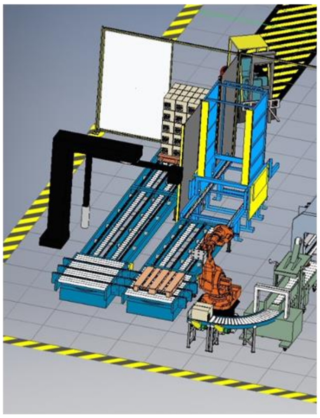
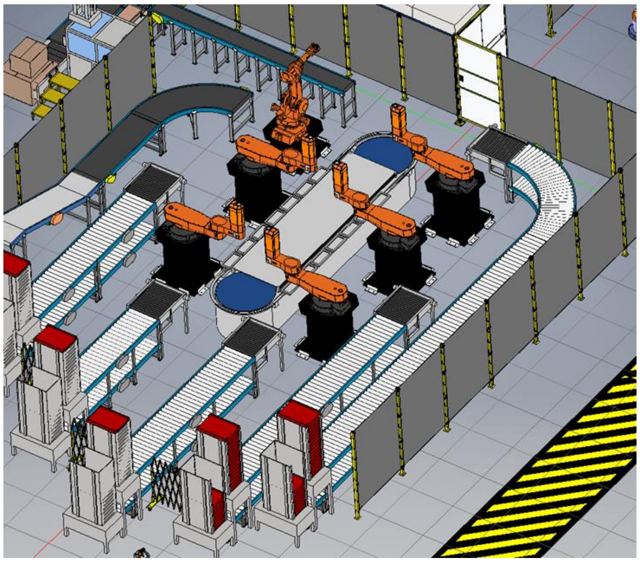
MULTIDISCIPLINARY DESIGN OF

INDUSTRIAL ROBOTIC AUTOMATION SOLUTIONS

- Practical guide for students -





Bogdan MOCAN

Stelian BRAD

Mircea FULEA

Mircea MURAR

Anca STAN

Sanda TIMOFTEI

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Director: Ing. Călin D. Câmpean

Recenzia: Prof.dr.ing. Claudiu Raţiu
Conf.dr.ing. Călin Vaida

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Chapter 1: An overview on robotics and industrial automation

Stelian BRAD

Abstract

In the age of exponential progress of technology, innovations in robotics are exploding by integrating in smart ways the latest developments in artificial intelligence, mechanics and control. Beyond this, integration of robots with other smart systems to meet the challenges of smart factories leads to the consideration of new communication protocols, standardization and remote monitoring and control. Major trends in robot development and integration in automated industrial production lines are highlighted in this chapter.

1.1 An overview and trends on robotics and industrial automation

Robots, in their incipient form of "automata", have the origins in the ancient world. However, the concept of "robot" appears in the times when "industrial revolution" reached a pick, in the first decade after the "Second World War", and it was imported from science fiction literature (i.e. the work of Czech writer Peter Capek, from 1921). Because the term "robot" was adopted for automated machines that handled parts in manufacturing plants, the term "industrial" was added to "robot"; thus, the inherited name was "industrial robot". The first industrial robot was designed in the USA by Unimate in 1954, when computer-controlled servomechanisms were also invented. The first industrial robot was, in fact, a programmable manipulator, hydraulically driven, dedicated to handle parts in a foundry. We can consider this moment the born of industrial robotics and robotics industry. Since then, industrial robotics has evolved as part of the "information revolution" paradigm.

Industrial automation has originated in the early 1970s, when the first PLC (programmable logical controller) was designed in the USA, too, followed by several inventions and innovations in HMIs (human-machine interfaces) and I/O communication protocols and technologies. The term "automation" or "automatic control" has the origin in 1930s, also inspired from the name "automaton". General Electric was the first company which set up an automation department in 1947. Industrial automation in production is about the use of "intelligent" machines, tools and devices to perform various operations with minimal or without any intervention of human operators. Industrial automation involves control systems, sensors, software, various forms of actuation (pneumatic, electric, and sometimes hydraulic), human-machine interfaces, in various combinations and complexities. Industrial robots are the top and most complex systems of industrial automation. Thus, industrial robots and industrial automation have evolved hand-in-hand.

An industrial robot is constituted from several interdependent systems. In the early phases of the life-cycle of robotic technology the goal was to actuate a mechanical system in order to perform predefined tasks that respect well-defined laws of motion (e.g. trajectory, speed, acceleration). This means the environment is also well-defined. In this respect, the focus in robotic technology development was on understanding the kinematic and dynamic laws of motion of versatile mechanical structures (both with serial and parallel chains, as well as mixed ones), on improving the actuation system (motors and speed reducers), but also on developing the control system, senzoric system and programming languages. Dependability of these systems was another line of improvement. After more than 60 years of research and technological developments, we might consider that mechanical system modelling and design reached a mature status. Driving systems also reach maturity, most of the latest practical solutions being electrical, with ac motors controlled in frequency. Nowadays, control algorithms work also well at speeds dictated by current industrial applications. Speed reducers are planetary, cycloidal or harmonic. They also reached a mature level of development. However, challenges are still in designing and manufacturing compact speed reducers with high transfer ratio, high efficiency and reliability and with small number of mechanical components. Sensing systems used in robotics are very diverse, from sensors that monitor position and speed in robot joints to sensors that monitor behaviour of the end-effector mounted on the robot arm (state, speed, force, etc.). Challenges are still in designing and manufacturing sensors that interact with external environment and their related interfaces with robot controller. In this area, of big importance are the vision systems, as well as sensing systems that are based on other working principles (e.g. magnetic field, thermal field). Still challenges are in developing the intelligence of these type of sensors, but also to make them robust to various noise factors (e.g. light variation). Robot programming languages are mostly structural languages, not object-oriented. They serve very well programming requirements. However, there are still several challenges in making these systems of higher performance. Robot producers have made constant efforts to improve the interface with robot programmers. Today we benefit of graphical interfaces, where robots can be programmed both off-line and on-line. Virtual controllers are used to develop applications on computer and to test virtually the processes where robots with be integrated. It is possible to develop customized interfaces with robot operators, to simulate sensors and other smart components, as well as to simulate the robotized process. Automation of processes can be also virtualized and tested before implementation in the physical system.

Future improvements are expected to make programming faster and easier, such as visual and intuitive programming.

Robotic technology is today capable to ensure communication between robot controller and various external devices, both through local networks and via internet. Various specific communication protocols have been developed and implemented in this respect (PROFINET, ETHERCAT, Modbus TCP, Ethernet/IP, CANOPEN, DEVICENET, etc.). Future in industrial robot development is in the area of interaction with operators in safe conditions (e.g. collaborative robotics or cobotics), in the area of smarter and multimodal human-robot interfacing, in making industrial robots much more intelligent using multi-modal interaction systems with the external environment, as well as in making robots adaptable from mechanical and control points of view to new circumstances (e.g. transformable and reconfigurable construction). Intelligence is about capacity to adapt to unexpected conditions and to take the best possible decisions in a given context. Capacity to negotiate with other systems, to optimize the task such as to maximize the result, to work with incomplete information are key issues in relation with robot intelligence. Autonomy is a proper term to capture all these features.

From another perspective, industrial robots still lack guaranteed accuracy below 0.1 mm (0.02 mm in few cases of parallel robots, but with low working spaces). This bounds somehow their scope, meaning they cannot be used for high-precision machining. Someone would say that CNC machine-tools are special kinds of robots that work in Cartesian coordinates and they reach 0.001 mm precision; however, they are not versatile and cannot perform other industrial operations (e.g. welding, handling, spray painting, gluing, laser cutting, inspection, etc.). Absolute accuracy of joint positioning cannot be yet guaranteed and the performance of control systems still limit the autonomy (e.g. adaptiveness) and capability of robots for real-time response to variable forces in the working environment.

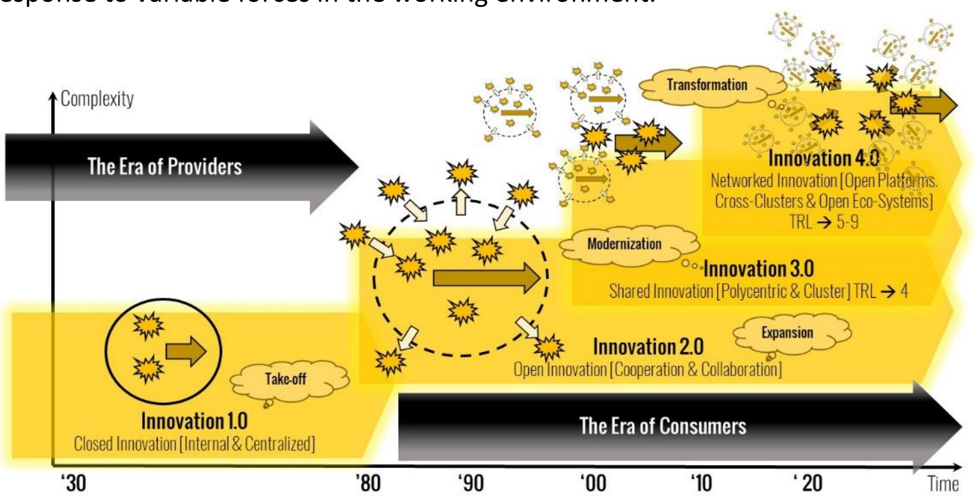


Fig. 1.1.1. From Innovation 1.0 to Innovation 4.0

In order to face with the challenges mentioned in the previous paragraphs, innovation in robotics must consider open platforms where the best experts cooperate to design complex robotic solutions (see Fig. 1.1.1).

In terms of both development and integration of industrial robots in production, the future is towards the paradigm of Industry 4.0 (Figure 1.1.2). Robots, as other equipment in the future factories, will have to be deep integrated with the other equipment from the factory, to exchange information and to adapt in due time to new working conditions. Evolution towards Industry 4.0 is shown in figure 1.1.3.

