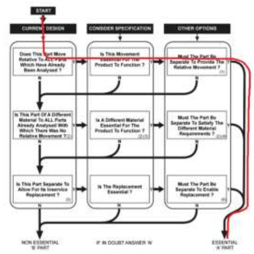
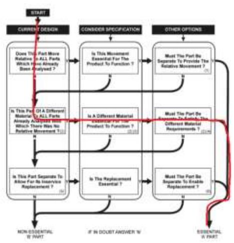
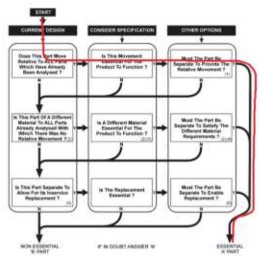
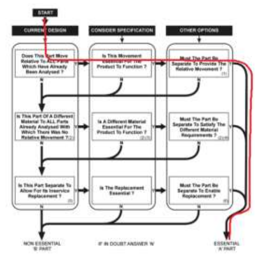
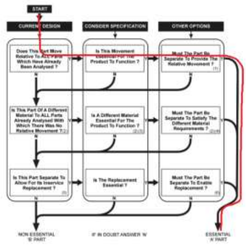
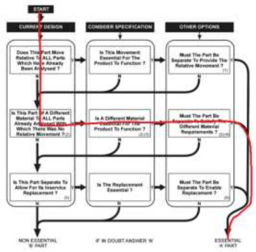
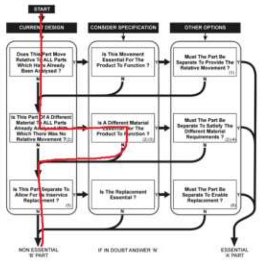
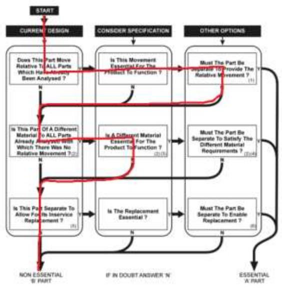


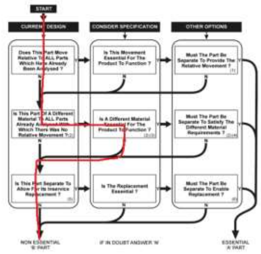
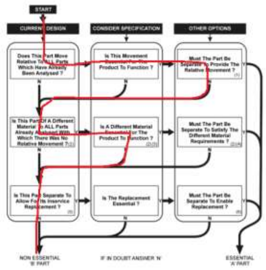
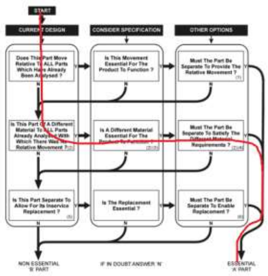
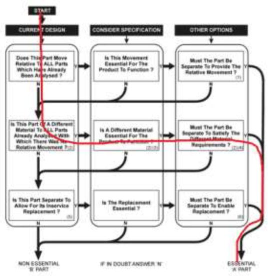
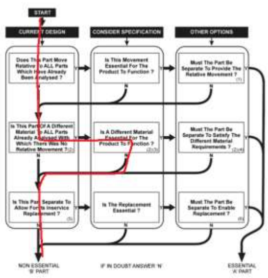
Figure 2. *The functional analysis chart*

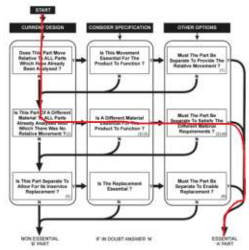
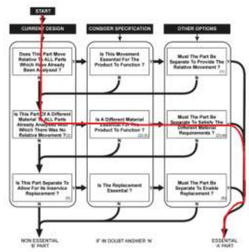
All the information derived from the analyses were summarized in table 1.

Table 1. *Characteristics of the parts in the product*

Parts (64x)	Image	Purpose	Problems	Options to improve design	Functional analysis (A/B)
Plastic1 base (1x)		- Provide base to mount all parts.	- Assembly with spark killers is difficult due to the small space available. - The fit of the spark killers and screw terminals is very tight. - Assembly with plastic top requires change of assembly direction.	- Design change to implement a snap-fit connection with plastic top. - Design change for more space to mount spark killers.	**A**
Rail slide (2x)		- To mount the plastic base on a rail.	- Complicated two directional mounting. - Mounting needs high force.	- Design new two-stage snap-fit connection.	**A** 
Spark killer (9x in top + 9x base)		- Kills arcs when the connection is made.	- Very small part, difficult to grip. - Tight fit, needs high force and accuracy to mount.	- Mount first onto a plastic holder, which is easy to install to plastic base - Design change for easier gripping.	**A** 
Screw terminal “up” (3x)		- Holds the wires in place for each pole.	- Tight fit and risk for misaligned mounting. - The parts are loose if screw is not tightened.	- Feed to robot with screw tightened.	**A** 
Screw terminal “down” (3x)		- Holds the wires in place for each pole.	- Tight fit and risk for misaligned mounting. - The parts are loose if screw is not tightened.	- Feed to robot with screw tightened.	**A** 

Parts (64x)	Image	Purpose	Problems	Options to improve design	Functional analysis (A/B)
Axle (1x)		- Holds switch connectors and turns them into place to form connection.	- Difficult to identify position when fed to robot in random orientation. - Needs to be installed in certain angle of rotation. - Difficult to grip.	- Change the circular geometries in the axle ends, so that there is a level face which stops rotation into correct position for gripping. - Add geometry where the axle is easily gripped.	A 
Connector (3x) (subassembly)		- Connects the poles together.	- Complicated assembly that "breaks" into separate parts easily. - Needs separate subassembly.	- Design change to help keep the assembly together. - Design change for simpler assembly on a jig. - Replace with one-piece flexible connector	-
Connector plate (2x/connector)		- Conducts electricity in the connector.	Small part. Hard to hold in place during assembly.	- Design change to make easier to hold in place during assembly.	A 
Connector plate holder (2x/connector)		- Holds connector plate. - Provides place to mount connector spring and spring holder.	- Small asymmetrical part which is difficult to grip.	- Design change to make easier to hold in place during assembly.	B 
Spring holder (2x/connector)		- Provides flexibility for the connector.	- Very small and hard to grip part. - Hard to hold and press into place during assembly.	- Design change to make easier to hold in place during assembly.	B 

Parts (64x)	Image	Purpose	Problems	Options to improve design	Functional analysis (A/B)
Connector spring holder (1x/connector)		- Holds the connector assembly together.	- Very small and hard to grip part.	- Integrate function into the connection springs.	B 
Axle spring (1x)		- Gives better feeling for disconnecting the switch.	- Hard to insert. - Subassembly. - Function is not critical for operation.	- Integrate spring action in to axle with flexible plastic geometry.	B 
Plastic top (1x)		- Covers the internal parts.	- Needs accurate positioning for mounting.	- Chamfered edges that guide insertion. - Replace screw connection with snap fits.	A -
O-ring (6x)		- Keeps out dirt from screw terminals.	- Small flexible part, hard to grip. - Difficult to position. - Needs additional assembly direction	- Replace with plastic window which covers screw terminals.	A 
Plastic window (1x)		- Gives visibility to the state of connection.	- Complicated 2-directional mounting.	- Replace with one-directional snap-fit connection.	A 
Screws (4x)		- Holds the plastic base and top together.	- Assembly needs change of direction for mounting.	- Replace with snap-fit connection between plastic top and base.	B 

Parts (64x)	Image	Purpose	Problems	Options to improve design	Functional analysis (A/B)
Sticker large (1x)		- Provides information regarding the product	- Flexible and difficult to grip. - How to feed part to robot?	- Insert information with a laser. - Apply sticker in packing phase with an automated labelling machine	A 
Sticker small (1x)		- Provides information regarding the product	Flexible and difficult to grip. How to feed part to robot?	- Insert information with a laser. - Apply sticker in packing phase with an automated labelling machine	A 

The part count for the product is 64 pieces. A design efficiency index E was calculated on the basis of the functional (A/B) analysis.

$$E = \left(\frac{A}{(A+B)}\right) \times 100\% = \left(\frac{44}{44+20}\right) \times 100\% \approx 68{,}75\% \qquad (1)$$

Where,
$A = Necessary\ parts$
$B = Unnecessary\ parts$

As can be seen from the calculation the design efficiency of the original product is quite high already. It is commonly suggested that 60% design efficiency is threshold of a ‘good’ design.

2.2 Assembly process of the original product

In order to do the assembly graph of the actual product, the Assembly Stage Decomposition Model (ASDM) was used. The ASDM model visualizes the order of the assembly and divides it into phases. The ASDM model of the main assembly of the product is shown in figure 3.

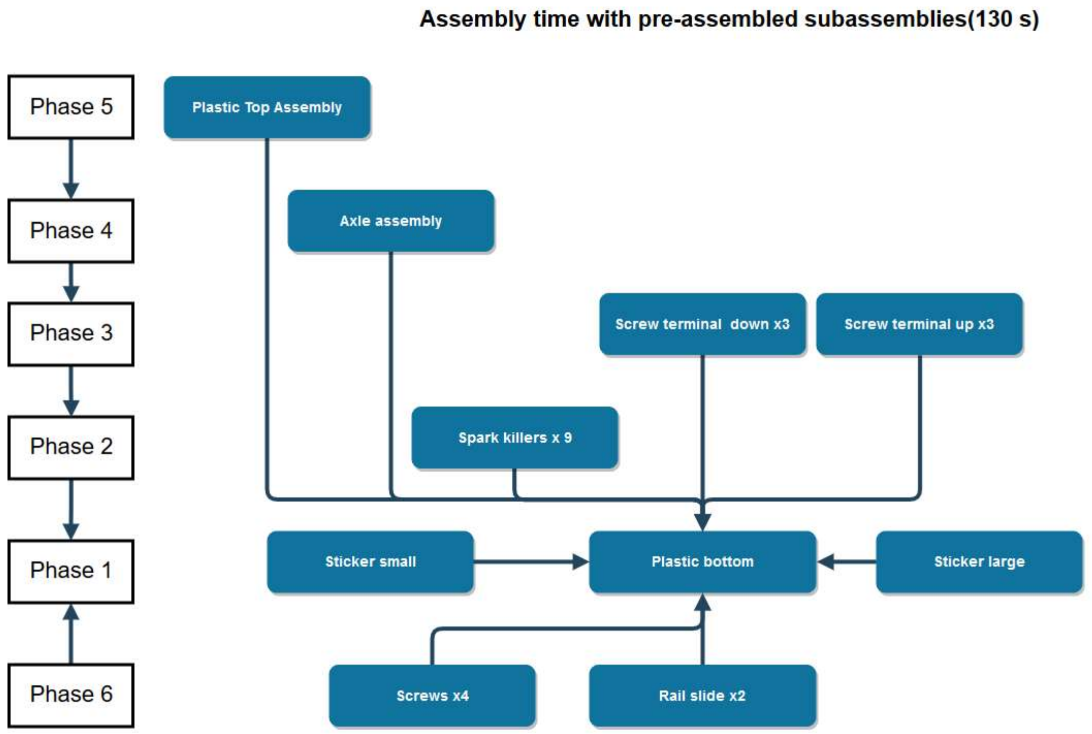


Figure 3. *Assembly graph of the product main assembly*

Similarly, an ASDM model which is shown in figure 4, was also made for the different subassemblies of the product.

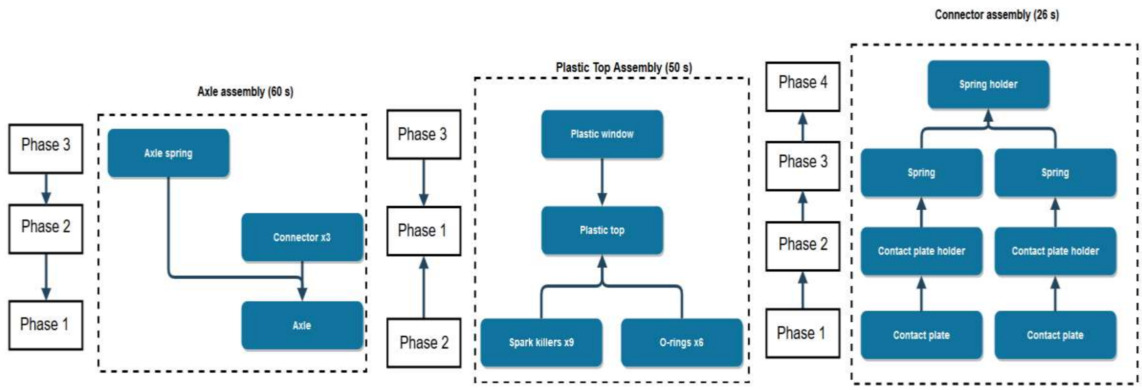


Figure 4. *Assembly graph of the product subassemblies*

Additionally to the ASDM models, it is useful to visualize the actual assembly process with the physical parts. This is shown in figures 5-10. The first step of the process is to assemble the connector subassemblies which is shown in figure 5. The two connector plates, two connector plate holders and the two connector springs are hold together with the connector spring holder. This provides flexibility to the connector in the current design.

Figure 5. *Connector subassembly*

After the connector subassemblies are ready, it is possible to assemble the axle with the 3 connectors and the axle spring (which requires a change of assembly direction). The subassembly of the axle, shown in figure 6, is then ready.

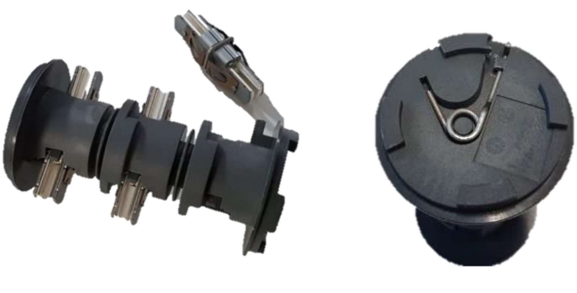


Figure 6. *Axle subassembly*

The final subassembly necessary is the plastic top, which is shown in figure 7. First the plastic window is mounted to the plastic top. After that, the 9 spark killers and 6 o-rings are mounted (from the opposite assembly direction) and the subassembly is ready.

Figure 7. *Plastic top subassembly*

In the plastic base assembly, shown in figure 8 the assembly is carried out by first mounting all the 9 spark killers 9 and then the 3 downward facing screw terminals and 3 upward facing screw terminals onto the plastic base. All of the assembly is done in the same direction.

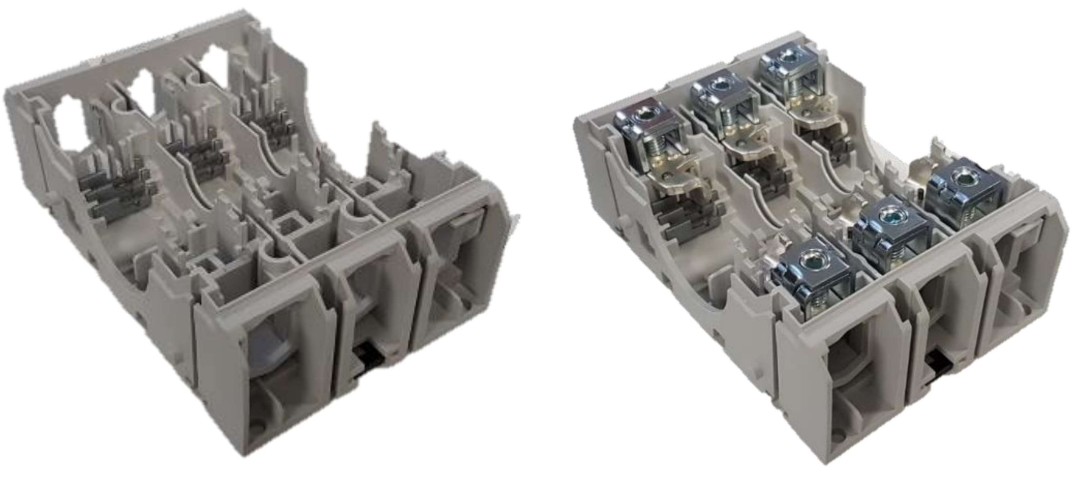


Figure 8. *Plastic base with spark killers and screw terminals*

Now it is possible to first mount the axle subassembly on the plastic base and then the plastic top subassembly as shown in figure 9. Assembly is again from the same direction.

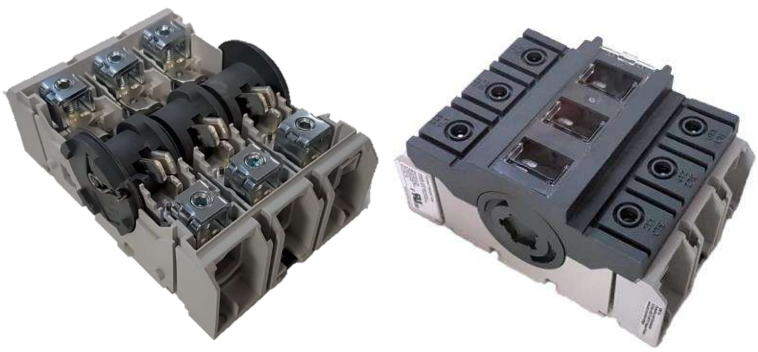


Figure 9. *Main assembly with subassemblies*

After this, the main assembly is tightened with the 4 screws and the 2 rail slides are mounted to the plastic base as shown in figure 10. The assembly direction is now opposite to previous main assembly phases.