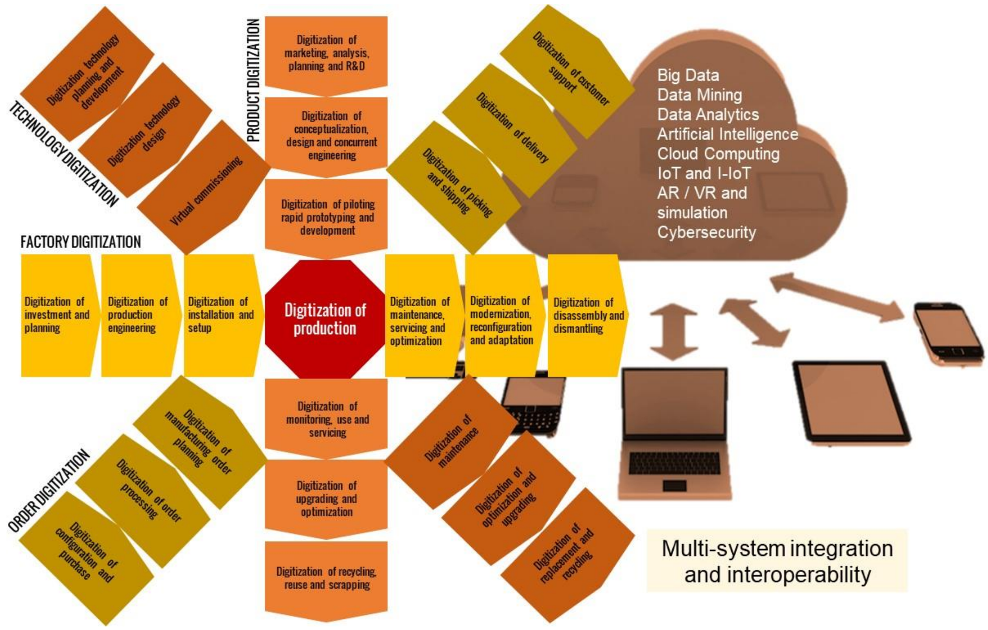


Figure 1.1.2. Industry 4.0: extended digitization of production

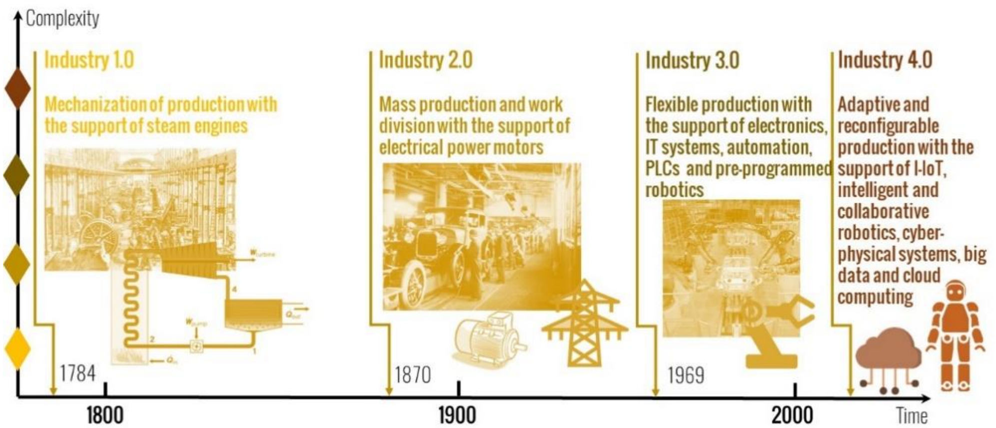


Figure 1.1.3. From Industry 1.0 to Industry 4.0

Industry 4.0 is the name given to the fourth revolution in industry, which is marked by profound digitization and extensive communication between all systems from the production floor, and beyond, from the overall value chain of production (e.g. including suppliers, distributors and support processes).

Future production environment will require seamless links between the real world and the digital world. Robotic cells and systems will be first designed and tested in the virtual world and then the physical solution will be implemented. Massive data about system during its operation will be collected in cloud and further interpreted. Any time, engineers will be able to replicate sequences from the real process in the virtual world, based on data collected from the real world, in order to optimize future designs. A possible robot system architecture would look like in figure 1.1.4, where "Industrial Internet of Things" combined with "blockchain" technologies will play a central role for smart integration of robots within industrial automation systems.

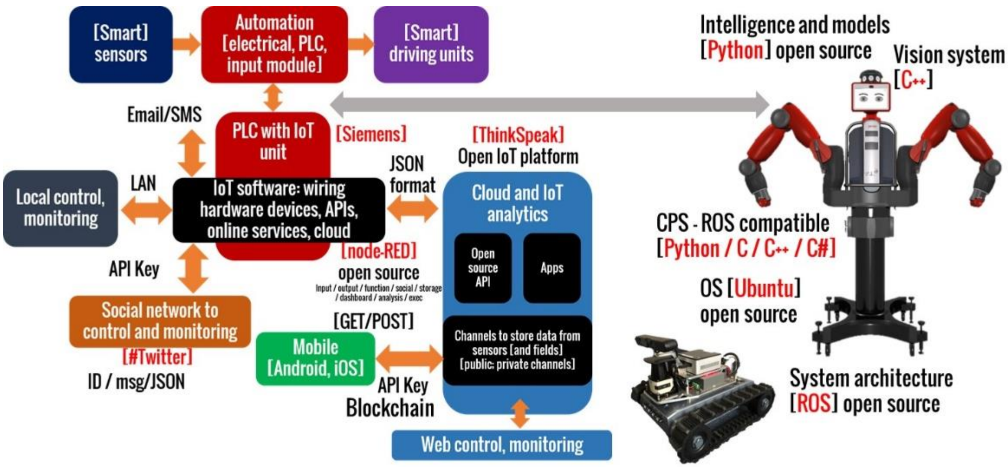


Figure 1.1.4. A possible architecture for robot integration in smart factories

As figure 1.1.4 illustrates, proprietary operating systems and programming technologies will be replaced by open source solutions. Thus, a worldwide community of experts will be able to contribute to the enhancement of robotic solutions. Beyond this, prototyping of new robotic systems for customized applications will be possible at affordable costs, too. In this paradigm, industrial robotics of the 21st century will have to move from an evolutionary innovation to a revolutionary one (see Fig. 1.1.5).

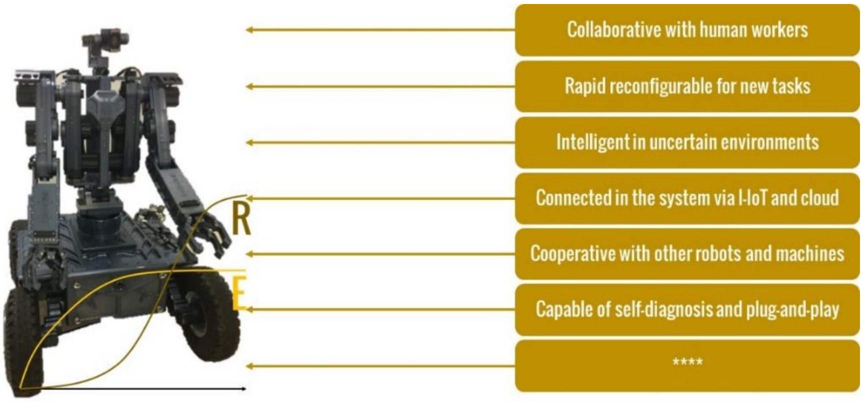


Figure 1.1.5. Future trends in industrial robotics

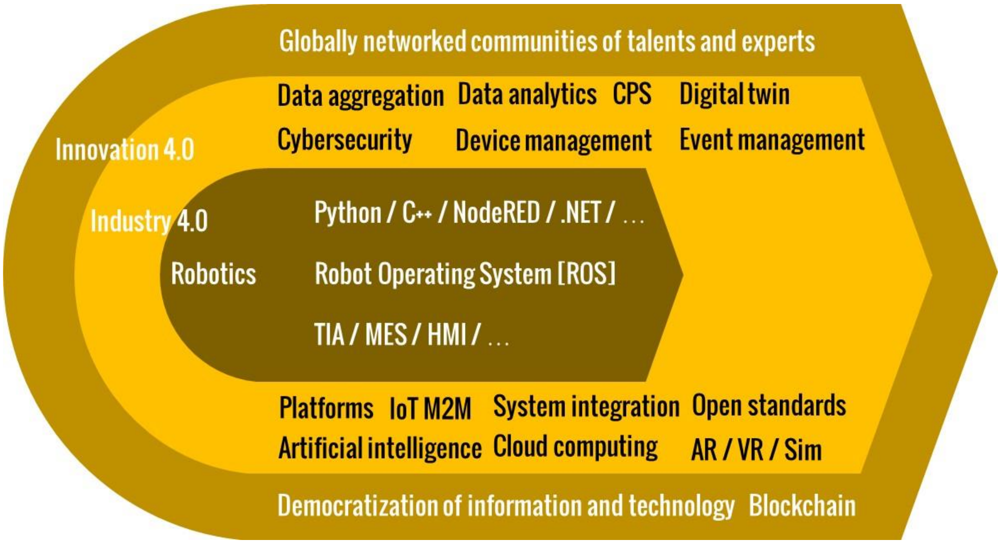


Figure 1.1.6. Intelligent industrial robotics and digital domains

Thus, to meet the requirements for intelligent networking and flexibilization of individual manufacturing and production processes, industrial robotic systems must consider an environment for innovation that aggregates cutting-edge paradigms and technologies, as it is illustrated in figure 1.1.6.

Besides this, novel business models have to be considered, such as robot-service systems and robot servitization (Fig. 1.1.7). In this business paradigm, robots and robotic cells will remain in the property of robot producers, they being entirely responsible for installation, maintenance, service, withdrawal and reconsideration for future use in the context of circular economy (disassembly, reconditioning, reuse, and recycling).

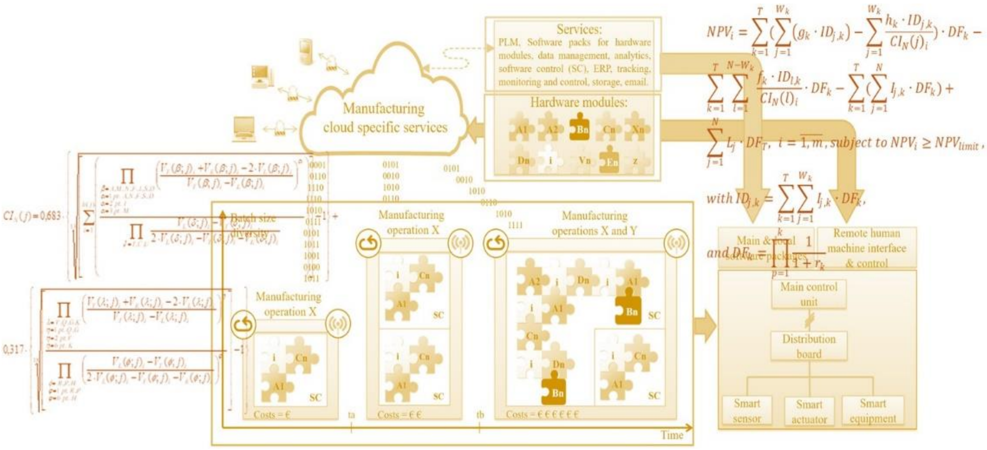


Figure 1.1.7. Servitization of smart industrial robots

Evolution of industrial robotics and automation is not a per-se issue, but it mainly should be seen in the context of economic evolution. Many of us agree that robotics and automation will have a tremendous impact in industrial production (and not only) in the years to come. Industrial robots, as we know them in terms of technological development at the beginning of the 21st century, are representing the 3rd generation of robotic systems (which evolved through incremental innovations since 1980s), following the pre-robots from the beginning of the 20th century (pneumatically or hydraulically driven), manipulators, tele-manipulators and NC manipulators from 1950s and 1960s (the 1st generation of robots), and the sensorized controlled robots from 1970s (the 2nd generation of robots). The 3rd generation of industrial robots have own controllers, dedicated programming languages, partially integrated vision and touch sensing systems, and capacity to be reprogrammed.