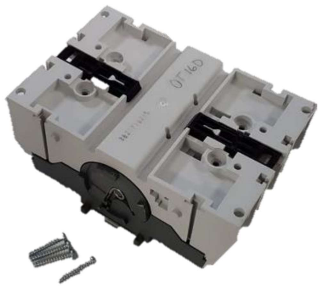


Figure 10. *Final product from the bottom and the screws*

After this, it is necessary to assembly 2 rail slides which can be seen in figure 10 and 11. To do this, the product needs to be upside down. The assembly process is done from up to down and then a slide movement for each rail slides.

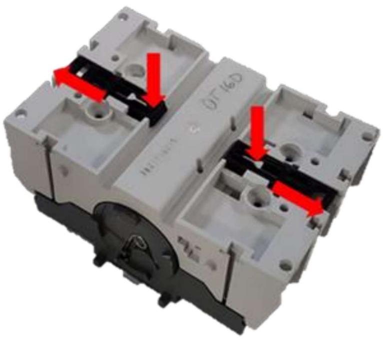


Figure 11. *Old rail slide assembly*

3. DESIGN FOR ASSEMBLY (REDESIGNED PRODUCT)

3.1. PRODUCT CHANGES

3.1.1. The connector

The assembly of the connectors is a very complicated process to do, for both humans and robots. It contains many small parts that are difficult to assemble. For that reason, two solutions were suggested:

First the subassembly could be substituted by a single flexible part that ensures the same functions. However, this change would most likely bring problems regarding optimization for a sufficient fatigue life and wear, and changes would be needed in the design of the mounting holes in the axle also, but it could potentially make the assembly process much simpler and decrease the assembly times. This suggestion is shown in figure 12 on the left.

The second solution that was suggested, was to lengthen the connector spring and make small holes in the end of all the connector parts. This way the parts could be positioned easily for automated assembly on a jig with two pins as shown in figure 12 on the right.

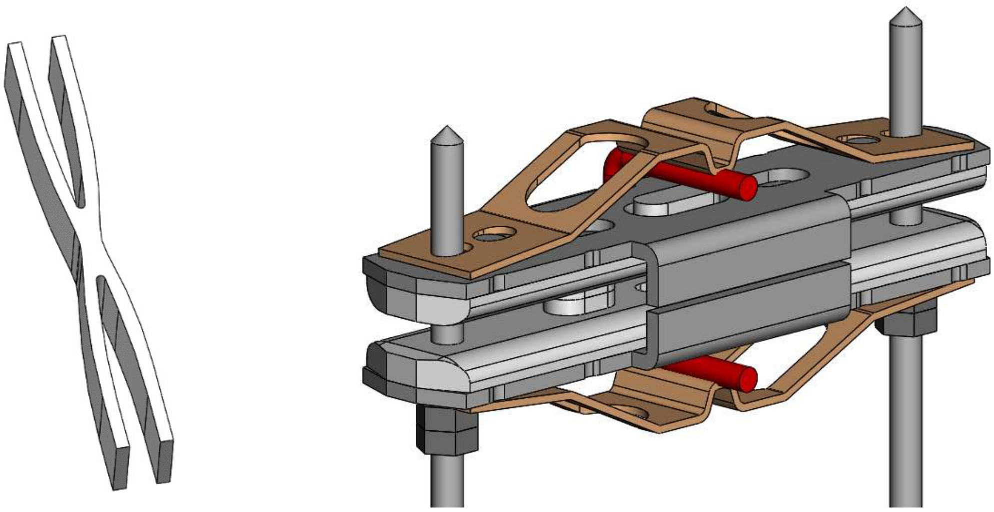


Figure 12. *Two new connector design suggestions*

3.1.2. Modifications to axle

If the one-piece connector design solution was chosen, the axle would have required modifications to the three mounting holes. However, the slightly modified old connector design solution was chosen to be used instead.

Due to this, the only modifications needed for the axle were, to add geometry where the axle can be reliably gripped (1.), and to add geometry which will position the axle correctly (2.) and (3.) in the feeding process for the robot. These geometries are visualized in figure 13.

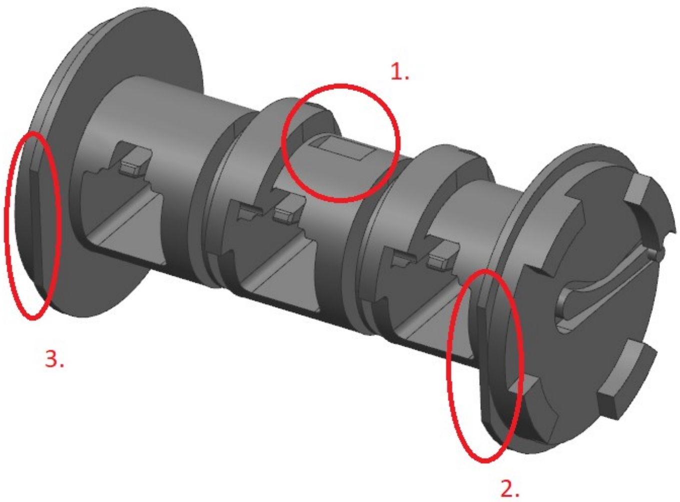


Figure 13. *Modifications made to the axle geometry*

3.1.3. Guiding chamfers for screw terminals

The mounting of the screw terminals was noted to be very tight and the mounting has a high risk of getting misaligned. As can be seen in figure 14. The plastic base had some chamfers designed already, but we decided to make them bigger to guide the mounting of the screw terminals more.

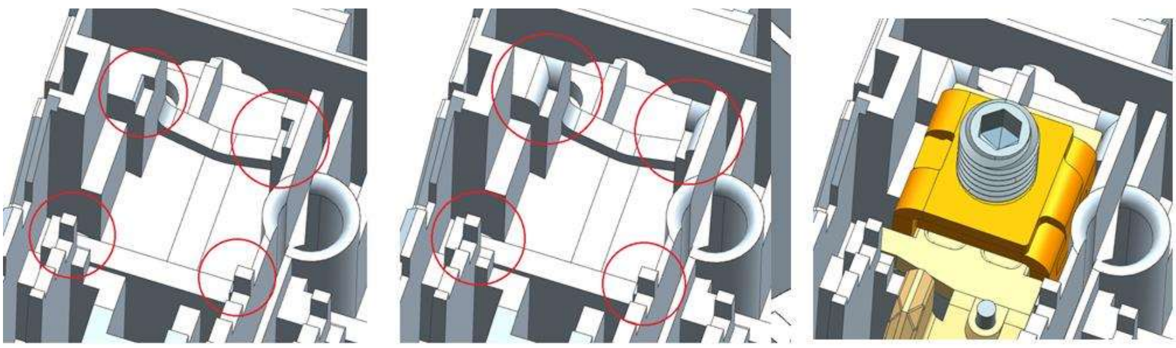


Figure 14. *Bigger guiding chamfers*

3.1.4. Snap-fit connection and guiding fillets between plastic top and base

The plastic top and the plastic base connection needed a redesign too. Our suggestion consists of a change to substitute the four screw mounts with four snap-fits connections as shown in figure 15. The connection location would be moved to the sides between the top and base as shown. In this case, a press to open snap-fit could be used. In this specific design a tool such as a flat head screw driver might be needed to press the prong and release each snap-fit one-by-one. However in the automated manufacturing process of the product, the robot would only need to press the plastic top into place, which is a much easier task than mounting the 4 screws from the opposite assembly direction.

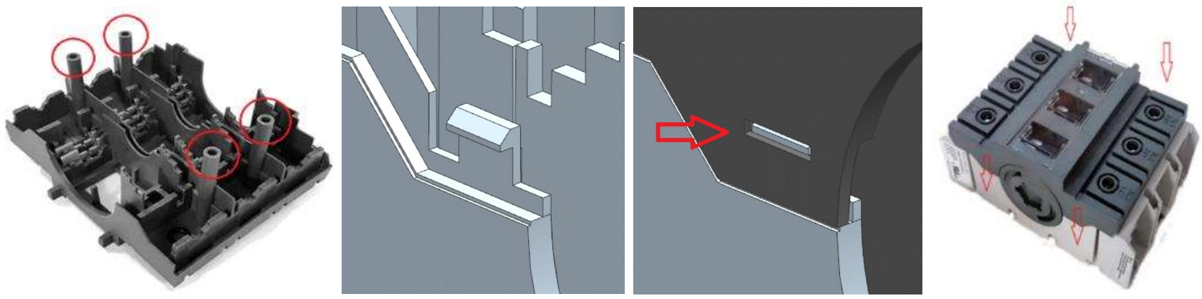


Figure 15. *New connection between the plastic top and the plastic base*

Additionally, the old screw mounting holes in the plastic base would be filled in the new design and the 4 "cylinders" for the screw threads in the plastic top would be used only to guide the mounting of the plastic top on to the plastic base. This guiding action could be improved also by adding fillets to the plastic base as shown in figure 16.

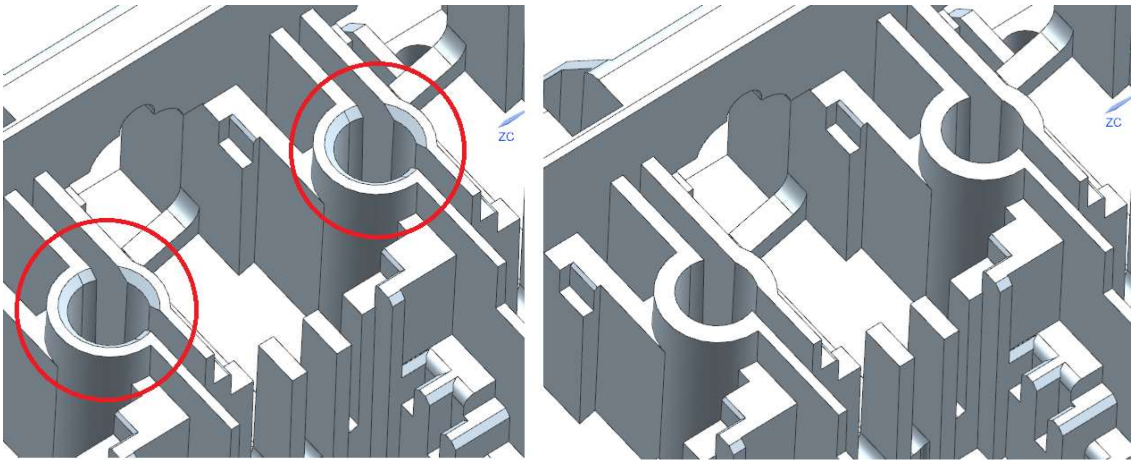


Figure 16. *Guiding chamfers in plastic base*

3.1.5. Improved rail slide

To improve the rail slide assembly with the plastic base, a solution was made:

Rail slide has been redesigned so that it could be pushed down in front of the plastic base instead a top-down and then a horizontal movement at back of the plastic base. This will simplify assembly when the base doesn't need to move in the assembly process.

Figure 17. *Original rail slide on left and improved rail slide on right*

Rail slide has a little cab at one end so that it will fit the little triangle shaped tightener through the rail slide.

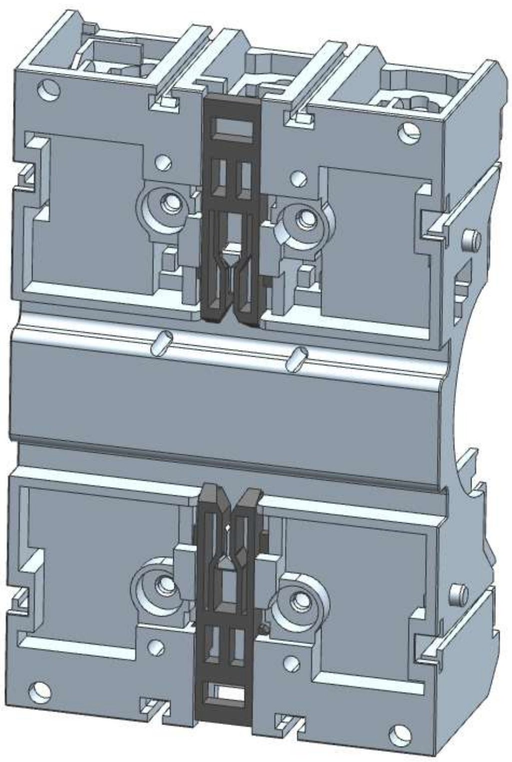


Figure 18. *Improved rail slide with plastic base*

3.1.6. One-piece spark killer

Spark killers are re-designed so that they are made of one plastic piece like in figure 19 with electroplating. Electroplating process is called selective electroless plating. Electroplating ensures that there are three electrically isolated areas. With this redesign, assembly becomes easier with larger and fewer parts. In the original design, there are 18 spark killers and this will reduce this number to 6.

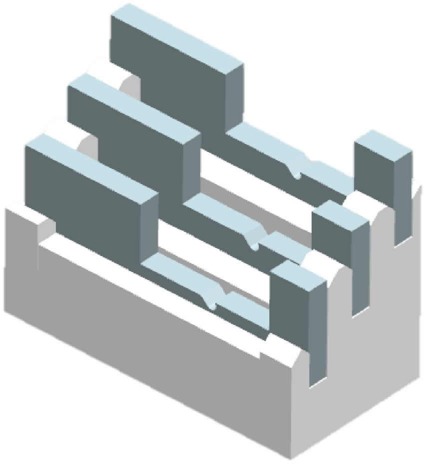


Figure 19. *Spark killer redesigned with electroplating*

Redesigned part will be fitted on the plastic base with a snap fit connection.

3.1.7. Redesign of axle spring

The redesign of the axle spring was suggested due to the difficulty of the current mounting process. Instead of a separate metal spring, it was suggested that the spring could be integrated in to the plastic axle geometry as shown in figure 20. This however would need optimization to provide sufficient flexibility without fracturing the plastic. The axle material might need to be changed to a softer plastic, but it should not be a problem.

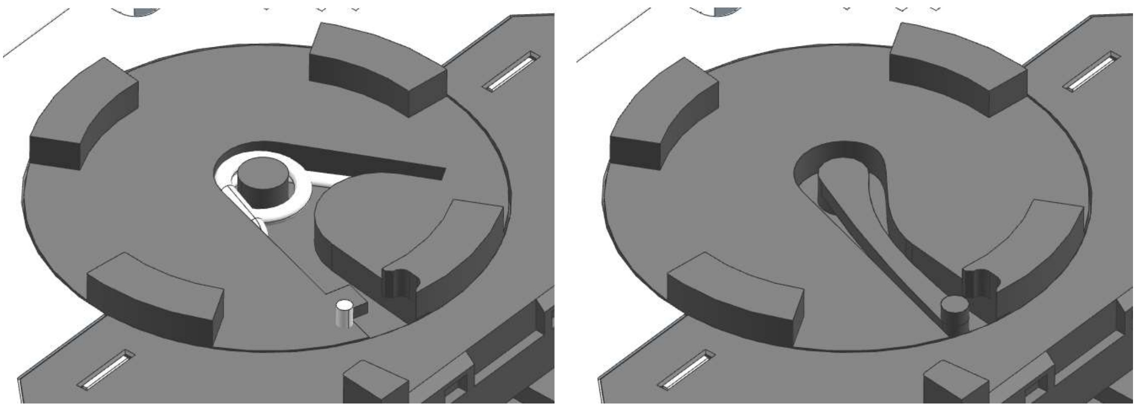


Figure 20. *Integrated axle spring.*

3.1.8. Snap-fit plastic window

The snap-fit plastic window has 2-directional mounting. This makes very difficult to assembly. For that reason, it was replaced with one-directional snap-fit connection.

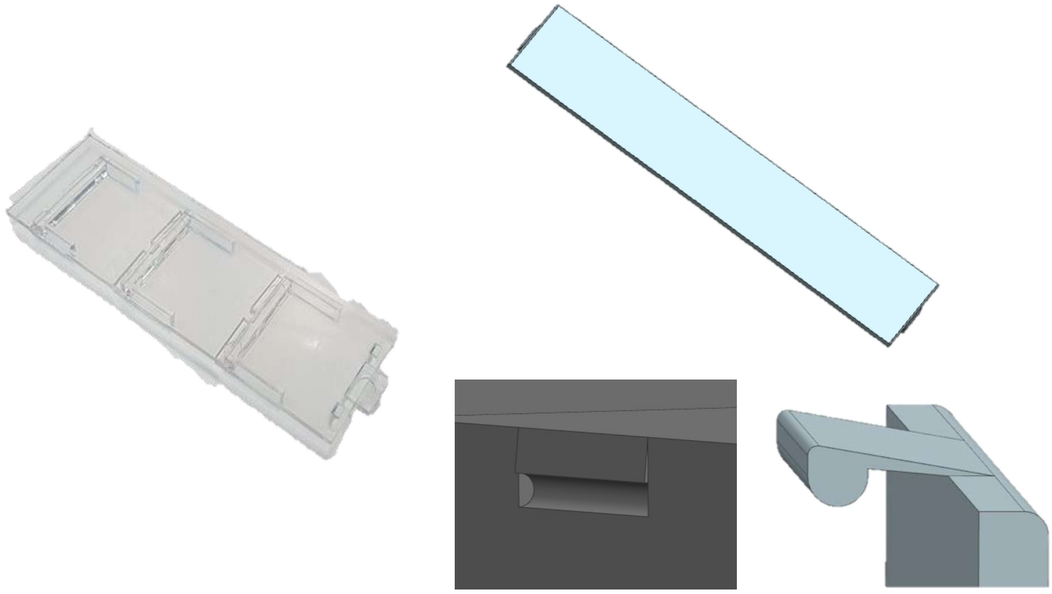


Figure 21. *Old plastic window (left) and new plastic window and snap fit (right)*

The new plastic window has 2 snap fits (one at each end) that allows to fix it to plastic top part and be assembled in just one direction (top to down).

3.1.9. Snap-fit plastic window to replace O-rings

To keeps out the dirt and remove the 6 o-rings (small flexible part, hard to grip, difficult to position) of the assembly, the top plastic part was redesign, where a plastic window (same as the center one) is added in both sides, covering the screw terminals.

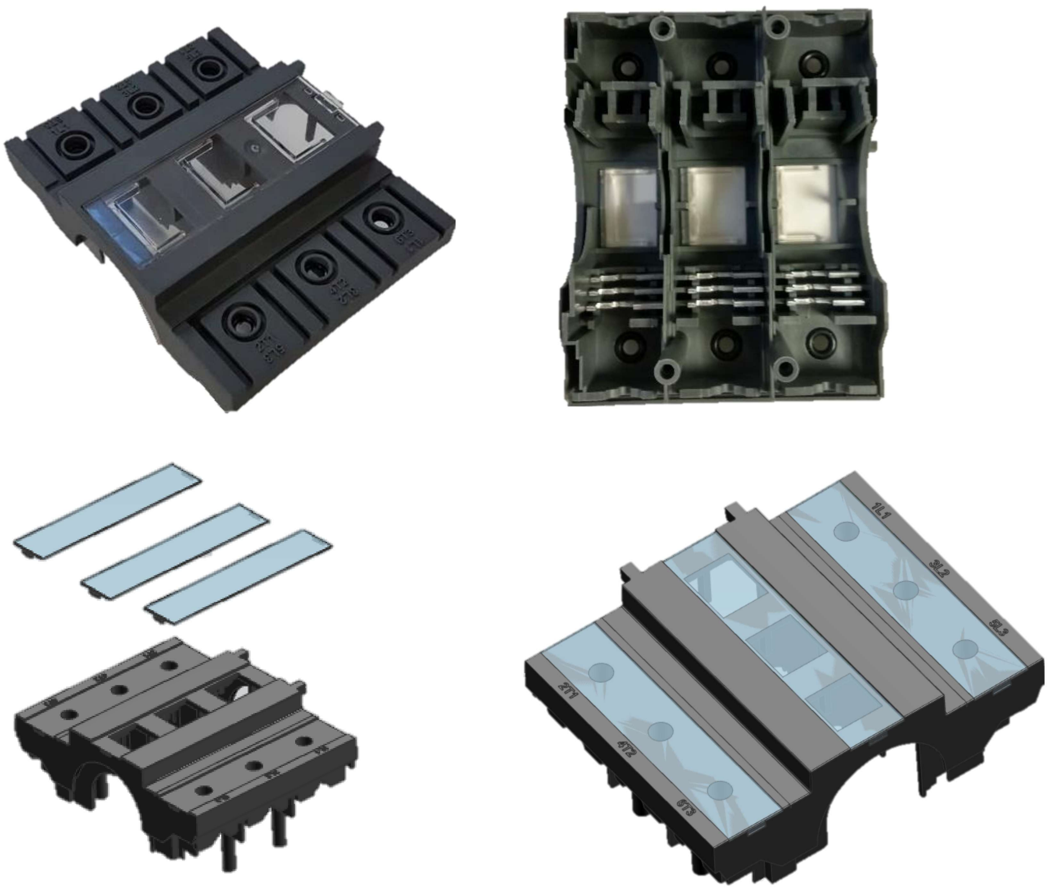


Figure 22. *Old top plastic part (top) and new plastic top with 3 windows (down)*

Changes (figure 22) on the top plastic part were made to use the same plastic window. Thus, it is necessary just one type of plastic window that can serve all the three cases (left, center and right).

4. ASSEMBLY PROCESS FOR IMPROVED PRODUCT

To plan the assembly of the product, a drawing was made to understand all processes and sequences of the line, position of subassemblies, feeding of the system and movements of components and this can be seen on the figure 23.

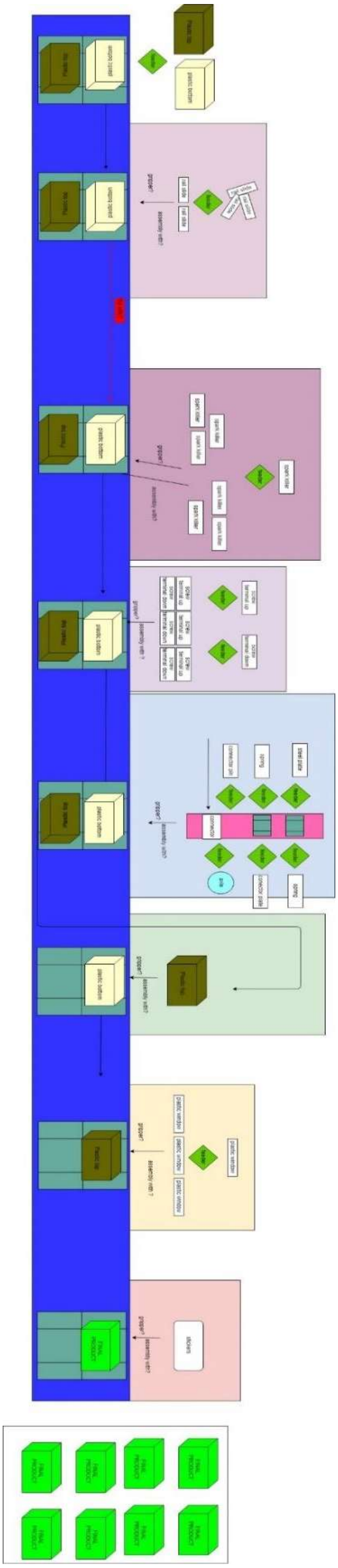


Figure 23. *Preliminary system design*

5. COMPARISON OLD VS NEW DESIGN

The estimated yearly production volume for the product is 500 000 units. The factory operates five days a week in three shifts. The estimated assembly time is 6 minutes and 24 seconds for full manual assembly. Labor cost were estimated by using 37 €/h as hourly cost of industrial labor. Yearly work time for one worker was estimated to be 1 920 hours. Number of assembled products per works was calculated

$$Assembled\ products\ per\ year = \frac{Yearly\ work\ hours}{Assembly\ time/product}.$$

When using these estimates 28 workers could assemble 500 000 units in a year. We estimated that 6 additional workers will be needed for as a reserve personnel and as support personnel (for logistics and for supervisors). Total labor cost for year was calculate by using this formula

$$Total\ labor\ cost = Number\ of\ workers * \frac{Yearly\ work\ hou}{worker} * \frac{labor\ cost}{hour}.$$

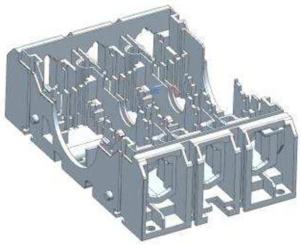
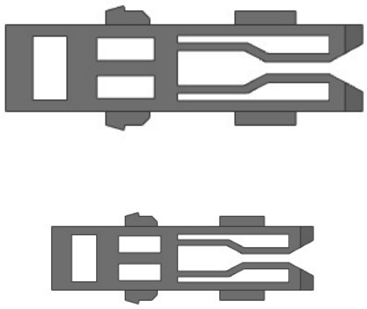
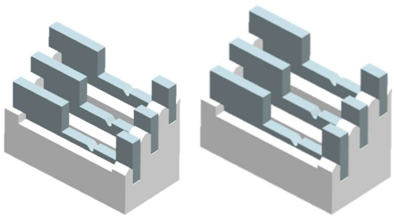
Results of these calculations are shown in Table 2.

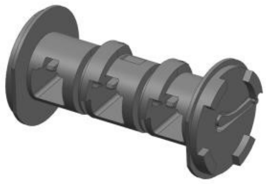
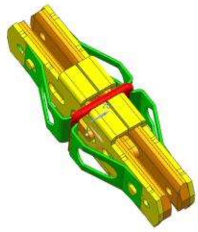
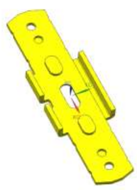
Table 2. *Old and new design comparison*

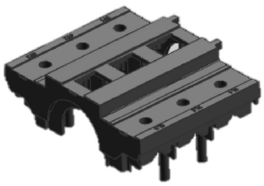
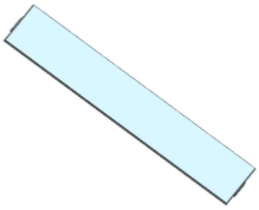
	Old Design	New Design
Work hours/worker (h)	1624	1624
Assembly time (min)	6,4	4
Assembled units in a year	18000	28800
Yearly production (pieces)	500 000	500 000
Needed assembly workers	28	18
Needed workers +support and reserve personel	34	24
Hourly wage	37	37
Labor cost in a year for one worker (€)	60088	60088
Total labor cost for year (€)	1682464	1081584
Machine operation costs		
Investment cost (€)	0	0
Total costs / year (€)	1682464	1081584
Total costs / unit (€)	3,364928	2,163168

The part count for the product is 58 pieces. It was made a classification on the redesigned parts of the new product, as is possible to see in table 3.

Table 3. *Characteristics of redesigned parts in the new product*

Parts (43x)	Image		Achieved improvements	Functional analysis (A/B)
Plastic base (1x)			-Easier assembly with plastic top was made possible with snap-fits	A
”Rail slide” (2x)			High accuracy is needed to assemble. -Only one assembly direction needed	B
Spark killer (3x in top + 3x base)			-Made possible to assemble with automation -Reduced assembly time -Difficult to produce.	A
Screw terminal “up” (3x)			-	A
Screw terminal “down” (3x)			-	A

Parts (43x)	Image		Achieved improvements	Func-tional analysis (A/B)
Axle (1x)			Some difficulties to identify position if fed to robot in random orienta-tion. -Removed the need for a separate spring. -Feeding and grip-ping the part was made easier	A
Connector (3x) and connector parts (subassem-bly)			-Easy assembly on a jig was made possible by small modifications	-
Connector plate (2x/connector)			-Holding the part in place during as-sembly was made easy by small holes that locate the part on a jig	A
Connector plate holder (2x/connector)			-Holding the part in place during as-sembly was made easy by small holes that locate the part on a jig	B
Spring holder (2x/connector)			-Holding the part in place during as-sembly was made easy by extending the part and adding small holes that lo-cate the part on a jig	B
Connector spring holder (1x/connector)			-	B

Parts (43x)	Image		Achieved improvements	Func-tional analysis (A/B)
Plastic top (1x)		Covers the internal parts and allows to see the con-nection.	-Easier assembly with plastic base was made possible with snap-fits -Modifications al-low for one direc-tionally mounted plastic windows	A
Plastic window (3x)			-Removed the need for 6 x O-rings -Assembly is now from only one di-rection.Some accu-racy is necessary to assemble	B
Sticker large (1x)			-Requires rotation of the product	A
Sticker small (1x)			Requires rotation of the product -	A

Efficiency index E for the new design:

$E = \left(\frac{A}{(A+B)}\right) \times 100\% = \left(\frac{9}{9+2}\right) \times 100\% \approx 81\%$ (2) $\left(\frac{28}{28+15}\right) \times 100\% \approx 65{,}12\%$

As we can see the efficiency index is actually lower than in the original product, but it does not mean that the design has gotten worse. The result comes from the fact that we have highly reduced the overall part count, and now the connectors “non-essential” parts are in a bigger role for the calculation.

Where,
$A = Necessary\ parts$
$B = Unnecessary\ parts$

The redesigned product has an efficiency index of 81% reveling a good using of the re-designed components.

6. SYSTEM DESIGN

Production system for improved product is designed for almost fully automated assembly. Manual phases are refilling parts for robots and removing pallet with finished parts.

6.1. SYSTEM LAYOUT

Assembly was divided to 8 workcells and this layout can be seen on figure 24. The process goes from left to right and starts with unloading bottom and top plastic parts on the main conveyor and then ends with finished products placed on pallet and leaving manually with pallet jack. It was assumed that finished product would leave to another facility and it will be a part of bigger assembly, so the finished parts are only placed on pallets with cardboard on it and a cardboard between layers.

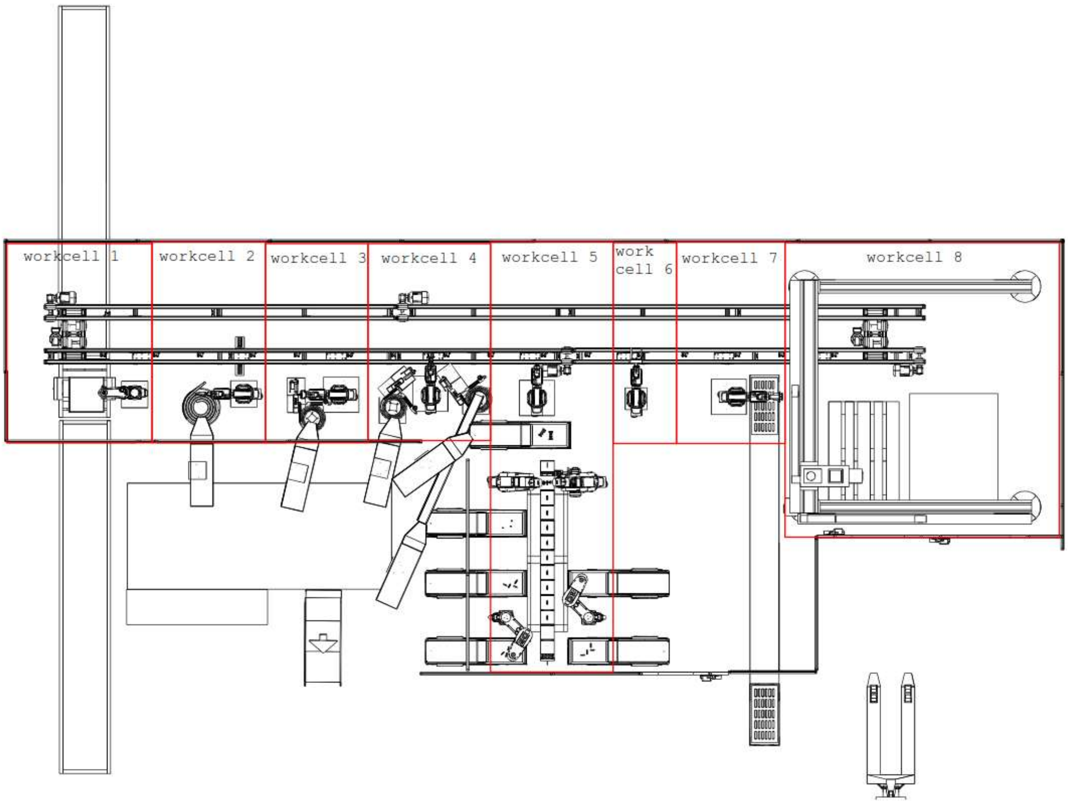


Figure 24. *Final layout*

Main conveyor is looping pallets with stops for individual workstations. Technical details are explained chapter 5.3. Figure 25 shows whole system with every part in place.