The 4th generation of industrial robots started with niche developments in advanced computing and artificial intelligence since 2000s. This generation is about intelligent industrial robots, because they do not only handle models and data, but are capable for learning and reasoning. An important milestone in intelligent robotics is year 2007, when the first dedicated operating system was born: ROS. In 2017 we notice the second generation of ROS and hardware compatible with ROS (H-ROS). Through these developments, neural networks and other models of artificial intelligence can be integrated within the robotic systems, making them capable to interact in a smart way with the external environment, to operate with “diffuse knowledge”, to learn from their own experience without human intervention and to continuously improve their performances. Vision systems and force control systems are deep embedded within intelligent robot’s architecture (Fig. 1.1.8).

Fig. 1.1.8. Example of force and vision systems embedded in the robot arms
(courtesy ABB)

The latest developments mentioned above indicate the dawn of the 5th generation of industrial robots, called "cobots" or "collaborative robots". These robots are capable to work in an interactive mode with human operators in safe conditions. Force and torque sensors are embedded in the robot arms to master collisions. However, not only the robot must be collaborative, but also the end-effectors and the whole robotic cell, including the objects that are handled. Therefore, extended vision and other sensing capabilities (e.g. to handle human gestures, human voice) must be considered within the robotic cell to really implement the concept of "collaborativeness". Moreover, intelligence of robots must be enhanced to make them capable to predict collisions by predicting trajectories of mobile objects that enter in the robotic cell in an ambiguous way. Reconfigurability will be an important characteristic of cobots, too. Reconfigurability is about modularity, integrability, scalability, convertibility and interoperability.

To develop the 5th generation of industrial robots, robot producers will also have to ensure interfaces with open standards and open platforms at the level of robot control and robot programming systems. To date, industrial robot manufacturers lock users into their proprietary programming systems and controllers. Portability of robot programs from one technology to others is an additional issue for future developments in robotics. Other issues related to standardization are the communication protocols, which differ from robot technology to robot technology, as well as the fact that logical and electrical interfaces are not standardized across robotic industry. This situation also affects developers of robot peripherals (e.g. smart grippers, welding guns, etc.), making them to spend a lot of time to develop interfaces that fit with every robotic technology. Leaders in this industry such as Kuka, ABB, Fanuc, Comau and Yaskawa Motoman will have to work together for setting up a common platform for electrical systems and communication protocols. Cooperation can enhance benefits for all, because optimum in business is beyond the so-called "Nash equilibrium". If this will not happen, the place will be taken by disruptive innovations, such as the results reported by Universal Robots and Rethink Robotics (see examples in Fig. 1.1.9).

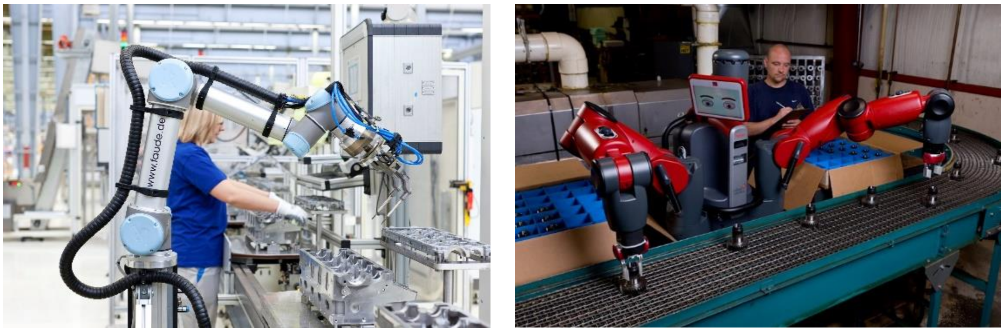


Fig. 1.1.9. Open platform robotic architectures for cobots
(courtesy Universal Robots (left) and Rethink Robotics (right))

Nevertheless, big robot producers such as Kuka, ABB and Fanuc make steps forward to launch industrial robots with open interfaces for ROS and with control systems that allow collaborative tasks between operators and robots (see Fig. 1.1.10).

Fig. 1.1.10. Collaborative robots (courtesy Kuka (left), ABB (middle), Fanuc (right))

Other suggestive example is the work of Yaskawa Motoman in a joint venture with Universal Logic to develop a plug-and-play intelligent robotic cell that uses intelligent 3D vision system and interactive motion control to handle unsorted parts at a speed and accuracy that exceeds human capabilities (Figure 1.1.11).

From economic point of view, prices of industrial robots constantly decreased over the last 30 years and the cost in production of a robot reaches nowadays about 5.5 $/hour (see Fig. 1.1.12). From 1990s, universities worldwide implemented study programs on robotics; thus availability of skilled engineers to design, implement, operate and maintain robots in industry is significantly improving. Robotic engineering is a job with wonderful perspectives on medium and long term. Software systems to model, simulate, program off-line and virtual commission of robotic cells and industrial automatic solutions significantly reduce risk and time to design new robotic cells, lowering the cost of new investments in these technologies.

Figure 1.1.11. Plug-and-play intelligent adaptive robotic cell
(courtesy Yaskawa Motoman and Universal Logic)

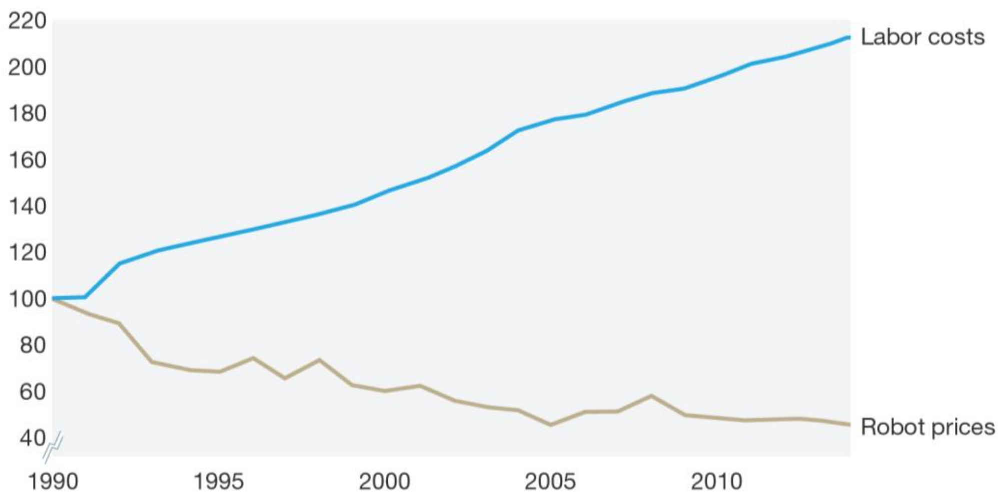


Fig. 1.1.12. Robot price versus labour cost along time (courtesy McKinsey)

Automation, alongside with robotics, will have to ensure a significant increase of agility for production systems. This refers to the capacity of production systems to adapt fast to new production volumes and new types of products, at affordable costs. This characteristic leads to quick and well-coordinated movements to ensure adaptability and versatility. An agile manufacturing process allows businesses to respond with high flexibility to customer needs as market conditions change, and to control their desired outputs while maintaining product quality and minimizing costs. In order to increase flexibility and intelligence of automation systems from manufacturing industry, expert software systems will have to master the work of all equipment from the production process in order to adjust the speed of the whole production line and to make adjustments in different points of the line to improve the overall balance of individual lines, or to maximize the whole productivity of the manufacturing system.

In this production landscape, industrial robots will need additional capabilities to those that are today important (e.g. to work at high-speed and required accuracy) such as to make adjustments on the fly, to switch between tasks without stopping the line in order to change programs and reconfigure tooling. All components of the manufacturing line will have to be connected in cloud and to exchange information. Information have to be exchanged with the manufacturing lines of all suppliers to ensure just-in-time delivery of customized orders. As robots, the manufacturing equipment will have to embed the same characteristics of changing from one operation to another one without stopping the line to change programs and tools.

Future automation will reconsider the transfer lines, too. Instead of fixed conveyors, intelligent automated guided vehicles (AGVs) will ensure fast reconfiguration of production flows; thus, parts can transfer from one workstation to another one in a highly flexible way. This mode of automation creates premises for reducing the lead time, for making tighter the link between demand and supply, for accelerating introduction of new products, as well as for implementing mass customization concepts (i.e. customized products at costs of mass production).

To implement an agile intelligent manufacturing system, intelligence must go beyond the intelligence of the equipment. Production, as a whole, must become intelligent; thus, expert software systems have to master the entire value chain of production. This is a very complex project, which definitely requires an integrated approach, as the one highlighted in Fig. 1.1.12. An example of versatile manufacturing system to assemble luxury cars is presented in Fig. 1.1.13.

Figure 1.1.13. Ultra-versatile assembly factory (courtesy Valmet Automotive)

Industrial automation requires proper decisions on multiple levels such as: which activities to automate, what level of automation to use, and which technologies to put in place. Problem has to be seen from a life-cycle perspective, and from financial point of view, too. Financial perspective is not only about initial investments, but also about return on investment and net present value. Multi-objective optimization is necessary from the early phase of manufacturing system design. This includes specialization, customization, flexibility, low cost, high manufacturing quality, low inventory, and short lead time.

In front of such complexity, technical feasibility is a necessary precondition for automation. Besides this important predictor, another important factor is the initial investment for developing and deploying the hardware and the software for the industrial automation system. The third factor is the cost of operators and engineers necessary to keep the automation system functional. To these factors one could consider externalities, such as labour substitution, higher quantities of output, better traceability of process, reduced variability and higher manufacturing quality, etc.

1.2 Conclusions

Looking ahead, on short term, the model of “productivity-driven automation” will continue, in which beneficiaries buy and implement robotic units and related automation in order to increase operational productivity and reduce production costs. In parallel, the model of “service-driven automation” will be growing, meaning “pay-per-use” business model. Thus, robots and robotic cells will be the property of integrators and they will sell solutions to end-beneficiaries to meet some productivity, cost and quality requirements. End-beneficiaries will pay a monthly fee proportional with the time the system is used. In this model, robots and automation systems will need higher connectivity capabilities, including remote monitoring and control because integrators will be responsible for maintenance and other related servicing and upgrading operations during the life-time of the system. In this model, Industrial Internet of Things (I-IoT) will play an important role.

On long term, industrial automation will adopt new models and will require new technological capabilities. Within possible models, two will be further commented. One is called “outcome-driven automation”, where robots and other automation solutions will be implemented in a “pay-per-outcome” model. In this model, beside Industrial Internet of Things (I-IoT), cloud computing and predictive analysis, together with blockchain solutions will play a key role. Robots will have superior communication abilities, both to communicate one another in the local network and with remote expert software systems, via cloud systems. This will allow both web-based remote monitoring and command, optimization based on big data analysis and artificial intelligence (e.g. deep learning of machines, neural networks, ontologies, etc.). Data collected from production will be of huge relevance to make production more agile and leaner, by transforming data into knowledge. The second model, strongly dependent by technological development will be the "fully autonomous manufacturing", in an "end-to-end automation" model. At this stage of development, which is the pick of technical system evolution, industrial robots and other manufacturing equipment will be deep connected to the overall business information system (BIS) of the company and will have continuous "demand-sensing functionalities". Optimization will thus run in real-time, by connecting all resources from production with the other resources from the value chain.

1.3 Recommended readings

[1] euRobo (cs aisbl 2013 & 2014 - Strategic Research Agenda for Robotics in Europe 2014-2020 (link: https://www.eu-robotics.net/cms/upload/ topic_groups/SRA2020_SPARC.pdf)

[2] Robotics & automation: Future trends with Blockchain (link: https://manucore.com/ robotics-automation-future-trends/)

[3] These four big trends are driving the robotics industry (link: http://www.zdnet.com /article/these-4-big-trends-are-driving-the-robotics-industry/)

[4] 2018 Trends in Robotics (link: http://www.tharsus.co.uk/2018-trends-in-robotics/)

[5] A Strategist's Guide to Industry 4.0 (link: https://www.strategy-business.com/article/A-Strategists-Guide-to-Industry-4.0?gko=7c4cf)

[6] Industry 4.0: the fourth industrial revolution – guide to Industry 4.0 (link: https://www.i-scoop.eu/industry-4-0/)

Chapter 2: Analysing the mechatronic product and planning its assembly performance. Equipment and devices selection or design

Mircea FULEA

Abstract

Automating an assembly process should be straightforward. However, it's not only the technical solution we should focus on – other factors like productivity, costs, maintenance or upgrades should also be considered.

2.1 Formulating the problem

To put it simple, the problem statement is "design a robotic assembly system for a given product". For instance, assemble an electric extender. Solving the problem should be straightforward: we analyse the product, its parts, the assembly system, and sketch the robotised process accordingly. We then model the robotised cell, we develop the control algorithm, and this should be it. Problem (apparently) solved.

Real life adds obviously more to it: for instance, what about costs? Return on investment? Productivity? Should we assembly 10 extenders per minute? Should there be 100 units produced per minute? Should the process be flexible, e.g. assembling extenders of different colours or with different "options" like USB plugs or on/off knobs? Should the robotised cell be compact? How many square meters should it fit in? Should it be assembled in one day, as our clients may be overseas? Should maintenance be done remotely, to reduce future operating costs? Should we guarantee a precise reliability level? For instance, no more than 30 minutes as a downtime per year?

How do we reconsider the problem, given all the questions above? Firstly, we should understand all the needs and requirements of all the stakeholders: the robotic cell user (the operator), the maintenance engineers, the safety engineers, and the management team. We should analyse these requirements and understand which are the most important, so that we can design our solution to specifically meet these requirements.

Secondly, we should explore general technical solutions for solving the problem. Simple sketches of cells having various layouts, using two or more robots, various part supplying methods, etc. Usually three such sketches, reflecting different concepts, should be developed. We should then see which of them best responds to the requirements identified in the above step – this concept (sketch) should be further developed.

Before detailing the sketch, we should decide how to measure its technical performance. This should be done by developing a list of metrics – quality (or performance) characteristics – to measure the robotised cell performance. Examples of such metrics could be the cycle time, the energy consumption, the footprint, etc. We should then plan these performance characteristics with respect to the requirements – i.e. set a target value for each characteristic so that the future cell will be *competitive* (have success on the market). For instance, 12 seconds for assembly cycle time (the time to assemble an extender), or 20 square meters for the cell footprint.

Next, we should determine what functions should our cell perform in order to assemble the electric extender *in such a way that target values for performance characteristics are met*. For instance, targeting 12 seconds for productivity may require two assembly spots (i.e. 2 robots), while a value of 30 seconds (if this would have been acceptable) might have required just one assembly spot (with one robot). We should therefore consider a function (or more) to get the assembled products from *both* the assembly spots and move them to the packaging spot. Some functions may have a software implementation, for instance a function warning the operator that some parts are running out.

Once it's clear what functions should be implemented, we can actually design our robotic cell. We should consider not only the actual hardware (robots, conveyors, etc.), but also the control algorithm and the software interface (for operating the cell or performing maintenance). When finished, we should check (and justify) that the target values for performance characteristics are likely to be met.

2.2 Structuring requirements

Before starting the robotised cell design process, the analysis team has to make several judgements and to take specific decisions regarding the key requirements related to the given application. Who's interested in the system we're developing (i.e. which are our stakeholders)? Note that it's not just the users of the future system (operators or maintenance engineers), but all those at the *business* or *enterprise* operations level: users, integrators, customers, and any other (type of) persons or organizations that relate to the problem. Each of these stakeholders may have his or her own requirements, which should be captured by the analysis team.

Some requirements or needs may be directly expressed, while others might not. A stakeholder may not formalise (or even understand) his complete needs – for instance, the customer may not consider *quick installation* as a requirement, but – at some time – he might move to a new facility and want to quickly reinstall all his systems. The analysis team should, however, "guess" this requirement and document it accordingly.

To extract requirements (and – later – define performance characteristics), the analysis team can also check against specific design guidelines to be found under the label *Design for X* (*Design for Excellence*) [1], [2]. Each design guideline addresses a given issue that is caused by, or affects the traits of, a product. These design guidelines cover all the product's life cycle phases (development phase, production phase, use phase, and disposal phase). Examples of such design guidelines: design for *short time to market*, design for *reliability*, design for *test*, design for *safety*, design for *quality*, design *against damage*, design for *minimum risk*, design to *cost*, design to *standards*, design for *assembly*, design for *manufacturability*, design for *logistics*, design for *low-quantity production*, design for *user-friendliness*, design for *aesthetics*, design for *serviceability*, design for *maintainability*, design for *recycling*.

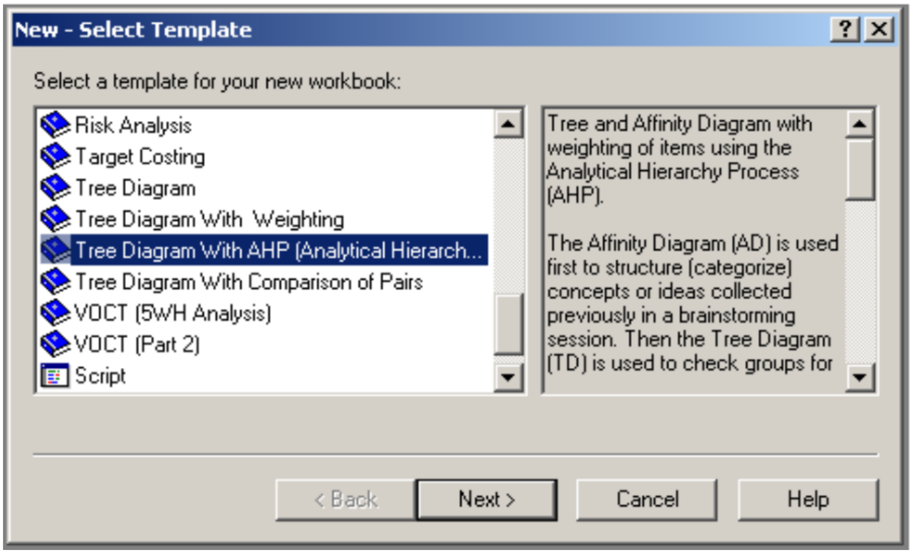


Fig. 2.2.1. Qualica QFD: Template selection

Once requirements are identified, the next important step is to rank them, to determine their importance level so that the design process can be oriented towards producing a robotised cell to fulfil these requirements. A systematic method like AHP – Analytic Hierarchy Process – should be used for requirement ranking.

Within this document, the AHP is exemplified by using the Qualica QFD software tool. The screenshots are made with Qualica2005. The instructions are adapted to the same software tool. One can use any other software tool, as the steps to follow should be similar.

After starting Qualica, create a new project and choose the template “Tree Diagram with AHP” (Fig. 2.2.1).

At “Select location” choose “Create new database” and then specify where to save your work (folder and file name), under “Target directory”. In the next step choose a relevant name for your new workbook (for instance *requirements analysis*). In the left corner of the Qualica window you will find a tree representation of the project structure (including all its workbooks) (Fig. 2.2.2).