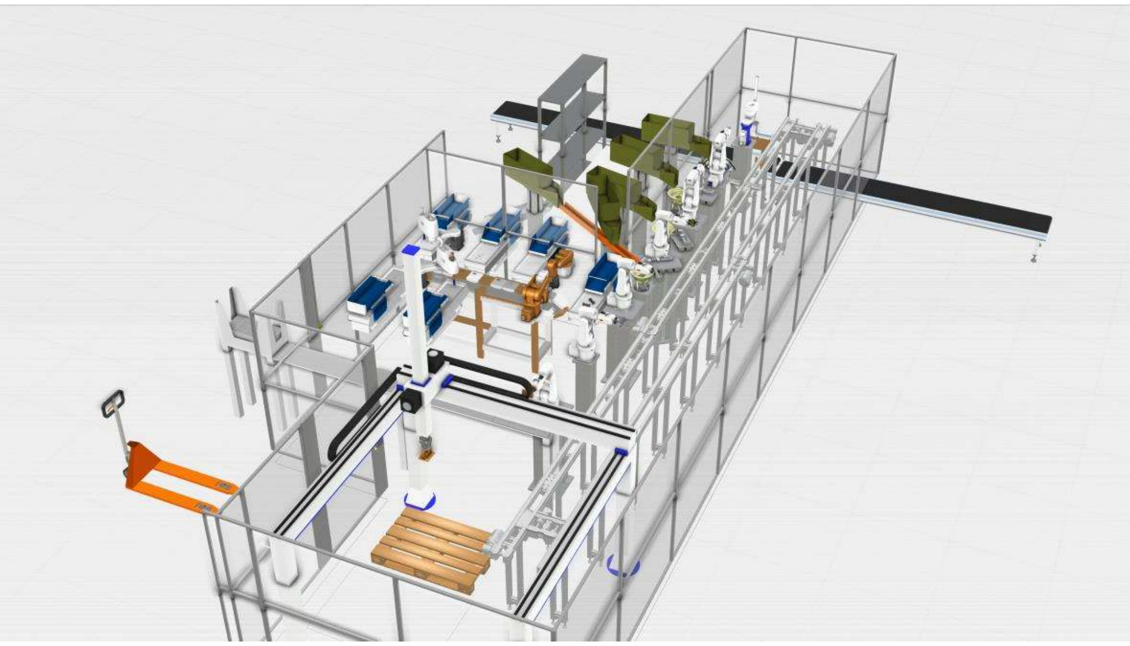


***Figure 25.** 3D model of the layout*

Whole assembly system is covered with fences and feeding the parts to robots can mostly be done outside the fences with the help of hoppers. It was considered that this is almost fully automated assembly system and the system should be able to work several hours without human intervention.

Capacity calculations

Capacity calculations are done on the assumption that yearly production is stable and this is warehouse product, which can be made to stock (MTS). Calculations, which are considered in our system design, are shown in table 4.

Table 4. *Capacity calculations*

Required annual volume	500000	products / year
Line efficiency	0,9	
1-shift working seconds / year	4536000	seconds /year
3-shifts working seconds / year	13608000	seconds /year
Required cycle-time 1-shift all-year	9,072	seconds
Required cycle-time 3-shift all-year	27,216	seconds

These calculations defined, that every workcell should have 27 seconds cycle-time at most. Cycle-time for 1-shift work cycle was not feasible and not considered further. Workcell assembly times are estimates based on our simulation and modified as seemed fit. For comparison manual assembly times estimates are shown next to estimated automated assembly times in table 5.

Table 5. *Cycle-times comparison*

	Automated assembly	Manual assembly	Difference in seconds
Workcell 1 Transfer system loader	17	0	17
Workcell 2 Railslide placement	26	10	16
Workcell 3 Spark killer	21	84	-63
Workcell 4 Screw terminal	24	22	2
Workcell 5 Axle assembly	27	65	-38
Workcell 6 Flipper	5	7	-2
Workcell 7 Plastic windows	24	24	0
Workcell 8 Palletizer	10	0	10
Throughput time =	143	235	-92

Improvements for the throughput time are mainly caused by better performance of axle, and spark killer assemblies.

6.2. Line Balancing

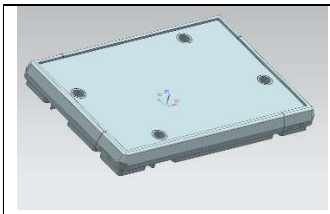
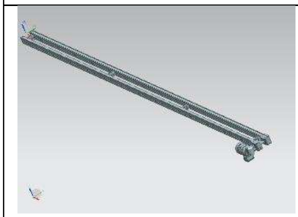
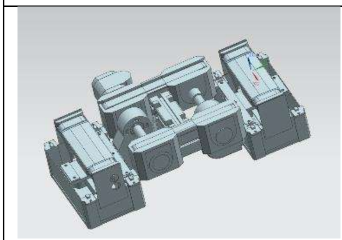
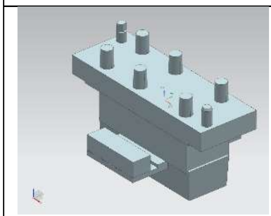
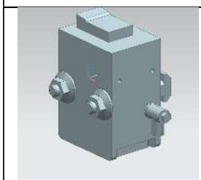
Line balancing was done by meeting the required cycle time as calculated in previous section. This was confirmed with simulation that all the workcells were able to meet this requirement. Simulation also confirmed that there was no excess idle on any of the workcells, because combining workcells would have violated the cycle time requirement.

6.3. Transfer system

Transfer system used for production system is called TS2plus and it is produced by Bosch Rexroth. TS2 plus transfer system is modular system which offers longitudinal and transverse conveyors, curves, workpiece pallets, leg sets, workpiece positioning units and transportation controls. TS2plus is designed for workpiece pallets from 160 mm x 160 mm up to 640 mm x 640 mm and for maximum load of 240 kg per pallet. For workpiece pallets WT 2 with dimensions 160 mm x 240 mm was chosen for this system because that pallet was smallest one that could have both plastic bottom and plastic top simultaneous. Selection of workpiece pallet determined selection of longitudinal and transverse conveyors and width of the track (160 mm). System was designed with two parallel conveyors in closed loop. The distance between parallel conveyors is 320 mm. One of the conveyors was fitted 8 positioning units for workstations. Positioning accuracy for positioning units is ±0,1 mm in x/y plane.

Table 6. *Components of the transfer system*

Picture	System component	Quantity

	Workpiece Pallet WT 2 (160 mm x 240)	16
	Belt Section BS 2 (track width 160 m, section length 6 m)	2
	Belt Section BS 2 (track width 160 m, section length 4 m)	2
	Electric Transverse Con-veyor EQ 2/T	2
	Positioning Unit PE 2	8
	Stop gate VE 2	19
	Leg set SZ 2 (height 1100 mm)	22

6.4. Jig for plastic base and top

A jig was designed to stand the plastic bottom part and plastic top part through all work-cells. In this jig cylindrical tubes were added to fix both parts (these features coincide with holes in both parts, fitting and fixing in a specific place).

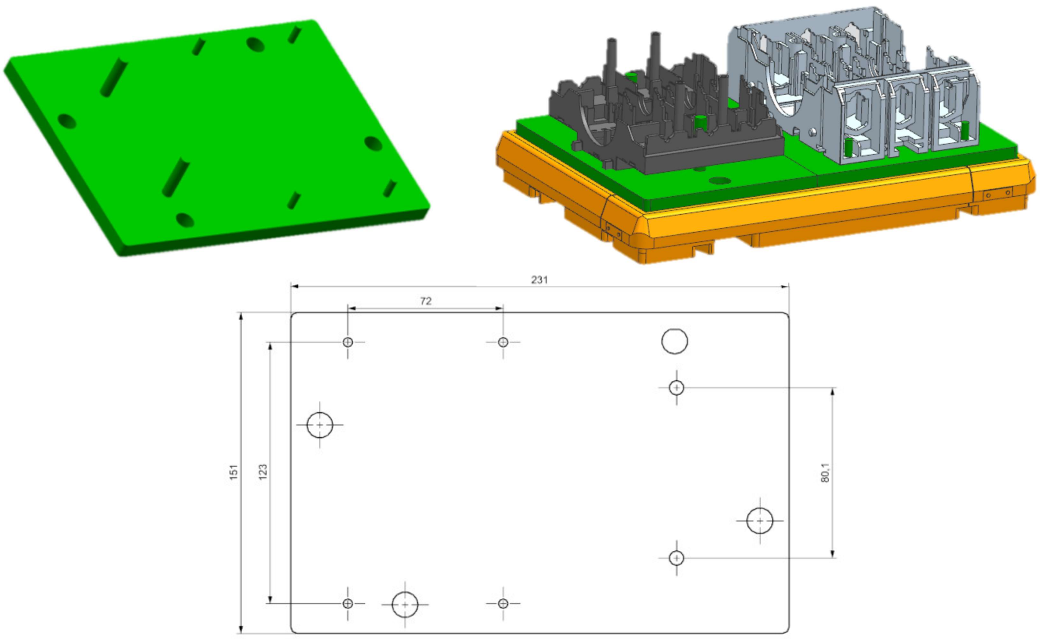


Figure 26. *Configuration of jig and dimensions*

6.5. Assembly processes

Every workcell has some kind of feeder and depending on the size of the bowl and part, these may not suffice for longer periods of operation. That is why we chose to feed bowl feeders with RNA BU-W Hoppers. It is an off the self-range of standard equipment. These function as reserve for parts and feed bowl feeders as needed. These hoppers have fill volume from 5-200 liters and driven by 3-phase motor and the adjustable raised face can be adjusted for different part sizes.

Figure 27. *RNA BU-W Hopper*

Hoppers are driven automatically with sensor reading from the feeder. These sensor could measure as an example surface level of the bowl. .

6.5.1. Transfer system loader

Robot type:	SCARA
Robot model:	ABB IRB 910SC
Gripper:	Festo BUB HGPL 14 A
	Festo BUB HGPL 63
Fingers:	(modiefied)
Feeders:	Conveyer
Conveyor:	MK-Group SPU-2040
Parts:	Plastic top + bottom

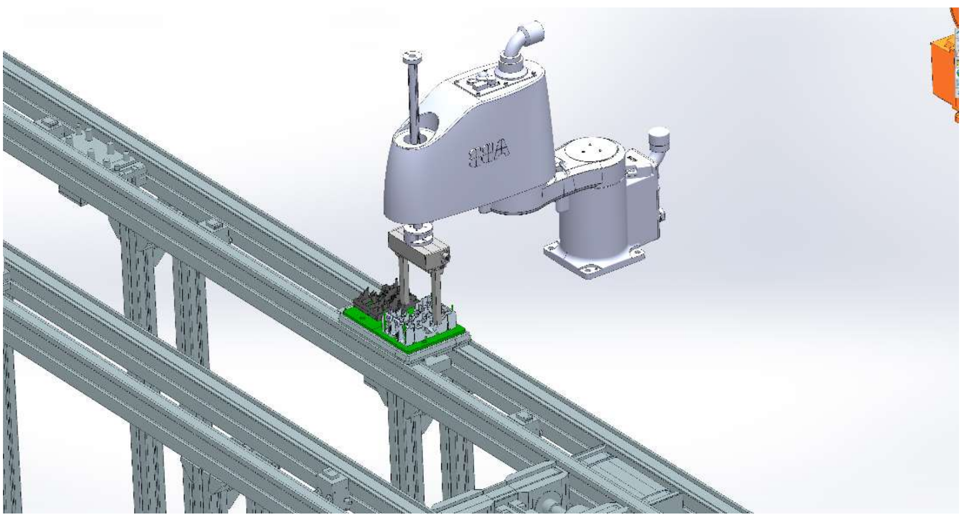


Figure 28. *Transfer system loader*

Transfer system loader feeds the main conveyor with plastic top and bottom from a cardboard box that is in another conveyor. This conveyor is not shown on the figure 28 but is shown at the layout. It is assumed that the box comes filled with plastic tops and bottoms with an accurately defined layout. As the box moves in smaller conveyor to the loader, it is then raised to the robot with a lift. As the box is empty, box is lowered and then moved under the main conveyor to be disposed of by operator. This second conveyor was designed because it was assumed that the one box could not hold enough plastic bottoms and tops for longer periods of operation.

6.5.2. Railslide placement

Robot type:	Six-axis
Robot model:	ABB IRB120
Gripper:	Festo HGPC 12 A
Fingers:	Custom fingers
Feeders:	Bowl Feeder AFAG 50279264
Parts:	railslide x2

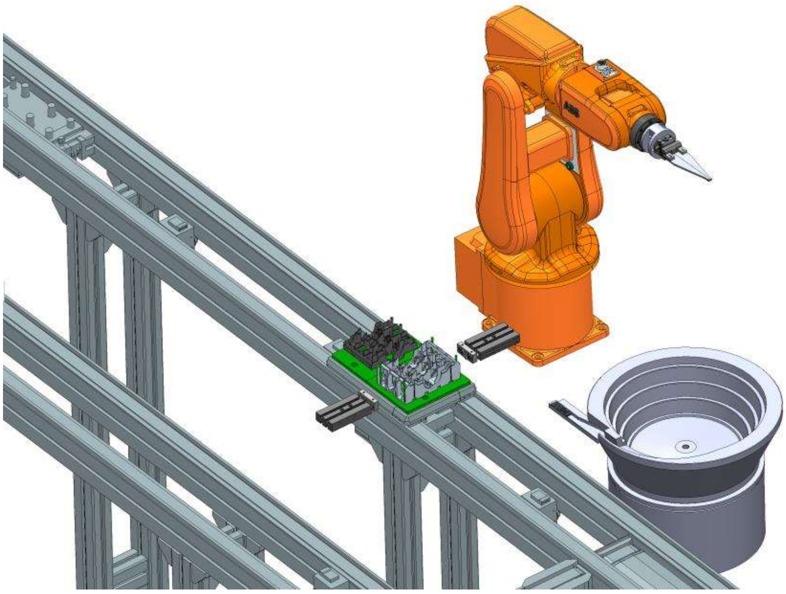


Figure 29. *Railslide placement*

Railslides are fed with a bowl feeder at certain orientation. Robot has custom fingers that able to go through the end of the small cavity in railslide. It then expands fingers and grips the part.

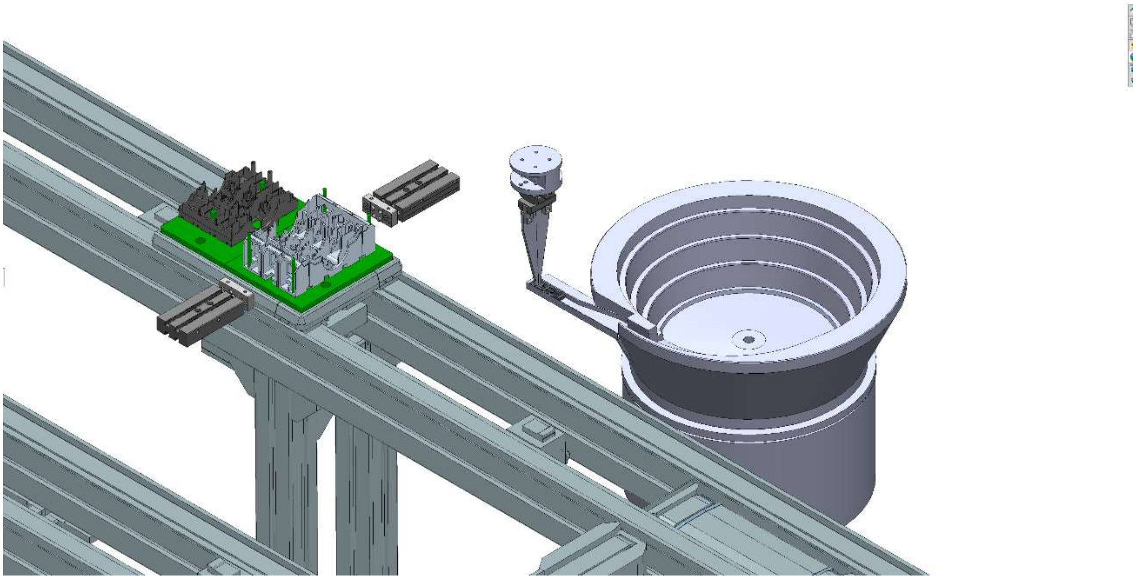


Figure 30. *Gripping railslide from feeder*

Railslide is the then positioned in the plastic bottom with gripper.

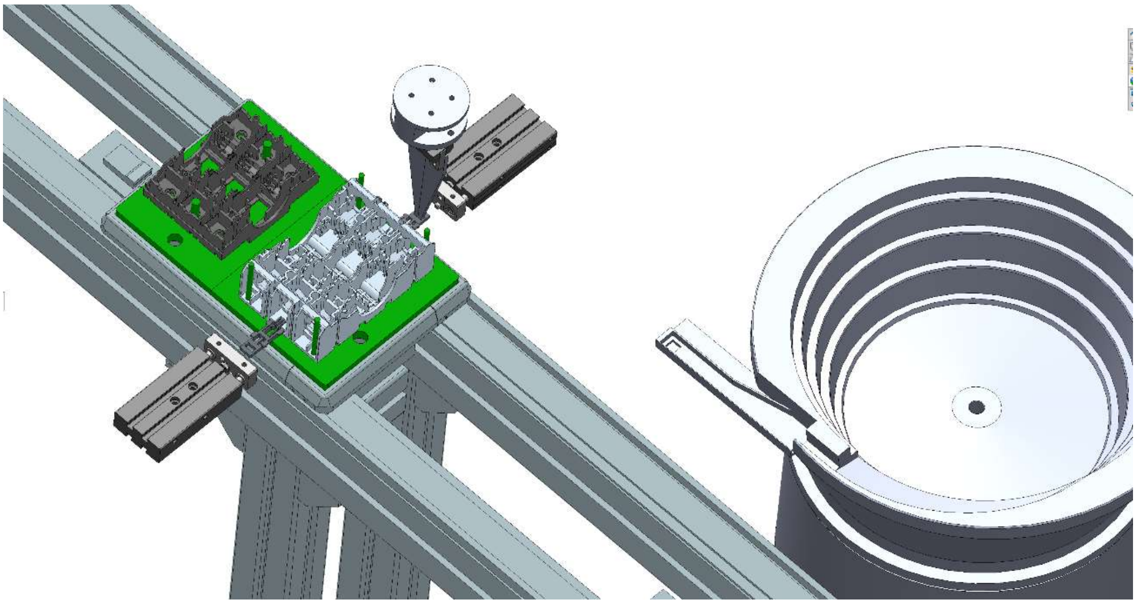


Figure 31. *Placing railslide on the pallet*

As both of the railslides are in place, two pneumatic actuators simultaneously push railslides in to the plastic bottom.

Individual tasks for the robot are estimated in the table 7. These estimates are rough and are overestimated, because precise placement is needed from the robot at the bowl and tray.

Table 7. *Tasks for railslide placement*

TASK	TIME (s)
Move to bowl feeder x2	6
Pick up railslide x2	4
Move to plastic bottom x2	6
Position railslide x2	4
Push railslides in with actuators	1
Move part to station	5
Cycle time workcell	**26**

Railslide gripper can be seen on figure 32, which shows detailed look on the custom fingers. Fingers are designed so that the railslide would slide on the hole at the end of the fingers to effectively place in on to the tray.

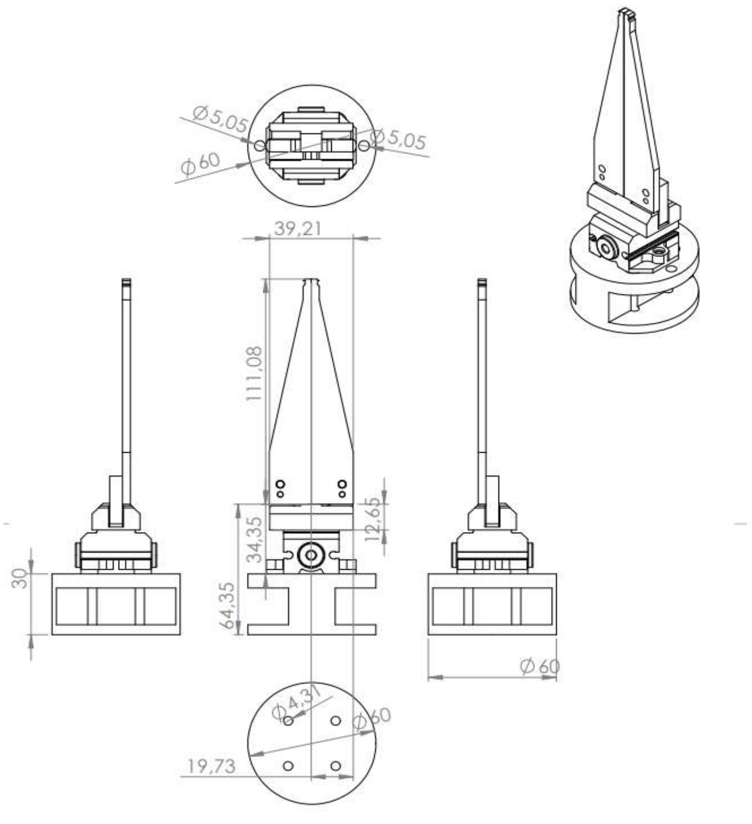


Figure 32. *Railslide gripper*

6.5.3. Spark killer workcell

Robot type:	6-axis
Robot model:	ABB IRB 120
Gripper:	SCHUNK PGB 80
Fingers:	Custom fingers
Feeders:	Bowl feeder RNA TAG-ZA 250 (541)-32-180
Actuators:	SKF CAT33, SKF CAHB-10
Parts:	Spark killers

Fingers were design to be able to pick up three spark killers and once. A feature was added at each finger to assemble the spark killers in the direction top to down. In the end, the fingers are prepared to assemble 3 spark killers at once in each part (plastic bottom and plastic top).

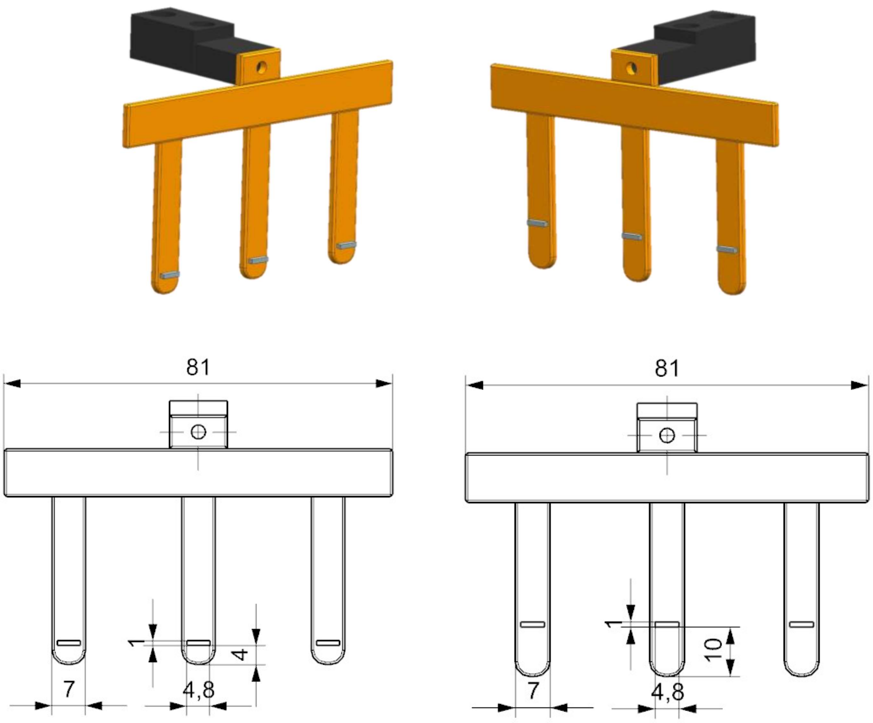


Figure 33. *View (top) and dimensions (down) of spark kill fingers*

In the next figure, is possible to see the designed fingers and gripper together attached to the robot.

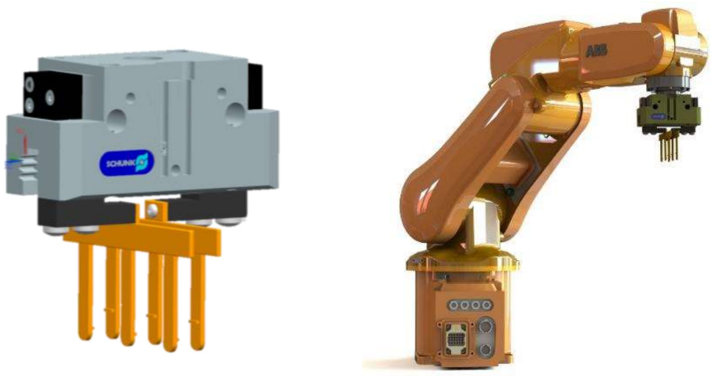


Figure 34. *Gripper and fingers (left) attached to the robot (right)*

Workcell process:

In this workcell the redesigned spark killers will be assembled on the plastic bottom and in the plastic top. For that, it is needed a bowl feeder with a guide, a carrier, 2 linear actuators (1 connected to the carrier and other with a tool), the designed fingers, a gripper and a robot. The system was designed to position the 3 spark killers at correct distance to be assembled.

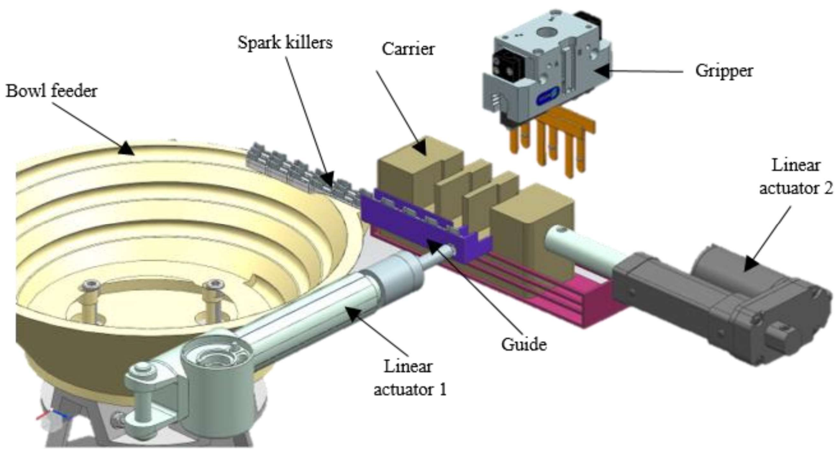


Figure 35. *Disposing of all components of workcell*

All the spark killers are dropped inside of the bowl feeder and will be ordered and enter on the designed guide. This guide has a hole that allows to start starts the first process where the linear actuator goes forward and push the first spark killer to the first space of the carrier. After this the second actuator will pull the carrier and align the second space of the carrier with the guide, allowing the first actuator push the second spark killer. A third spark killer will be pushed in the same way to the third space of carrier and then 3 spark killers are in the carrier.

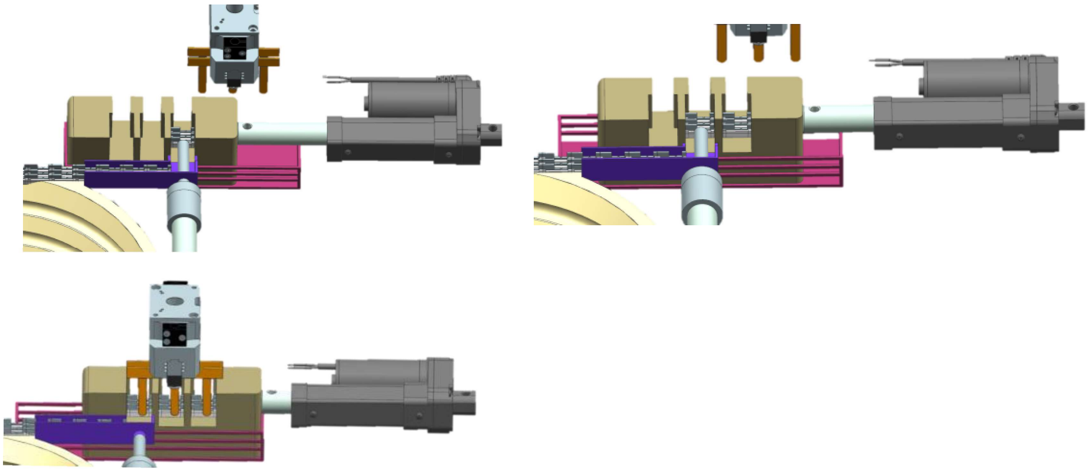


Figure 36. *Process of position the spark killers on carrier*

Thus the 3 spark killers are aligned and in the correct position to be assembled in the main parts. To do that, the robot moves to the carrier, picks up the spark killers (the 3 at the same time) and assemble first on the plastic bottom (at the same time the it is happening the first process) and then picks other 3 spark killers and assemble on the plastic top.

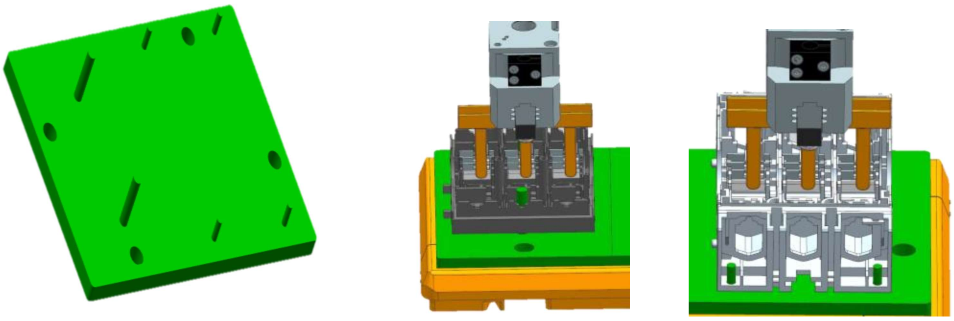


Figure 37. *Assemble of spark killers on plastic bottom and plastic top*

Estimated times of the movements were made to realize how long is the cycle time of this workcell. It was considered the task of actuator 1 than actuator 2 because it has a bigger space to travel and 7 seconds to robot pick up 3 spark killers, move them, assemble on the part and return to the initial position.

Table 8. *Times of the movements to assemble spark killers*

TASK	TIME (s)
Push 1 spark killer	1
Move carrier	0.5
Push 2 spark killer	1

Move carrier	0.5
Push 3 spark killer	1
Move carrier	0.5
Robot pick up parts and assemble	7
Move carrier initial position	1
Push 1 spark killer	1
Move carrier	0.5
Push 2 spark killer	1
Move carrier	0.5
Push 3 spark killer	1
Move carrier	0.5
Pick up parts and assemble	7
Cycle time workcell	**21**

6.5.4. Screw terminals

Robot type:	6-axis
Robot model:	ABB IRB 120
Gripper:	SCHUNK PGB 80
Fingers:	Custom fingers
Feeders:	Bowl feeder RNA TAG-ZA 250 (541)-32-180
Actuators:	SKF CAT33, SKF CAHB-10
Parts:	Screw terminals

Fingers were design to be able to pick up three screw terminals at once. Finger shown below are designed using the same design as the fingers for spark killers. Only few modification were made for original design. Fingers for spark killers have two configurations but fingers for screw terminals were designed with only one configuration.

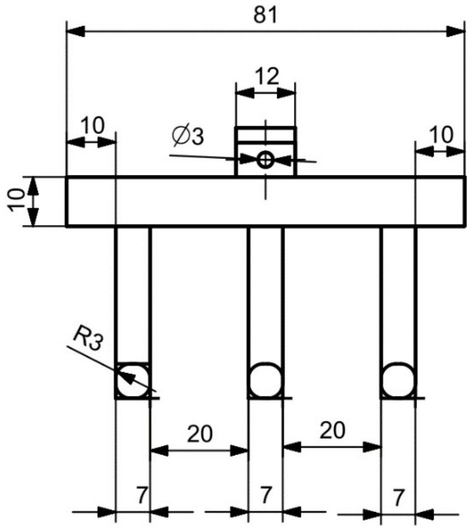


Figure 38. *Dimensions of fingers for screw terminals*

Screw terminal assembly stattion operates with same principles as spark killer assembly but gripper and postioning jig are slightly modified. Because screw terminals have two different modifications screw terminals positioning jig has two configurations. Screw terminals are fed to positioning jig by using bowl feeder and they are assembled three at a time. Even thought assembly process for screw terminals works with same principle as for spark killers there are few differences between theese two proceses especially in time required for movements. Modified feeder for screw terminals is shown in the figure below. More detailed drawings are available in apendix.

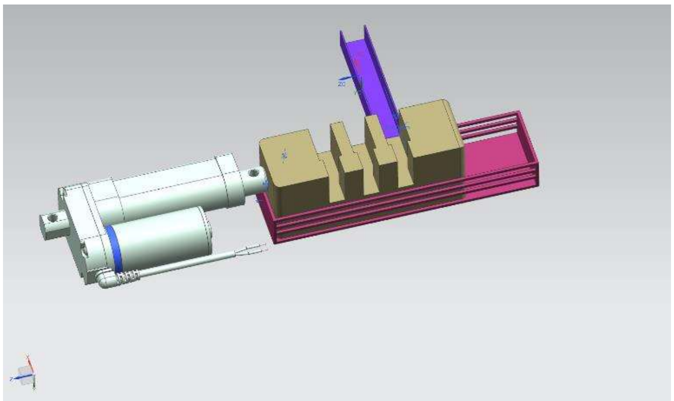


Figure 39. *Carrier and actuator position for screw terminal "up" feeder*

Table 9. *Times of the movements to assemble screw terminals*

TASK	**TIME (s)**
Robot pick up parts and assemble	12
Pick up parts and assemble	12
Cycle time workcell	**24**

Because screw terminals are fed from two different feeders time needed for positioning of three screw terminals are not included in Table 9. This is because while robot picks up screw terminals and assembles them other feeder can position next three screw terminals during that operation

6.5.5. Connectors and axle

Robot types:	6-axis, SCARA
Robot models:	2 x IRB 120, 3x IRB 910SC -3/0.55m
Gripper:	5 x SCHUNK EGP 25-N S/N-B
Fingers:	10x Custom finger
Feeders:	Adept AnyFeeder SX-240
Conveyor:	MK-Group SPU-2040
Jigs:	27 x Custom connector pallet jig
Machine Vision:	ABB integrated vision camers
Parts:	Connector + axle

A separate subassembly line (shown in figure 40) had to be designed for the assembly of the connectors and axle. The subassembly line has three stations which are all designed to run on a circa. 25 second cycle time.