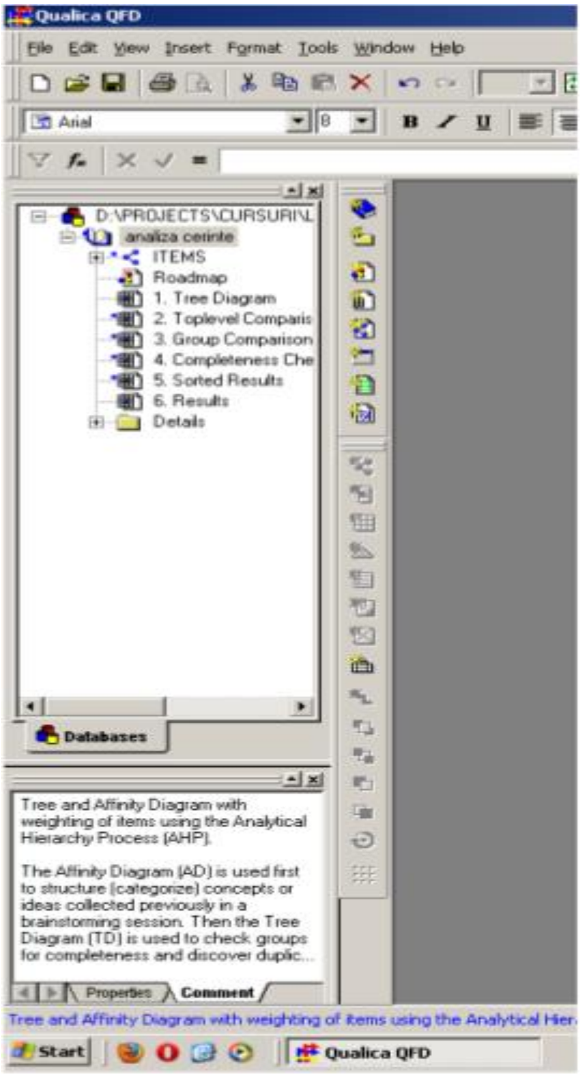


Fig. 2.2.2. Qualica QFD: The project tree

Double-click on “ITEMS” and enter here the list with the requirements for the robotized cell. Use the  buttons to add new requirements or to reorder the already introduced ones. Then click “Toplevel comparison matrix”. If the displayed matrix is “empty”, right-click in the “Input ...” area, choose “Replace tree” (Fig. 2.2.3), and select ITEMS.

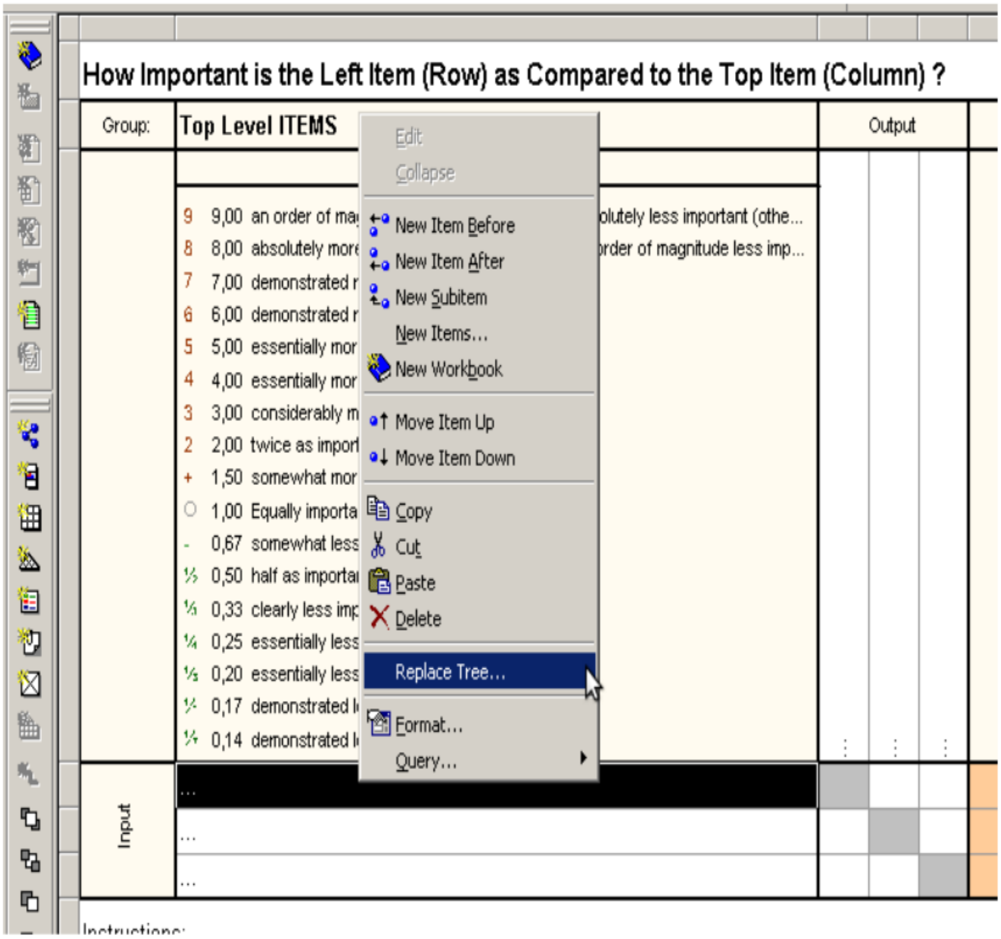


Fig. 2.2.3. Qualica QFD: How to set up the AHP analysis matrix

Complete the matrix by comparing each two requirements and determining a relative importance of that one on the row against that one on the column. To specify the relative importance, click in the corresponding cell and select a value above 1 if the requirement on the row is more important than the one on the column. Select a value below 1 otherwise (or exactly 1 if the requirements are equally important) (Fig. 2.2.4).

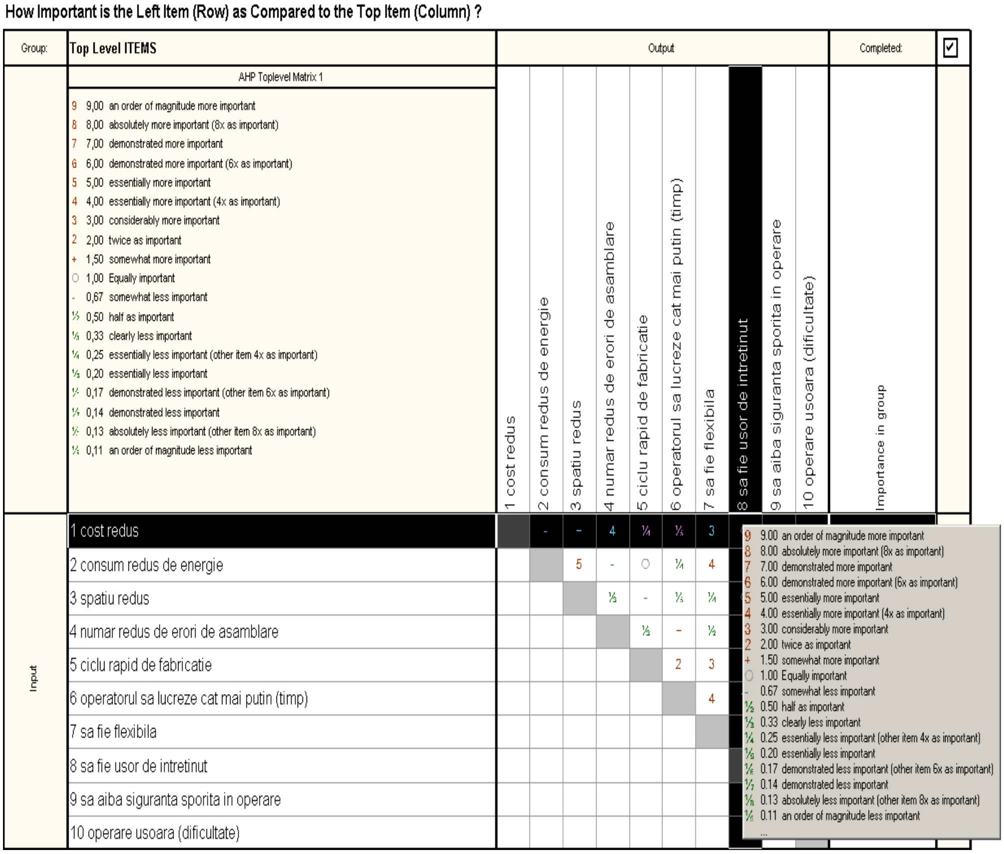


Fig. 2.2.4. Qualica QFD: How to complete the AHP analysis matrix

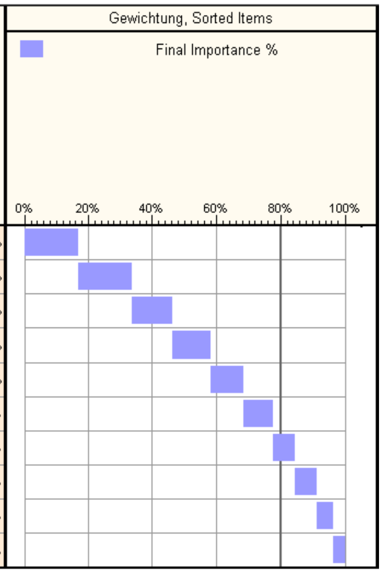
When finished, click on the *Recalculate now* button (Fig. 2.2.5).

Fig. 2.2.5. Qualica QFD: The toolbar containing the Recalculate Now button

The (relative) importance of each requirement is the numerical value (percent) in the column in the right part of the analysis matrix (*Importance in group*). You can visualise the sorted requirements by choosing Sorted Results from the project tree (the top left part of the Qualica window) (Fig. 2.2.6).

You can also compute a consistency index for your analysis. Details can be found here [3].

Sorted ITEMS 1 / Importances	Calculated Importance %	Final Importance %
10 operare usoara (dificultate)	17,3%	17,0%
5 ciclu rapid de fabricatie	16,8%	16,5%
9 sa aiba siguranta sporita in operare	12,6%	12,5%
6 operatorul sa lucreze cat mai putin (timp)	12,1%	12,0%
2 consum redus de energie	10,5%	10,5%
7 sa fie flexibila	9,2%	9,3%
4 numar redus de erori de asamblare	6,7%	6,8%
1 cost redus	6,6%	6,7%
8 sa fie usor de intretinut	5,1%	5,3%
3 spatiu redus	3,2%	3,4%
Most important item:	17,3%	
Least important item:	3,2%	



Most important item is	5,44	times as important as least important item
Make most important item	5,00	times as important as least important item

Fig. 2.2.6. Qualica QFD: The sorted results view

2.3 Exploring variants

Usually, at the beginning of the design process, several possible solutions may seem appealing. One can explore various layouts for the cell, do assembly with one or two robots, do a pre-sorting of parts before assembly or sort them afterwards, implement quality inspection in several ways, etc. A good practice is to sketch three possible technical solutions (variants) for the problem we're considering (i.e. designing a robotised cell to assembly, pack and palletize a product) so that the requirements above are fulfilled as good as possible. Variants should not be too detailed in this step, but rather serve as a base to be further developed. Advantages and disadvantages should be provided for each variant.

The variants will then be checked against the requirements. The one that best fulfils them will be further considered in the design process, i.e. the solution will be built upon the variant that best fulfils the requirements.

A way to assess (rank) the variants is the Pugh method, also implemented in the Qualica QFD software. Select some items in the workbook tree (the upper left part of the Qualica window) and choose New – Pugh New Concept Selection. For *New Concepts* choose *Leave Unchanged*, while for Criteria choose *Link to existing tree* and select ITEMS (i.e. the requirements you have just ranked with the AHP method) (Fig. 2.3.1, a). Specify a name for the new workbook, for instance "variant selection". The new workbook will be displayed in the workbook tree (Fig. 2.3.1, b).