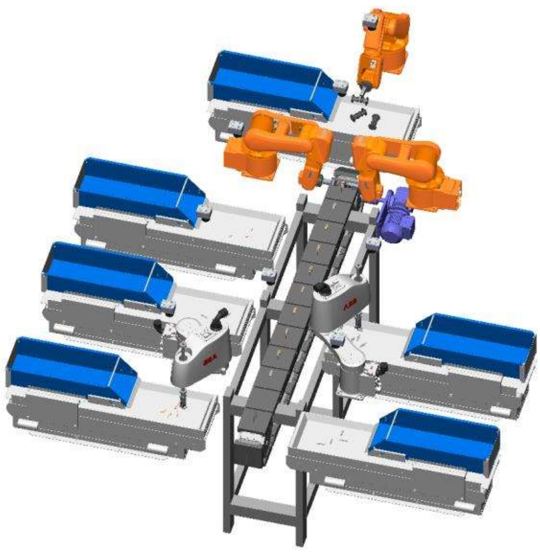


Figure 40. *Connector and axle subassembly line*

In the first subassembly station two IRB 910SC SCARA robots assemble the connector on top of a pallet jig which move on a circulating conveyor. The connector parts are fed for the robots from 4 Adept AnyFeeders. Each feeder vibrates the parts to a random orientation, from which a machine vision system detects suitably oriented parts to be gripped with the robots. The needed orientation is determined by the current assembly phase. The robots are designed to assemble the connector on one pallet at a time, by assembling the parts on top of each other on the jig turn by turn. Both robots have specific grippers. The *left-side* robot can pick the **springs** in both orientations *normal* and *upside-down* and the **connector plate** in the *normal* orientation. Additionally, the *right-side* robot can pick up the **steel plate** in both orientations *normal* and *upside-down*, and the **connector plate** in the *upside-down* orientation. The machine vision system is also used to check that the gripped connector parts are in correct orientation before mounting the parts on the jig. After the two SCARA robots have assembled the connector parts on top of the jig, the pallet moves one place forwards toward the second subassembly station.

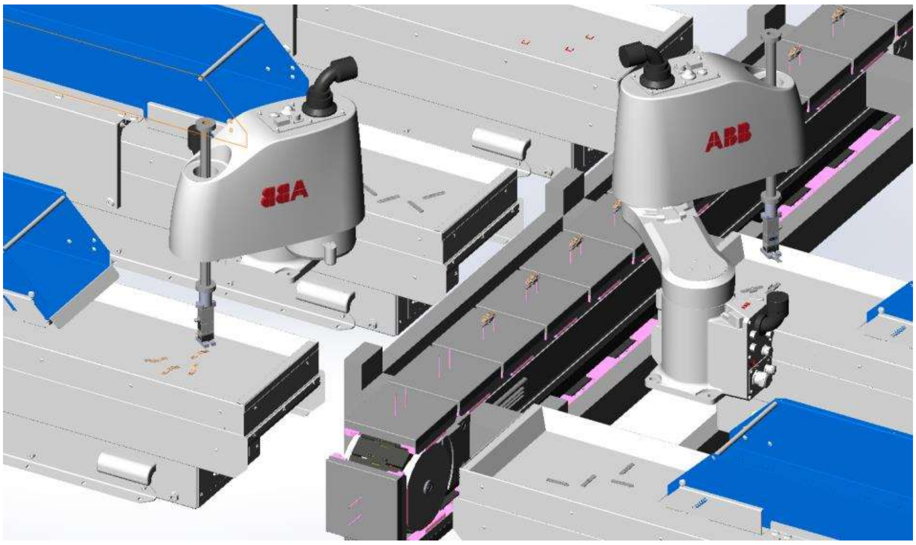


Figure 41. *First station of the subassembly line*

The assembly times of the first subassembly station are shown below in table 10. The parts are assembled mostly in turns. This way, time is saved in simultaneous robot movements.

Table 10. *Assembly times of the first subassembly line station*

Robot	TASK	TIME (s)
Left SCARA	Pick upside-down **spring** and assemble	1,5
Right SCARA	Pick upside-down **connector plate holder** and assemble	1
Right SCARA	Pick upside-down **connector plate** and assemble	1,5
Left SCARA	Pick normal **connector plate** and assemble	1
Right SCARA	Pick normal **connector plate holder** and assemble	1
Left SCARA	Pick normal **spring** and assemble	1
Conveyor	Move pallets one step forward	1,0

	Cycle time workcell	**8,0**
	Cycle time workcell (3x nearly finished connectors)	**24**

In the second subassembly station a pallet arrives with the almost fully assembled connector, and two ABB IRB 120 robots perform the next two assembly phases. One Adept AnyFeeder is used to feed the **connector spring holder** for the *left-side* robot. The *left-side* robot picks the **connector pin** and corrects the parts orientation on a jig next to the feeder. The same machine vision system design is used here also. Simultaneously the *right-side* robot uses its gripper to compress the springs on the connector. Next the *left-side* robot continues to move the pin towards the connector and finally into its mounting position. The right side robot then grabs the connector and lifts it off the jig and offers it towards the third subassembly station. At this point the empty pallet jig moves one step forward towards the beginning of the subassembly line.

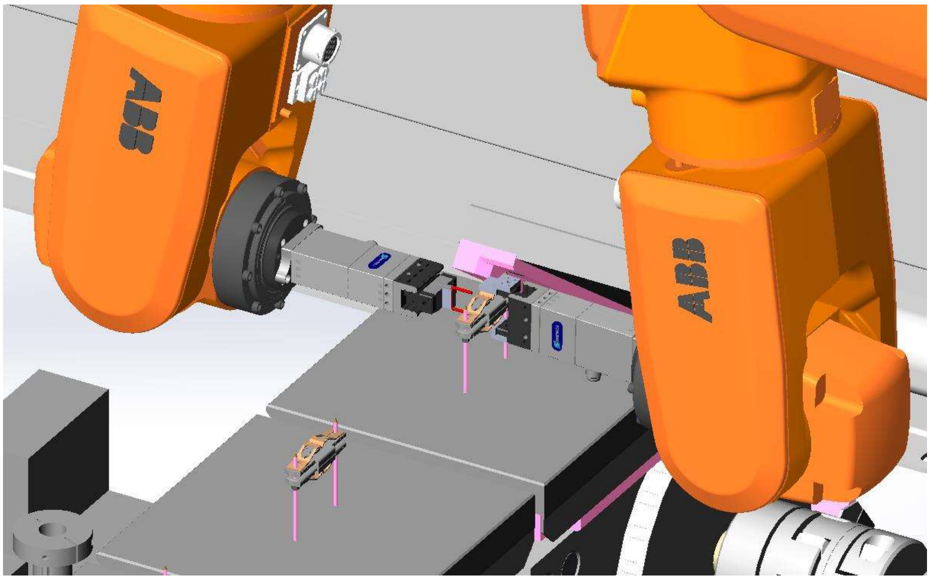


Figure 42. *Second station of the subassembly line*

The assembly times of the second subassembly station are shown below in table 11.

Table 11. *Assembly times of the second subassembly line station*

Robot	**TASK**	**TIME (s)**
Left IRB 120	Pick **connector spring holder** and mount to con-	4,5
Right IRB 120	Press down the **springs** on the connector assembly	0 (simultaneous)
Right IRB 120	Pick assembled **connector** and offer towards next	3
Conveyor	Move pallets one step forward	0,5
	Cycle time workcell	**8**
	Cycle time workcell (3x connectors)	**24**

In the third subassembly station a single ABB IRB 120 robot and a single Adept AnyFeeder is used. The feeder presents the axles for the robot as in the previous stations. The same machine vision system design is used here also. The single robot grabs the **axle** and moves it to face the *right-side* robot of the previous assembly station which is offering the assembled **connectors**. The robot from the previous station mounts the connectors one-by-one into the axle as they get assembled. Once the three connectors have been mounted on the axle, the machine vision system checks the **axle-connector assembly**, and the robot is instructed to turn and face the main assembly line and mount the **axle-connector subassembly** on to the **plastic base**.

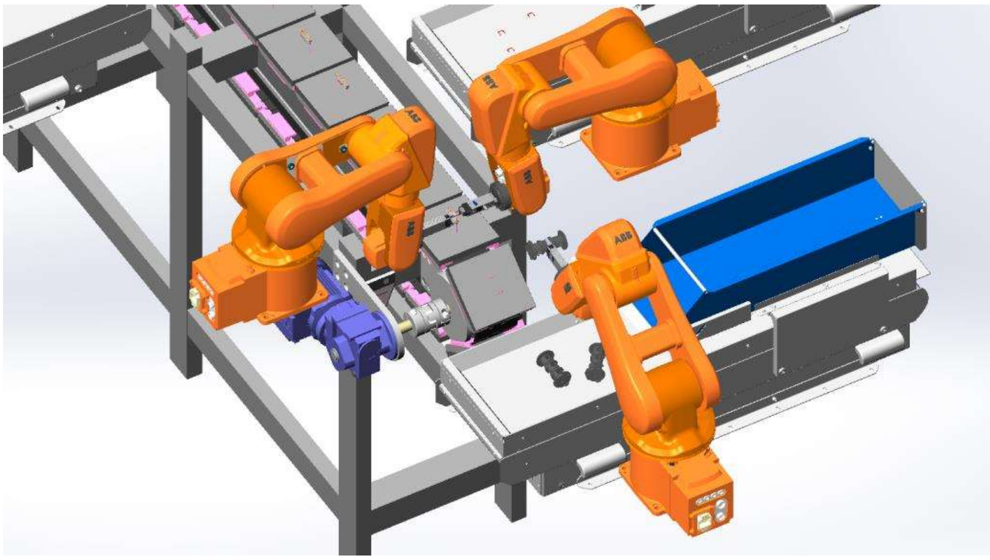


Figure 43. *Second and third station of the assembly line*

The assembly times of the third subassembly station are shown below in table 12.

Table 12. *Assembly times of the third subassembly line station*

Robot	**TASK**	**TIME (s)**
Center IRB 120	Pick **axle** and move towards previous station left robot	0 (waiting for prev. station)
Left IRB 120	Mount **connector** to axle	8
Left IRB 120	Mount **connector** to axle	8
Left IRB 120	Mount **connector** to axle	8
Center IRB 120	Turn and mount **axle** to **plastic base**	3
	Cycle time workcell (1x axle)	**27**

All the needed components for the assembly station are listed in table 13.

Table 13. *Needed components of the subassembly line*

Robots:	**Amount (pcs.)**	**Price (€)**	**Total (€)**
IRB 910SC – 3/0.55m	2	20 000	40 000
IRB 120	3	20 000	60 000

Grippers:	**Amount (pcs.)**	**Price (€)**	**Total (€)**
SCHUNK EGP 25-N-N-B	5	1000	3000

Fingers:	**Amount (pcs.)**	**Price (€)**	**Total (€)**
Custom finger	10	50	500

Conveyor:	**Amount (pcs.)**	**Price (€)**	**Total (€)**
MK-Group SPU-2040	1	10 000	10 000

Machine Vision:	**Amount (pcs.)**	**Price (€)**	**Total (€)**
ABB Integrated vision cameras	8	300	2400
Machine vision control system	1	27 600	27 600

Jigs:	**Amount (pcs.)**	**Price (€)**	**Total (€)**
Custom connector pallet jig	27	150	4000

Feeders:	**Amount (pcs.)**	**Price (€)**	**Total (€)**
Adept AnyFeeder SX-240	6	30 000	180 000

Pictures of how the grippers are used are shown in figures 44 – 48.

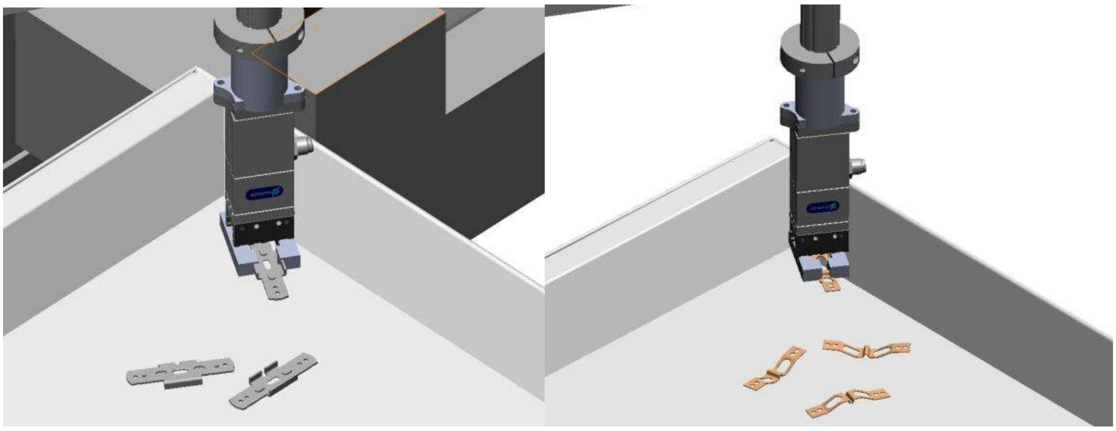


Figure 44. *How the connector parts are gripped*

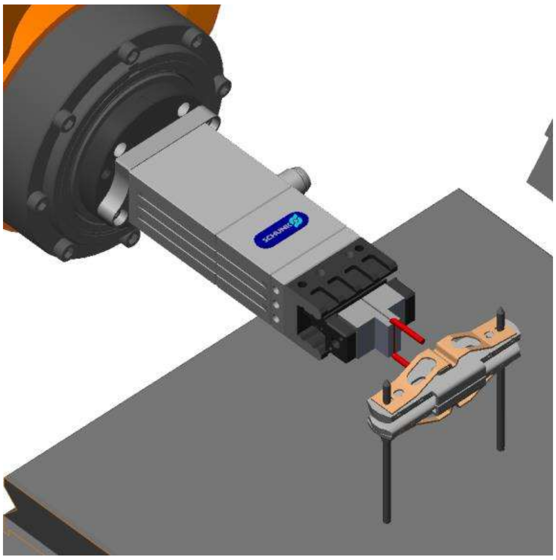


Figure 45. *How the spring holder pin is gripped*

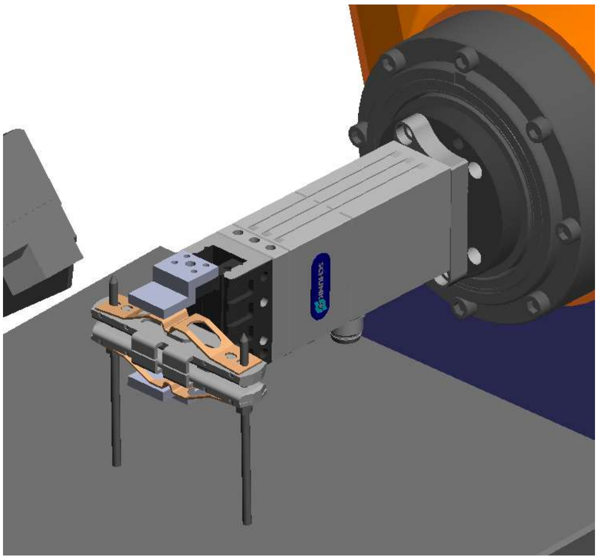


Figure 46. *How the connector springs are compressed*

Figure 47. *How the axle is gripped*

The gripper fingers for the spring holder pin, connector spring compression and the axle are very simple. However, for picking up the connector parts, much more complex gripper fingers have to be used. These are shown in figures 48 and 49. The geometry on the fingers are meant to directly follow the geometries of the parts.