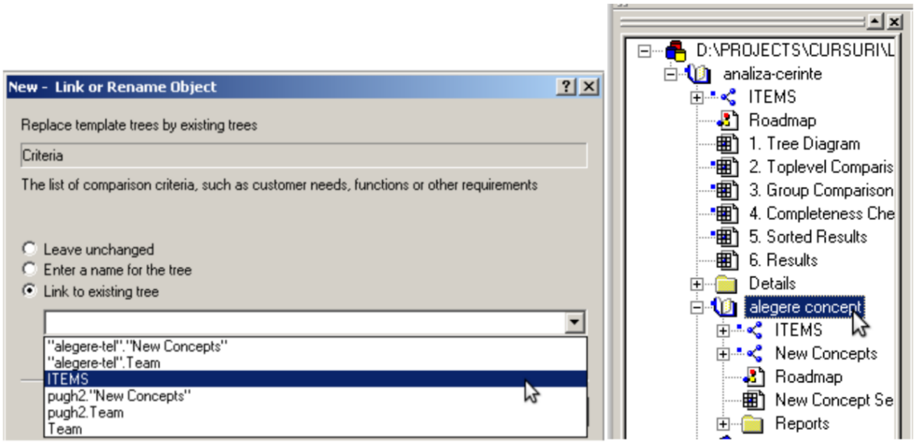
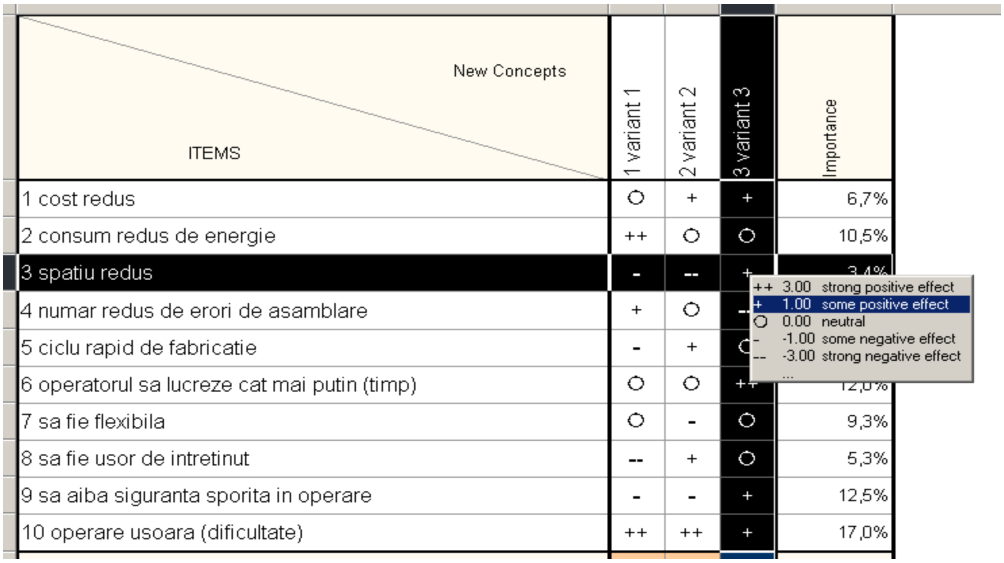


Fig. 2.3.1. Qualica QFD: (a) Linking the ITEMS tree; (b) the updated project tree

To enter the three variants, choose New Concepts in the workbook tree. Type the solutions in the corresponding table. Select then New Concept Selection and complete each matrix cell by identifying the relation between the selected variant and the selected requirement (i.e. how much does the selected variant fulfil the selected requirement) (Fig. 2.3.2).



ITEMS \ New Concepts	1 variant 1	2 variant 2	3 variant 3	Importance
1 cost redus	O	+	+	6,7%
2 consum redus de energie	++	O	O	10,5%
3 spatiu redus	-	--	+	3,4%
4 numar redus de erori de asamblare	+	O	-	[illegible]
5 ciclu rapid de fabricatie	-	+	O	[illegible]
6 operatorul sa lucreze cat mai putin (timp)	O	O	++	12,0%
7 sa fie flexibila	O	-	O	9,3%
8 sa fie usor de intretinut	--	+	O	5,3%
9 sa aiba siguranta sporita in operare	-	-	+	12,5%
10 operare usoara (dificultate)	++	++	+	17,0%

Fig. 2.3.2. Qualica QFD: completing the Pugh method matrix

When finished, click the *Recalculate Now* button. You will get, in the bottom lines of the matrix, the scores for each variant. The scores reflect how well each variant responds to the requirement set (Fig. 2.3.3).

If two variants get similar scores (i.e. a difference up to 5%), you are advised to define more criteria to differentiate them.

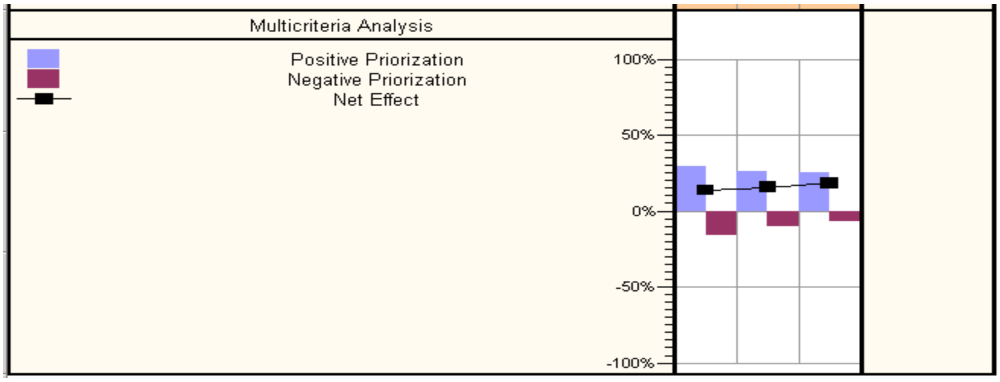


Fig. 2.3.3. Qualica QFD: the results of the Pugh analysis.

2.4 Planning technical performance

The needs or requirements discussed above represent the so-called Voice of the Customer. They're expressed using plain language and are quite vague for an engineer. They should be translated into something that engineers can understand and further transform in an effective design. One of the established methods to do this is the Quality Function Deployment – QFD. It transforms the needs (requirements) into technical characteristics – the so-called Voice of the Engineer. In other words, it helps create operational definitions of the requirements, which may be vague when first expressed. The QFD method prioritizes each product or service characteristic while simultaneously setting development targets for the product or service. It translates often subjective quality criteria into objective ones that can be quantified and measured and which can then be used to design and manufacture the product. For example, a requirement for a pen would be *ease of writing*. This is unclear for an engineer – *pen ink viscosity* or *pressure on ball-point* would be much more interesting to him, as these *characteristics* can be measured.

Typically, the QFD consists of four phases (Fig. 2.4.1). These phases are: product planning, product design, process planning and process control.

This material will focus on the first QFD phase, or product planning – the so-called House of Quality (Fig. 2.4.2). Many organizations only get through this phase of a QFD process, although effective quality planning requires all the four phases.

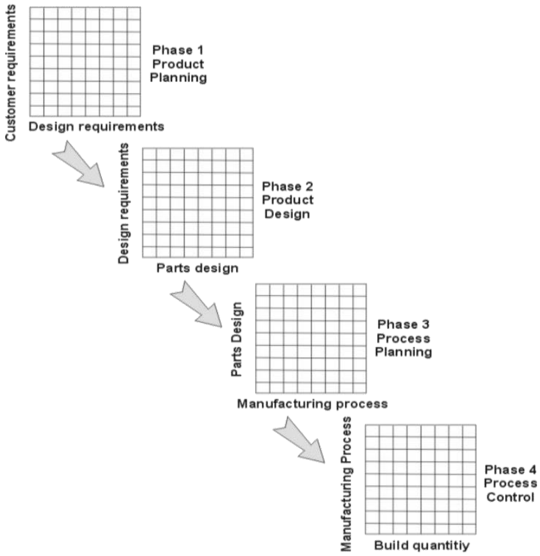


Fig. 2.4.1. The four QFD phases

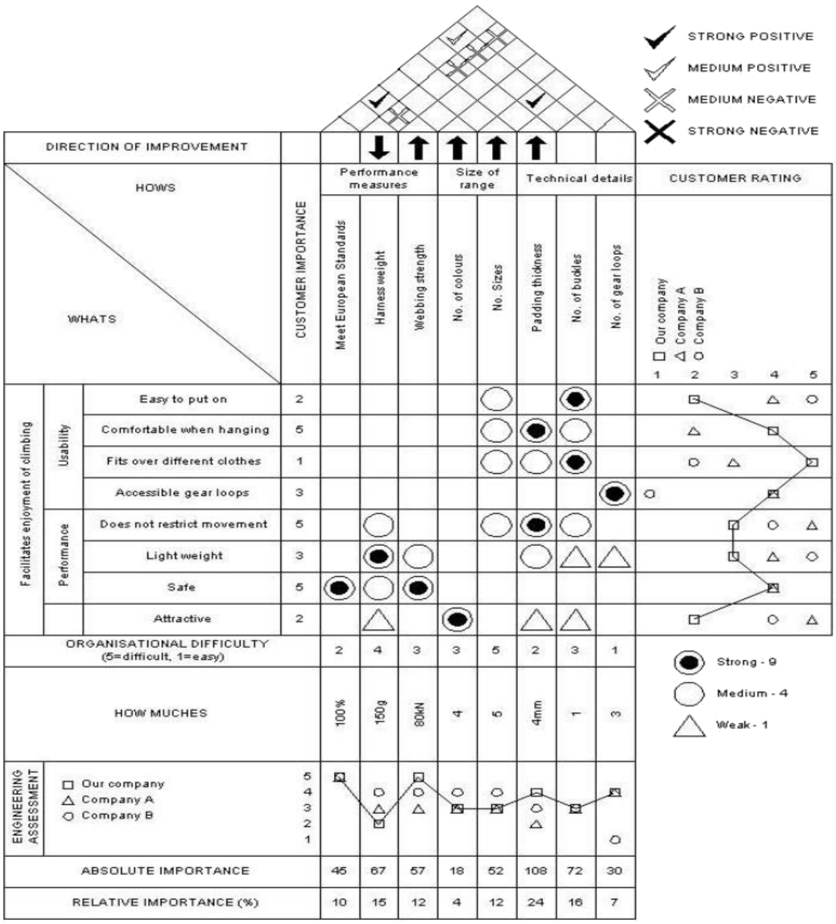


Fig. 2.4.2. The House of Quality.

This material discusses how to build the House of Quality (i.e. the first phase of QFD). The next three phases are similar in terms of graphical support, excepting the House of Quality Roof and – of course – the data on rows and on columns.

Completing the House of Quality typically implies twelve steps:

- *Step 1: Customer Requirements - "Voice of the Customer"*
- *Step 2: Regulatory Requirements*
- *Step 3: Customer Importance Ratings*
- *Step 4: Customer Rating of the Competition*
- Step 5: **Technical Descriptors - "Voice of the Engineer"**
- Step 6: **Direction of Improvement**
- Step 7: **Relationship Matrix**
- Step 8: Organizational Difficulty
- Step 9: Technical Analysis of Competitor Products
- Step 10: **Target Values for Technical Descriptors**
- Step 11: **Correlation Matrix**
- Step 12: Absolute Importance

Steps 1-3 are typically done by applying the AHP method described above. If information regarding competitors is available, we can also rate how well the competition responds to the requirements we have identified (Step 4). The results should be similar to the example in figure 2.4.3.

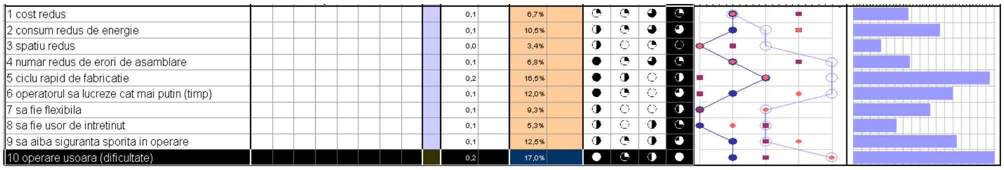


Fig. 2.4.3. Qualica QFD: Customer requirements data.

Step 5 consists of identifying the technical descriptors, i.e. the *Voice of the Engineer*. The technical descriptors/performance characteristics are attributes about the product or service that can be measured and benchmarked against the competition. Your organization may already use specific metrics to determine product specification, however new ones can be added to ensure that your product is (or will be) meeting the customer's needs. Step 6 implies identification of the improvement direction for each metric – what means improving its value?

Step 7 requires the completion of the relationship matrix. The analysts team determines the relationship between customer needs and the company's ability to meet those needs (via the metrics or technical descriptors). Each matrix cell should reflect the answer to this question: W*hat is the strength of the relationship between the technical descriptors and the customers' needs?* Relationships can either be none, weak, moderate, or strong and carry, for example, a numeric value of 1, 3 or 9.

Different scales may be used as well. Not all requirements are related to a metric and not all metrics are related to a requirement (several “none” values will exist in the relationship matrix). In other words, the relationship matrix will not be “fully completed”. An example is shown in figure 2.4.4.

Optimization	↓	↑	↓	↓	↓	↓	↓	↓					
CTQs / ITEMS	1 consum energetic	2 numar produse diferite ce pot f	3 timp de reconfigurare pentru n	4 numar de rebuturi pe schimb	5 cycle time (palet)	6 footprint	7 fiabilitate (downtime / 1000h)	8 timp planned maintenance (trin	Number of significant relationships	Importance to Customer	Unique Selling Point	Relative Importance	Improvement Factor
1 cost redus	⊙	△	△	△	△	△	○	⊙	3	0,1		6,7%	
2 consum redus de energie	⊙				○		△		2	0,1		10,5%	
3 spatiu redus						⊙			1	0,0		3,4%	
4 numar redus de erori de asamblare	○	△		⊙	○		⊙		4	0,1		6,8%	
5 ciclu rapid de fabricatie	○				⊙	△			2	0,2		16,5%	
6 operatorul sa lucreze cat mai putin (timp)	○	⊙	⊙	○	⊙		△		5	0,1		12,0%	
7 sa fie flexibila		⊙	⊙			△			2	0,1		9,3%	
8 sa fie usor de intretinut			△			○		⊙	2	0,1		5,3%	
9 sa aiba siguranta sporita in operare						△	○		1	0,1		12,5%	
10 operare usoara (dificultate)			○						1	0,2		17,0%	
Number of significant relationships	5	2	3	2	4	2	3	2					
Importance	17,6	13,8	17,2	7,0	21,3	6,2	9,6	7,3					

Fig. 2.4.4. Qualica QFD: The relationship matrix

Step 8 requires technical descriptors ranking from an organizational (not technical) difficulty perspective.

Step 9 consists of a technical analysis of competitor products (if adequate information is available), to better understand the competition. The process involves reverse engineering competitor products to determine specific values for each technical descriptor identified in step 5 above.

Step 10 implies setting target values for the technical descriptors. The target values represent "how much" for the technical descriptors, and – from this stage on – the product (service, process) design should be done *to obtain these target values*.

Step 11 requires the completion of the correlation matrix (the roof of the House of Quality). The analysis team members must examine how each of the technical descriptors impact each other. The team should document strong negative relationships between technical descriptors and should work to eliminate physical contradictions. Innovative problem-solving tools like the TRIZ Contradiction Matrix can be used in this step.

Step 12 implies the determination of the absolute importance of the technical descriptors (automatically done by software tools that implement the House of Quality). The most important descriptors matter the most to your customer.

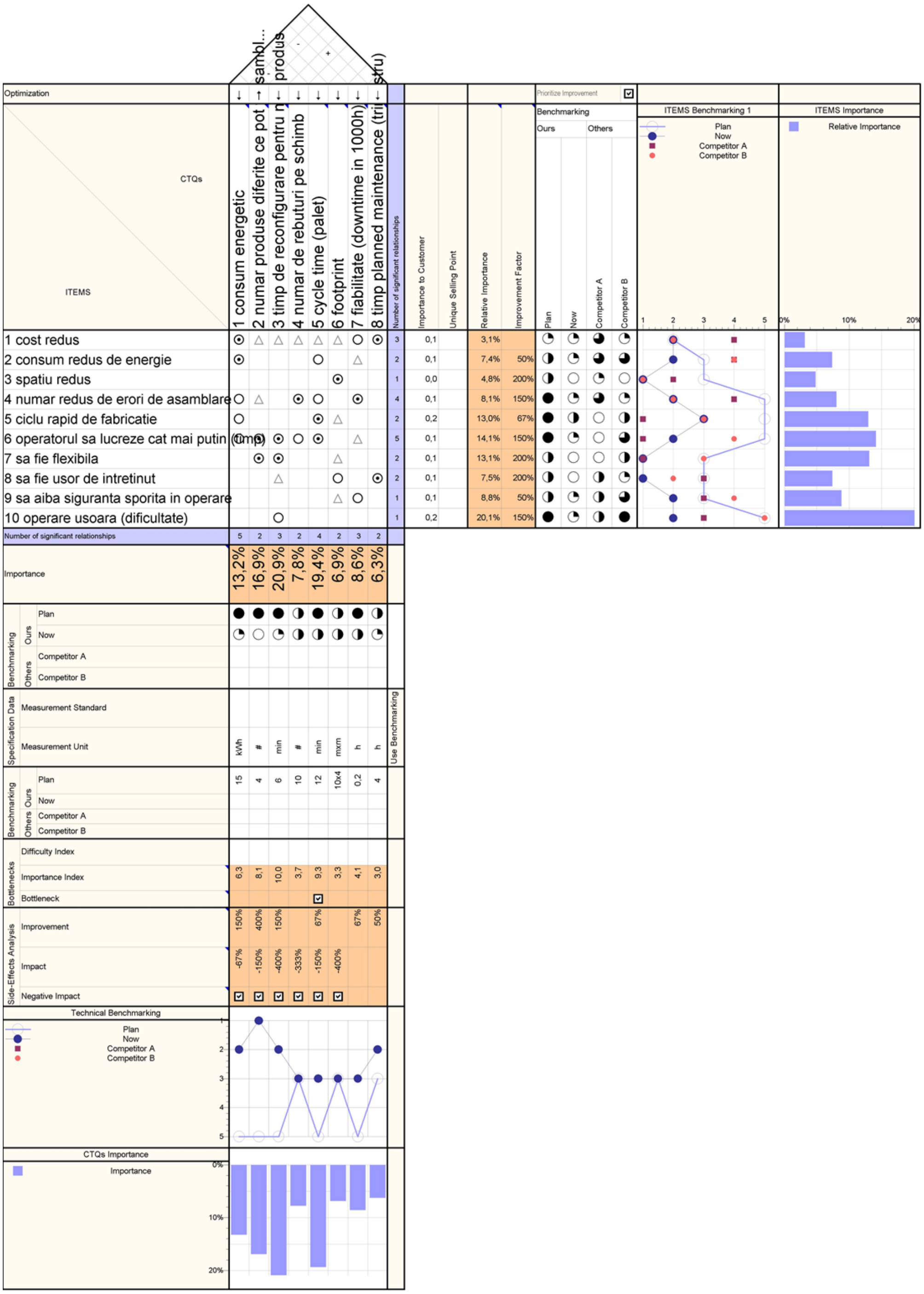


Fig. 2.4.5. Qualica QFD: An (almost) completed House of Quality

As a final note, before declaring the House of Quality complete, have a short check if, in the relationship matrix, there is at least one strong relation on each row and each column. If there is no strong relation on a column, the technical characteristic on that column may not be relevant (it's not related to any requirement), so either remove it or check if the requirement list is complete. If there is no strong relation on a row, you probably should extend the technical characteristic set, as the requirement on that row will probably not be fulfilled through the current quality level. You can see in figure 2.4.5 an example of a complete House of Quality.

2.5 Planning functions and hardware components

Up to now, we know *what* is needed/requested from the assembly system we're designing. We also know what *quality level* our assembly system should have. But before starting to actually design it, it is a good practice to identify all the required functions of the assembly system: what should it actually do? We already have a concept: the variant from section 2.3 that best responded to the requirements. We should now decide upon all the functions that should be built in our assembly system. We should consider both core and auxiliary functions. Some may be implemented purely hardware, but some will also have a software component (or be even completely software implemented).