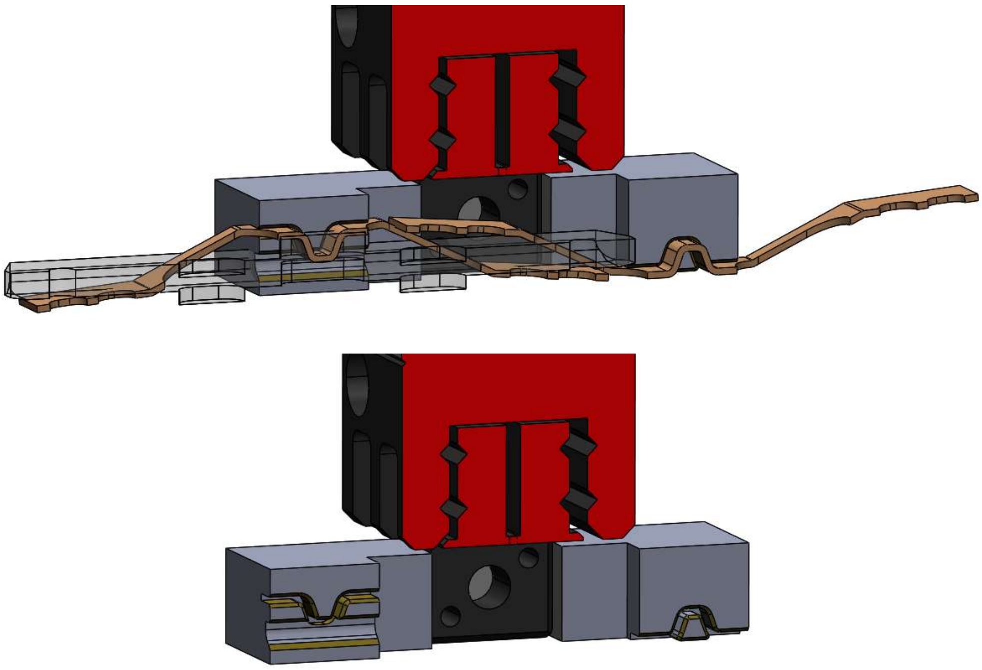


Figure 48. *Gripper fingers for the left side SCARA robot*

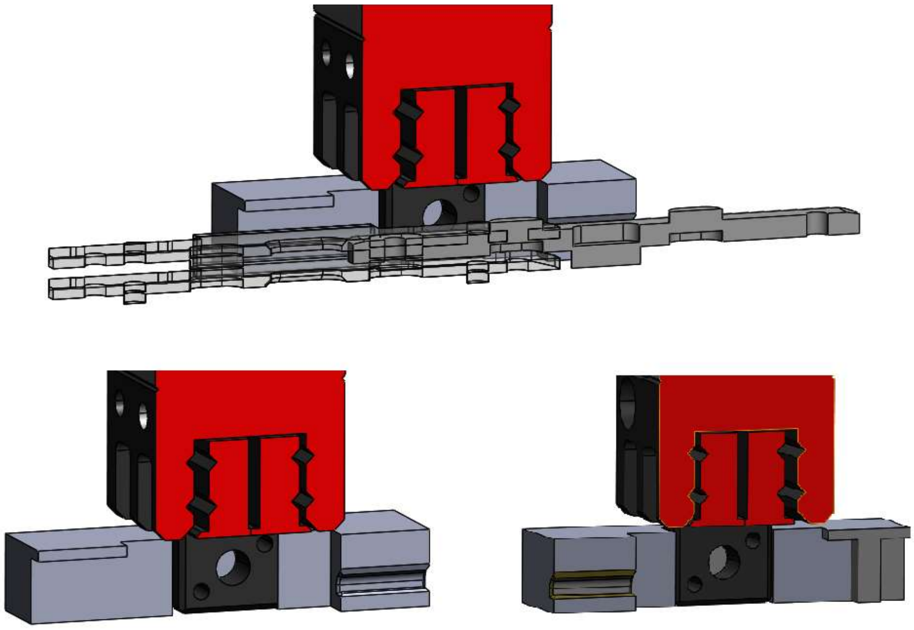


Figure 49. *Gripper fingers for the right side SCARA robot*

6.5.6. Flipper

Robot type:	Six-axis
Robot model:	ABB IRB120
Gripper:	Festo BUB HGPL 14 A
Fingers:	Festo BUB HGPL 63 (modified)
Feeders:	-
Parts:	-

Flipper robot only job is to flip the plastic top and place it on plastic bottom. Figures 49, 50 and 51 are not showing correct phase of the product because every part should be visible at that point except plastic windows. This flipping has to be done by individual robot although it will not be so occupied with tasks, because it needs precise placement and other robots don’t have available capacity to do this.

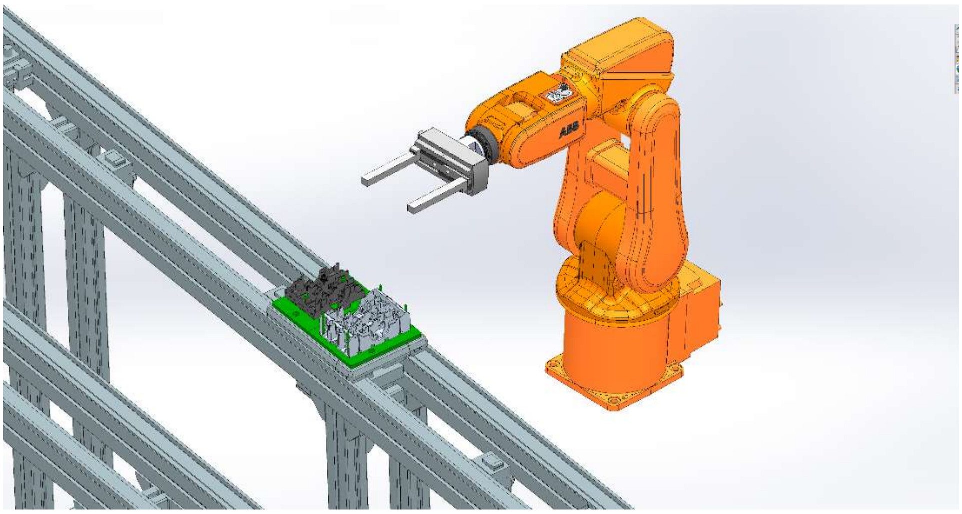


Figure 50. *Flipper*

Figure 20 shows how the gripper takes the plastic top out of the tray. It is the most secure gripping position and it can be done with many different types of ordinary grippers. Gripper that is used here, is the same one on the first SCARA robot which picks up the plastic bottoms and tops to place them on the track.

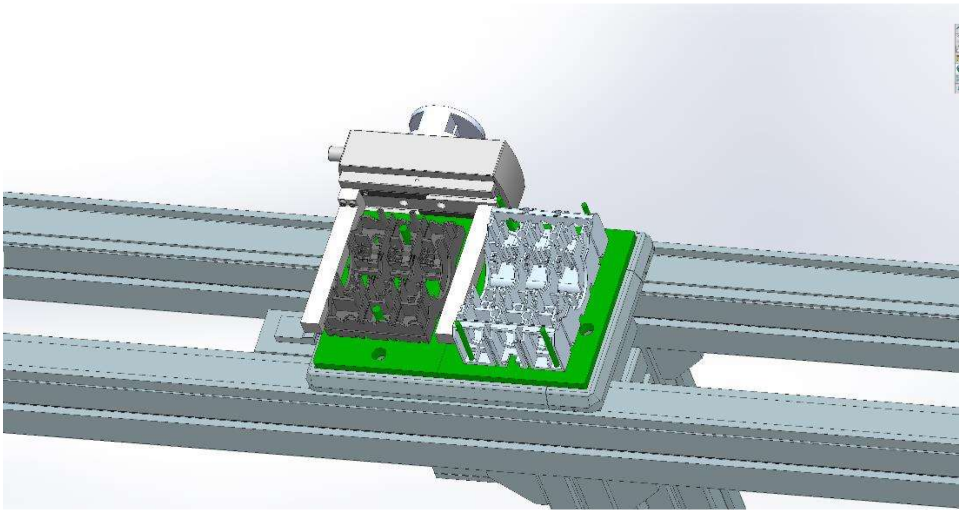


Figure 51. *Gripper grapping plastic top*

Placing the bottom is straight forward thing but it would need to tested can the robot push down part gripping from the sides or does it need to just place it and the push it in from the top of the plastic part.

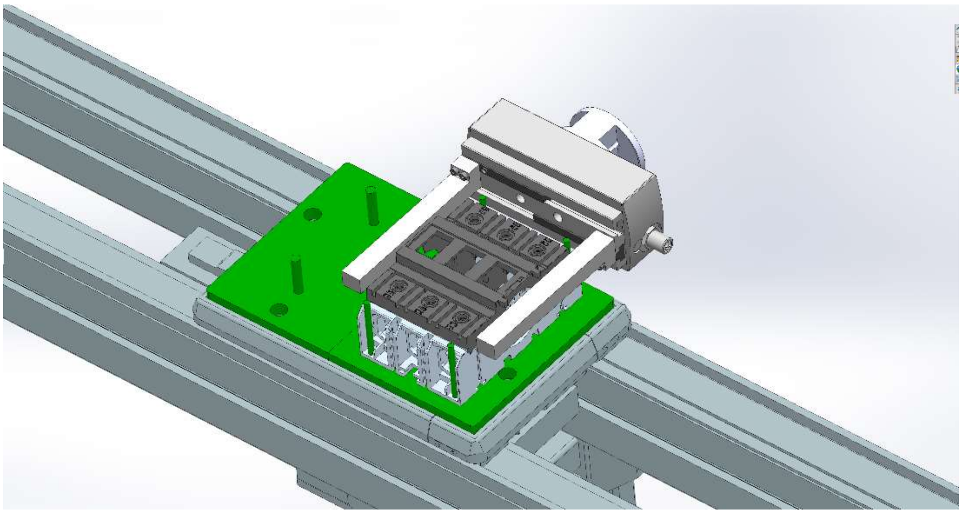


Figure 52. *Placing the top on plastic bottom*

Robot gripper is a standard gripper and is shown at figure 52. Festo fingers were modified to be narrower that the original, because the plastic top and bottom didn’t have enough space between them.

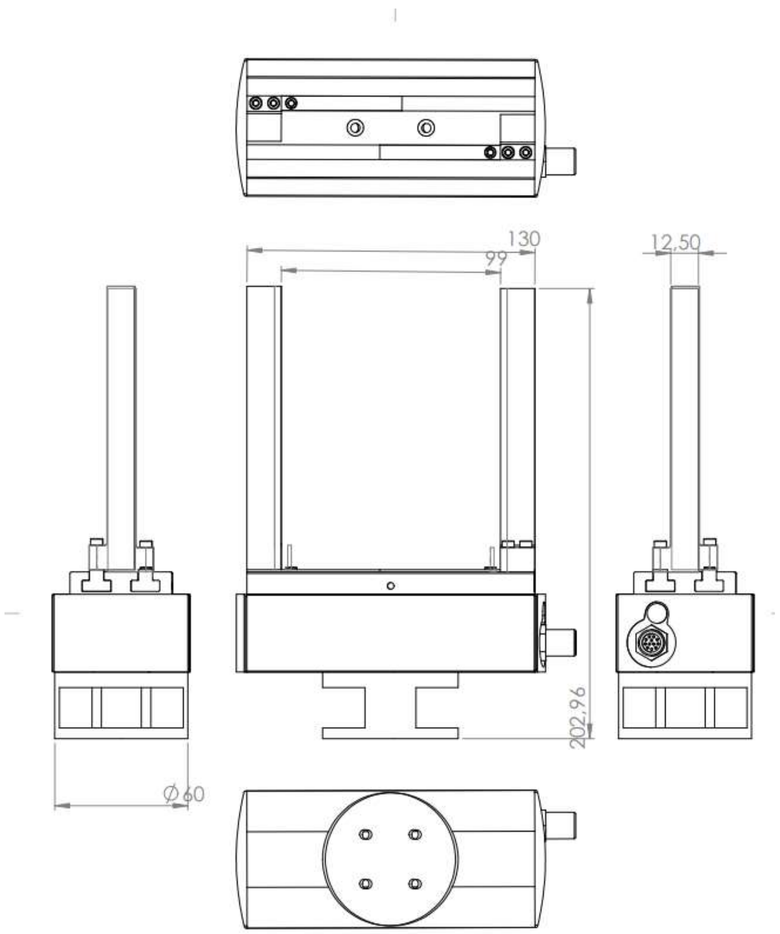


Figure 53. *Plastic top gripper*

6.5.7. Plastic window

Robot type:	6-axis
Robot model:	IRB 120
Gripper:	3x Schmalz SGON 24 x 8 mm suction cups, 6x FESTO pneumatic cylinders
Feeder:	Devprotek FTF-21P with custom trays
Parts:	Plastic windows

Plastic windows are assembled with one robot seen in figure 53 The robot is ABB IRB 120 and it can assemble all three windows at the same time with a custom gripper. Gripper works with suction cups and pneumatic cylinders.

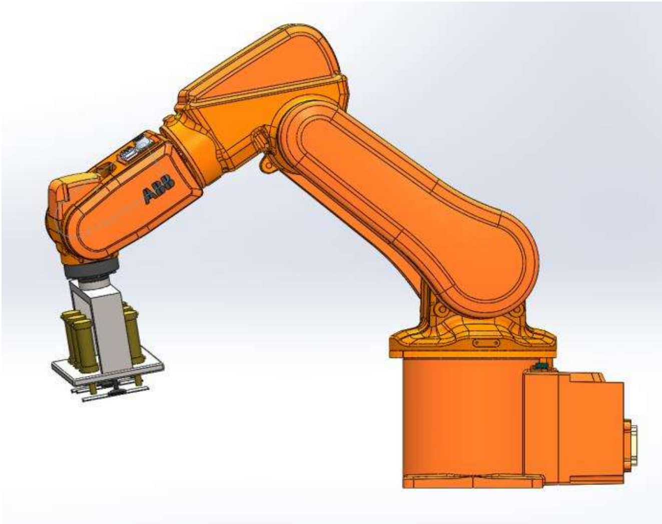


Figure 54. *Robot and the custom gripper*

Table 14. *Cycle time of plastic window assembly*

TASK	TIME (s)
Move to tray feeder	5
Pick up three windows	4
Move windows to their place	5
Push windows with pneumatic cylinders	4
Change tray	6
Cycle time workcell	24

Plastic windows come in a tray from a tray feeder. Tray feeder must be loaded manually. Tray feeder can carry 30 trays at the time. Feeder slides one tray in the end of the line so that robot can operate with it. Feeder changes the tray automatically when it gets empty. Robot takes 3 windows from the tray with suction cups and takes them to the right place. The cycle time of this workcell can be seen in table 14. Suction cups are made of rubber, so they don’t harm the surface of the window.

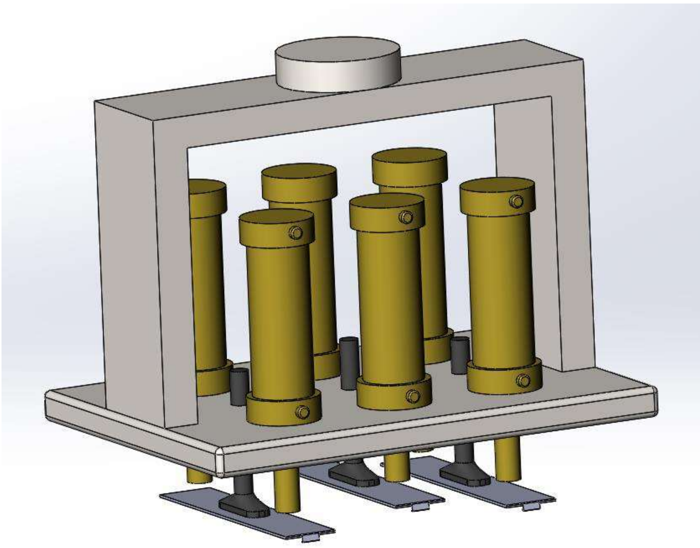


Figure 55. *Custom gripper*

Pneumatic cylinders in the gripper are used to push the window to its place because suction cups can't be used for pushing parts. There are two pneumatic cylinders for each window as in figure 54 shows. Cylinders push the window near the snap-fits so that window doesn't bend when pushing it.

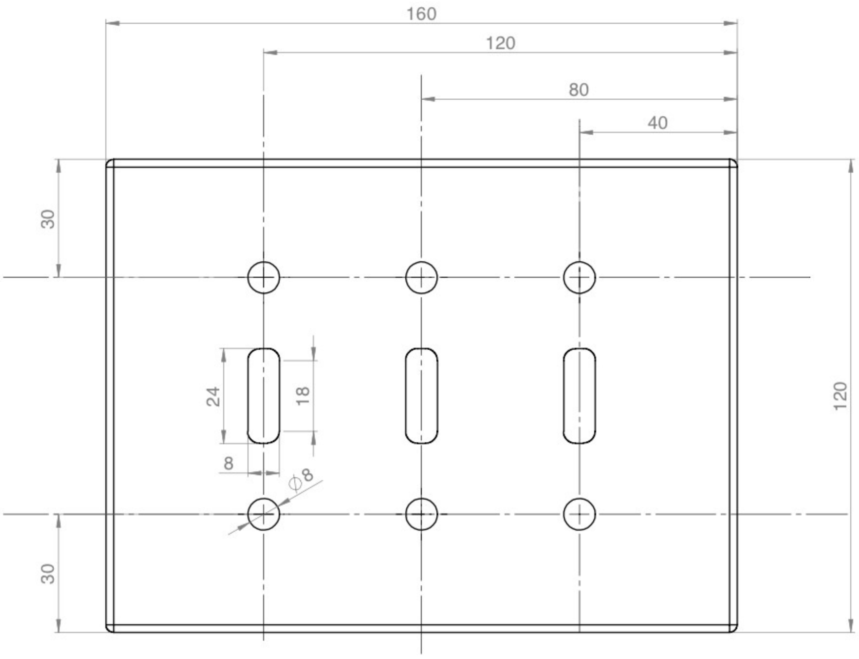


Figure 56. *Drawing of the gripper*

In the drawing in figure 55, you can see the dimensions of the gripper that is used. Suction cups are the oval shaped in the middle and the circles describes the piston of the pneumatic cylinder.

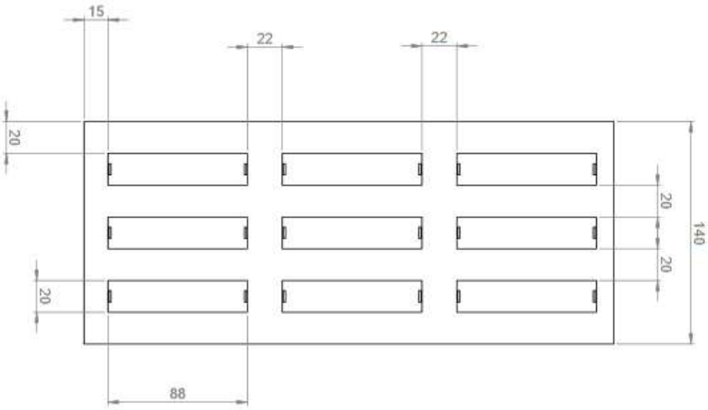


Figure 57. *Drawing of the tray*

The tray can carry 9 windows at the same time. The dimensions can be seen in figure 56. Size is limited because of the tray feeder we use.

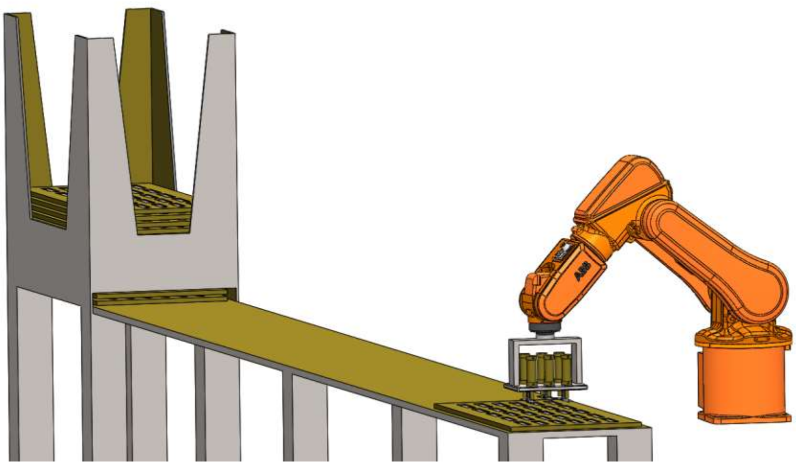


Figure 58. *Tray feeder and the robot*

6.5.8. Place workcell

Robot type:	Cartesian
Robot model:	Omron palletizer
Gripper:	3x Schmalz SGON 24 x 8 mm suction cups, 6x FESTO pneumatic cylinders
Parts:	Finished product

Last workcell on the line takes the finished product and swipes stickers on it and place it on pallet. No 3d-model was available for this product but figure 58 represent a concept of how it would be implemented in this conveyor. In the layout picture, cartesian robot is modelled with generic model. Works is done with same gripper as the windows placement, because it can also pick up the cardboard to put between layers.

Figure 58. *Omron palletizer*

Unlike the figure 58, no conveyor is present at the of this assembly system because the products are considered so small that pallet could have hundreds of pieces, so pallet is removed only once per shift by pallet lifter.

Table 15. *Cycle time of palletizing*

TASK	TIME (s)
Move to conveyor	4
Pick up finish product	4
Move to labeler	3
Place stickers	4
Move to pallet	6
Place the finish product on pallet	2

Cycle time workcell	23

Figure 59. *HERMA 400 labeler*

Two pieces of Herma 400 is put sideways for the cartesian robot and robot swipes the finished product as it moves to pallet.

6.6. Simulation

Completed production system was simulated for 60 minutes with Visual Components Premium 4.1. In simulation new work piece pallet is entered to the production system every 27 seconds. During the 60 minutes 124 pieces were produced (Figure 60). With this information production volume for 8 hours would be 992 pieces and for 24 hours 2 976 pieces and 732 096 pieces for yearly production volume. If 90 % availability is assumed yearly production would be 658 886 pieces.

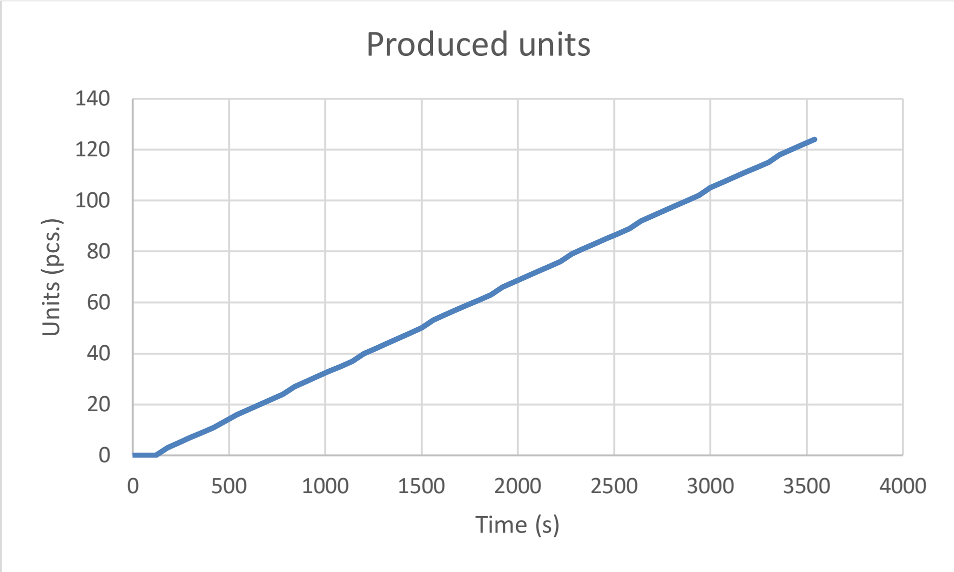


Figure 60. *Number of produced units during 60 minutes*

Simulation estimated only time for robot movements from feeder to pallet. These movements were not optimized. Time for positioning and other movements were not simulated. This means that there some sources of error in cycle times shown in the table below. But because optimization would make cycle times shorter and inclusion of time needed for positioning would make cycle time longer when these points are considered cycle times, shown in the table below, can be trusted as an approximation of real cycle times.

The target for cycle times was 9 seconds for connector subassembly (Connector phase 1, Connector phase 2 and U-pin). The target for actual work cells was 27 seconds. As shown in the table 27 second target was accomplished by all process. Unfortunately these cycle times to long for each process that combining of two separate process to one would be very difficult. Target for connector subassembly was not met but this subassembly process could be faster after the optimization of robot movements.

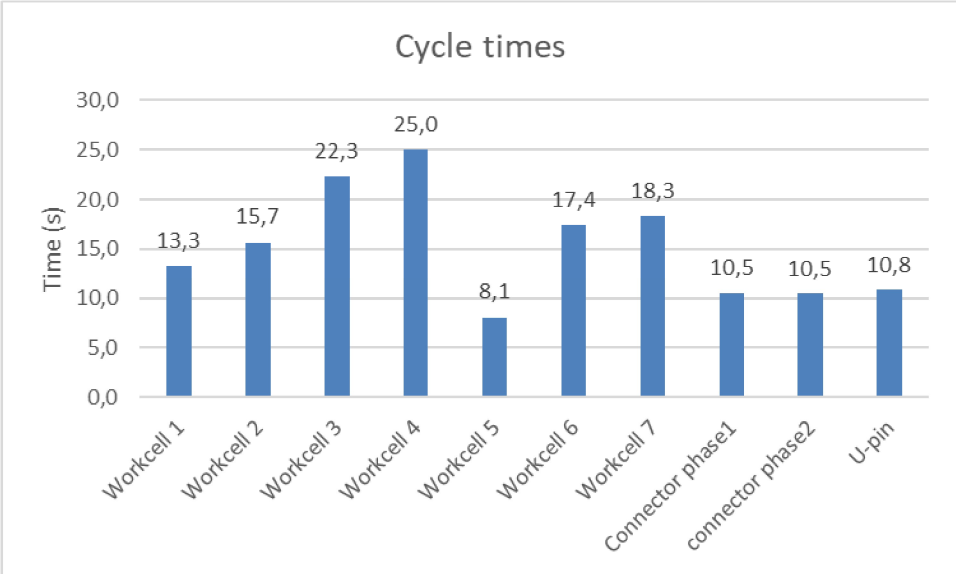


Figure 61. *Cycle times during the simulation*

Utilization of robots is also imported from simulation are shown in figure below. As shown in figure below utilization of robots in connector subassembly (SCARA 1, SCARA 2, U-pin robot and Spring holder robot) is very high (almost 90 %) for all of them except Spring holder robot. Utilization of Spring holder robot is much lower than U-pin robot because in simulation Spring holder robot made only one movement after 3 connectors were ready. In real system Spring holder robot would hold the axle on place during the assembly of 3 connectors.

Utilization of robots in the main assembly line (Wokcells 1 to 8) are much lower than utilization of robots in connector subassembly. Utilization of main assembly line changes from 18 % up to 42 %. This means that efficiency of could be improved for main assembly line robots.

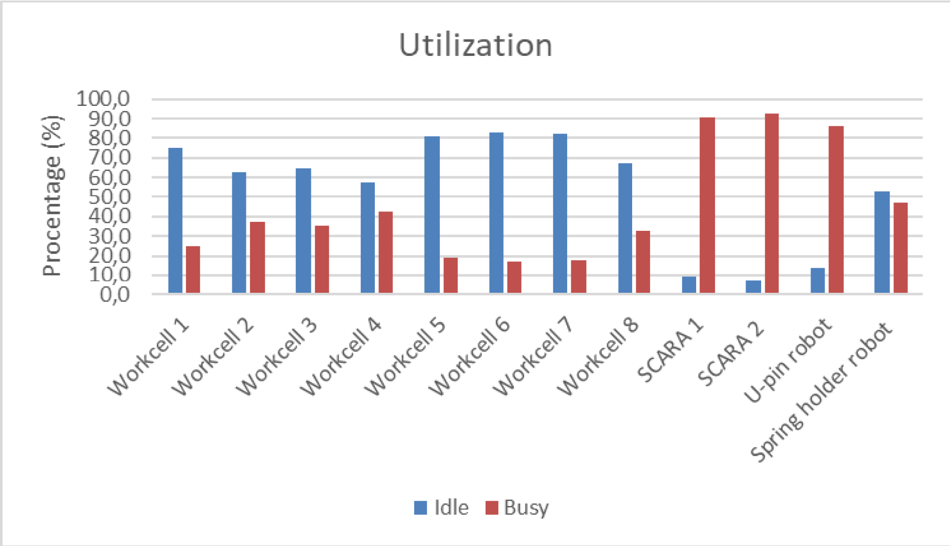


Figure 62. *Utilization of work cell*

Simulation results show that this assembly system has a bottle neck in connector subassembly. With this simulation no bottle neck was formed but if new work piece pallets would be entered to the production system faster than every 27 second bottleneck would form to axle assembly station. If faster cycle time would be needed connector sub assembly should be improved. This improvement would not make possible to lower cycle time more than 2 seconds because bottleneck would form first to screw terminal assembly station and then to spark killer assembly station. Overall designed system performed well in the simulation no bottle neck was formed and production goal was reached.

7. ECONOMIC JUSTIFICATION

To achieve and build this automation line, the costs of machines and components needs to take in consideration. For that, a list of all components and quantities used were collected and an estimated price was defined per unit. In the end, the line components cost 556 550 €. In the table 16 is possible to see all the data considered and final cost.

Table 16. *Approximated cost for different components*

Quantity	Device	Cost unity	Cost aprox €
20.6 m	Transfer system		40000
10 m	Conveyor	1000+400/m	4200
8	ABB IRB 120	20 000	160 000
3	ABB IRB 910	20 000	60 000
1	Omron Cartesian robot	20000	20 000
5	Hopper	1500	7500
4	Bowl feeder	2500	10 000
10	simple Gripper	600	6000
6	pneumatic cylinder	1500	9000
4	Suction cups	150	600
13	Customized finger	150	1950
2	customized Jig	150	300
6	Actuator	1250	7500
2	Machined parts	250	500
6	Adept anyfeeder	30000	180 000
1	tray feeder	1000	1000
1	Conveyor lift	3000	3000
1	Conveyor spu-2040		12000
1	Vision system		30000
1	Fences		3000
		Total	**556 550 €**

To go full automation assembled line (without considering the operators to place parts and feed the hoppers) and achieve the 500 000 units in a year, an investment of 556 550€ needs to be done for the components. In the calculations, we used multiplier 3x to estimate needed investment for programming, safety and control components, which counts as 1 669 650 € as total investments.

Table 17. *Cost comparison of automated and manual assembly*

	New Design	New Design (automated)
Work hours/worker (h)	1624	1624
Assembly time (min)	4	4
Assembled units in a year	28800	28800
Yearly production (pieces)	500 000	500 000
Needed assembly workers	18	6
Needed workers +support and reserve personel	24	24
Hourly wage	37	37
Labor cost in a year for one worker (€)	60 088	60 088
Total labor cost for year (€)	1081584	360528
Machine operation costs		62 400
Investment cost (€)	0	1669650
Total costs / year (€)	1 081 584	422 928
Total costs / unit (€)	2,163168	0,845856

Machine operation costs are calculated as follows:

Working days per year * 24h * Number Of Robots * 5€/h

In the beginning of this project, it was estimated that 28 workers were necessaire to have the same number of products in the end of the year. The line developed can replace the 10 workers and the payback time can be calculated.

$$\text{Payback period} = \frac{\text{Money paid for the solution}}{\frac{\text{units}}{\text{year}} * \text{difference(assemblycost)}}$$

Substituting in this equation the money paid for the solution per the cost of the assembled automation line and the annual cost reduction per the cost of 10 workers, the payback period will be:

$$\text{Payback period} = \frac{1\ 669\ 650\ €}{659050\ €/\text{year}} \approx 2{,}53\ years$$

After 3 years the automation assembly line will be already paid the investment made and starts to be profitable comparing to the manual assembled line.

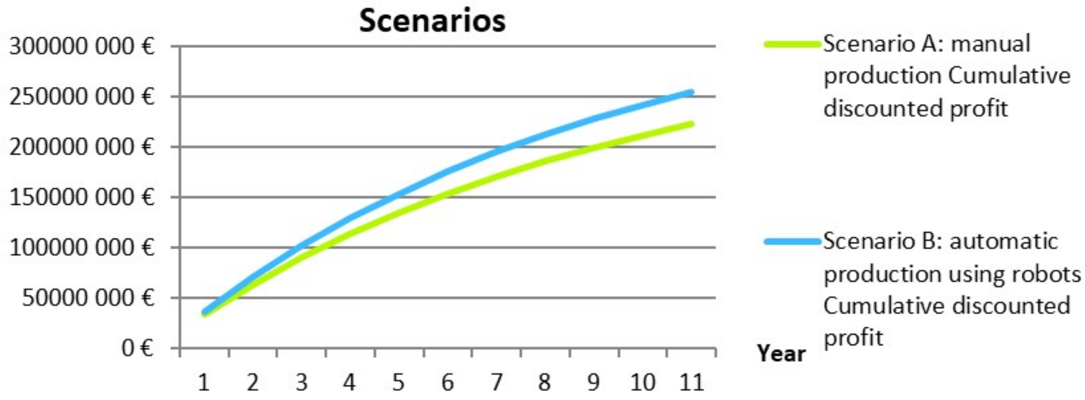


Figure 63. *Cumulated profit over time*

Cumulative profits are calculated based on the knowledge on volume and costs. Manufacturing/shipment costs are estimated to be 10x assembly costs and sales price for the finished product around 100€. Figure 63 shows how assembly system cumulates profits over time. This comparison is done between old-design and manual assembly versus new design and automated assembly.

8. CONCLUSIONS

Our work began with analyzing the product ABB OT160 and focusing on the functions of the product parts. With DFA analysis we found that some of the parts were unnecessary to be separated so we were able to reduce number of parts for the product. This was the first step in making a more straightforward assembly tasks. Some of the improvements didn’t reduce parts but nevertheless improved assemblability. Comparing the old and new design made an impact on needed workforce to assembly the product by reducing almost 10 operators from the line.

With the new design, we started developing a system that would be able to automatically assemble the product. This design process started with analysis of the assembly process and how the new design was put together. Afterwards we made a preliminary layout of the system and analyzed what was the needed cycle-time to meet required capacity. After each cell was created, we simulated the results to verify our system met the requirements.

New automated line had a payback time of three years and we conclude that the new design and automated process is justified in economic point.