To exemplify, some functions of the palletizing zone of the assembly system could be:

- to allow supplying the process with pallets (to be done at any time needed – pallets should be placed over the existing pallet stack, e.g. with a forklift)
- to extract one pallet from the pallet stack on the conveyor towards the loading point
- to move (and precisely position) the extracted pallet to the loading point
- to move the (loaded) pallet from the loading point onto the conveyor which takes it to the wrapper
- to wrap the loaded pallet
- to move the wrapped pallet outside the cell

Examples of functions to be implemented software:

- allow operator login and logout
- display cell status screen (number of extenders assembled, number of loaded boxes, of loaded pallets, number of parts, etc.)
- display warnings (when the process should be supplied with specific parts)
- display process status (running, idle, stopped)
- display issues and errors (if any)
- adjust settings (e.g. pressing force)
- display maintenance information (e.g. warnings, reminders)

Hardware components (and software modules and interfaces) should then be selected and integrated in the assembly cell. We should then check if all functions can be adequately performed with the hardware components we have selected. We can use the graphical support of the QFD method for this – by placing functions on the lines (the inputs) and hardware modules on the columns (the outputs). When building the relationship matrix, we should have at least one strong relation on each row and each column.

2.6 Conclusions

The roadmap discussed above should support a design team to focus not only on the technical solution, when designing the assembly cell, but also on other factors like productivity, costs, maintenance or upgrades that should also be considered. The proposed roadmap is based on well-known quality planning methods (QFD), translating the stakeholder needs into quality characteristics, quality-related target values, functionalities and eventually the technical concept of the assembly cell. As a final step, the roadmap also requires checking (and justifying) that the target values for performance characteristics are likely to be met. The students are thus encouraged to design systems to specifically meet a required performance level.

2.7 Recommended readings

1. Brad, S., Brad, E., Mocan, B., Fulea, M., *Tools and Methods of Competitive Design in Robotics*, Editura UT Press, ISBN 978-606-737-067-6, 183 pg., Cluj-Napoca, 2015.

2. Brad, S., Ciupan, C., Pop, L., Mocan, B., Fulea, M., *Manualul de Bază al Managerului de Produs în Ingineria și Managementul Inovației*, Ed. Economică, 700 pg., ISBN 973-709-265-1 / 978-973-709-265-6, București, 2006.

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[1] ***, Design for "x", (link: https://www.creativemechanisms.com/blog/design-for-x-dfx)

[2] Wikipedia, Design for X, (link: https://en.wikipedia.org/wiki/Design_for_X)

[3] Brad, S., Brad, E., Mocan, B., Fulea, M., *Tools and Methods of Competitive Design in Robotics*, Editura UT Press, ISBN 978-606-737-067-6, 183 pg., Cluj-Napoca, 2015.

Chapter 3: Facility layout problem regarding robotic manufacturing systems

Bogdan MOCAN

Abstract

This chapter deals with solving the facility layout problem (FLP) in general and with machine layout problem (MLP) especially within the modern manufacturing facilities, and addresses design issues of production layout. Modern manufacturing facilities in our approach means automation based robotic for manufacturing production system.

3.1 Introduction

New manufacturing technologies and philosophies such as group technology, flexible manufacturing systems, just-in-time and robots have emerged in recent years. Plant layout of an industrial production facility is such a systematic and efficient functional arrangement of various departments, machine tools, equipment and other supports services that it will facilitate the smooth processing of the proposed or undertaken product in the most effective, most efficient and most economical manner and in the minimum possible time.

Determining the physical organization of a production system is defined to be the facility layout problem (FLP). What equipment should be purchased, how facilities should be organised, and where the facilities should be located are fundamental strategy issues facing any manufacturing organization. Some research [1] estimated that 8 percent of the U.S. gross national product has been spent on new facilities annually, since 1955. This does not include the cost of modification of the existing facilities. If the estimation is correct, the annually expenditures are more than $500 billion on construction and modification of facilities [2]. According to [2] approximately 20% to 50% of costs can be attributed to facility planning and transportation in a manual and/or mechanized production system.

An important aspect of the enormous success of Japanese companies in achieving manufacturing dominance in several key industries is efficient production. Efficient production means efficient design of the product, employee involvement, lean inventory material management systems, and layout and organization of facilities.

For FLP, the most common objective used in mathematical models is to minimize the materials' handling cost, which is a quantitative factor. Reduced material movement

[3, 4] lowers work-in-process levels and throughput times, less product damage, simplified material control and scheduling, and less overall congestion. Hence, when minimizing material handling cost, other objectives are achieved simultaneously. Qualitative factors such as plant safety, flexibility of layout for future design changes, noise and aesthetics can also be considered [2]. Each layout problem is unique by its assumptions, constraints, limitations, and the intrinsic activity of the components. The output of the FLP is a block layout that specifies the relative location of each department and how they interact with their functional areas. Detailed layout of a department can also be obtained later by specifying aisle structure, and input/output point locations, which may include flow line and machine layout problems.

Effective automation production systems rely on good business process design, with multiple factors to consider, including systems' use, business impact, ROI of labour, and investment. In fact, automation can lead to cost reduction of 30% or more with a typical implementation time of three months, according to [15].

Robotic based automation for flexible manufacturing system has been widely implemented in modern factories. For an efficient utilization of the material handling system used to serve the machines, the layout of the FMS must take into consideration the performance characteristics of the material handling system. In developing the layout of FMS served by an industrial robot, the location of "target points" (*target point* - that point in the robot workspace where the TCP -tool center point - should reach) is determined by taking into consideration the reachability and mobility criteria of the robot. Using these considerations, machines are located within the feasible and achievable region of the robot. The optimal cell layout is obtained by minimizing the *cycle time* of the robot joints required to perform a sequence of travel. Minimizing the cycle time of the robot will enhance the production rate of the manufacturing system and increase the usage time.

3.2 Considerations regarding layout of automation based robotics systems design

The starting point of automation system design is a thorough detail understanding of the process to be automated. Implementation of a process robot requires a focus on manipulation as a process factor. The *pose* and *path* requirements of the process are independent of the used robot. It is useful to conduct a static spatial analysis of manipulation requirements and then examine the mechanical and dynamic requirements when designing or selecting a process robot manipulator. For this there are several software tools for offline robot programming and robotic process simulation (e.q. RobotStudio, RoboGuide, MotoSim, Kuka SimPro) that facilitate the spatial evaluation of the process's needs and enables the mechanical and dynamic assessment for different robot models [4].

A spatial description of the relative positions and orientations of the workpiece and tool during processing provides the basis for describing the required manipulation. *Tool poses* are graphed in an appropriate reference frame, usually the frame of the workpiece, or in case of machine loading, the work holding fixture may be used. *Path* requirements are secondary for these applications. The path taken does not affect the process. For continuous path processes entire paths must be graphed or mapped. If continuous analytical descriptions of the path are not available, a sampling of discrete points along the required path can be used to represent the space occupied by the path. The result in both cases is a Cartesian mapping of spatial requirements of pose and path. A description of the pose and path precision requirements should be included. Next the mechanical and dynamic requirements are defined. *Payload* and force reactions at each position and along the path must be understood. Other important dynamic requirements such as acceleration and power should be quantified. The manipulation requirements are the basis for design and selection of both the robot arm, the machine tools and the auxiliary equipment.

All the above presented aspects related to the needs of the process, which is to be automatized, can be accomplished using software tools for offline robot programming and robotic process simulation.

In terms of designing the production facility layout there are different methods used to solve the FLP within the manufacturing systems. These methods can be classified as the constructive, improvement, heuristic, exact, hybrid, discrete, quantitative, qualitative, and analytical methods [5]. The following methods and approaches [5] can be referred amongst the plethora of published papers: Genetic algorithm; Tabu search; Ant colony; Simulated annealing; Entropy-based algorithm; Computerized relative allocation of facilities technique (CRAFT).

Several factors and design issues clearly differentiate the nature of the FLP to be addressed, in particular: *the products variety/complexity and volume*; *the material handling system chosen*; *the facility shapes, dimensions and the pickup and drop-off locations; the different possible flows allowed for parts*; *the number of floors on which the machines should be assigned, the robotic operational characteristics, and cycle times – usually desired/imposed by client(s)/beneficiary*.

Products variety/complexity and volume

The layout design generally depends on the products' variety and the production volumes. A typical work cell consists of a robot or several robots and their peripherals made up of part presentation mechanisms, feeders, conveyor, and end-of-arm tooling. For a small number of part types, parts are presented to the robot by feeders or magazines. As these take up space, only a limited number of different parts can be fed to one robot. In mechanical assembly, normally, a maximum of five to six different parts can be presented in this way. To extend the robot(s)'s accessibility to a large number of parts, mechanized component feeding systems can be mounted on data-driven carousel conveyors spaced around the robot(s), each with a fixed dispensing point within reach of the robot(s)'s gripper. The carousel can accommodate up to several hundred positions onto which magazines, tapes, or other modular dispensing systems can be attached. With multiple programmable carousels, the robot(s) can access several thousand different parts.

End-of-Arm Tooling Exchange: many systems use different gripper exchange systems in order to cope with different parts. Tool exchanges are often considered as "nonproductive" since they do not contribute to assembly operations. The exchange is serially coupled to the assembly operations. This means that the cycle time increases due to the extra time needed for pickup and drop-off for tool changes as well as travel time between the assembly point and the end-of-arm tooling station. In order to reduce time loss due to the gripper, exchange should be minimized and/or in parallel with other activities, and the distance between pick-up point and assembly point should be very short. This problem could be avoided if a fast-revolving gripper head is used, provided that space, weight, and cost of the revolving head do not pose a problem. Alternatively, the pallet carries batch-specific equipment such as grippers, fixtures, and end-of-arm tooling and can be presented to the robot on a conveyer in a similar fashion as the parts.

Three different cell layouts have been examined in the literature: robot- centred cells (where the robot movement is rotational), in-line robotic cells (where the robot moves linearly), and mobile-robot cells (generalization of in-line robotic cells and robot - centred cells) [5]. An in-line robotic cell with m machines is shown in figure 3.2.1. It is generally known that robot - centred cells are preferred in practice because they reduce the required physical space. It is demonstrated that changing the robotic cell layout from an in-line (Fig. 3.2.1) to a robot-centred cell (Fig. 3.2.2) can improve the effectiveness of these systems.

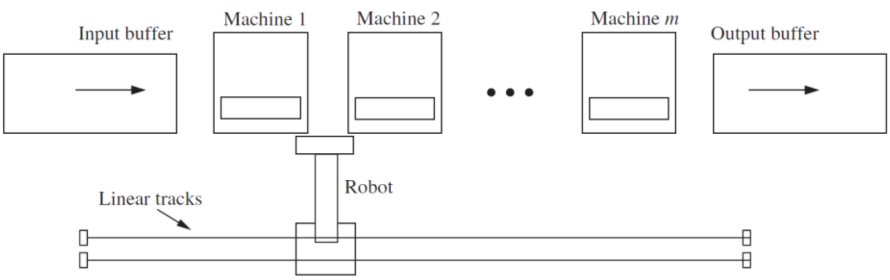


Fig. 3.2.1. In-line robotic cell layout [6]

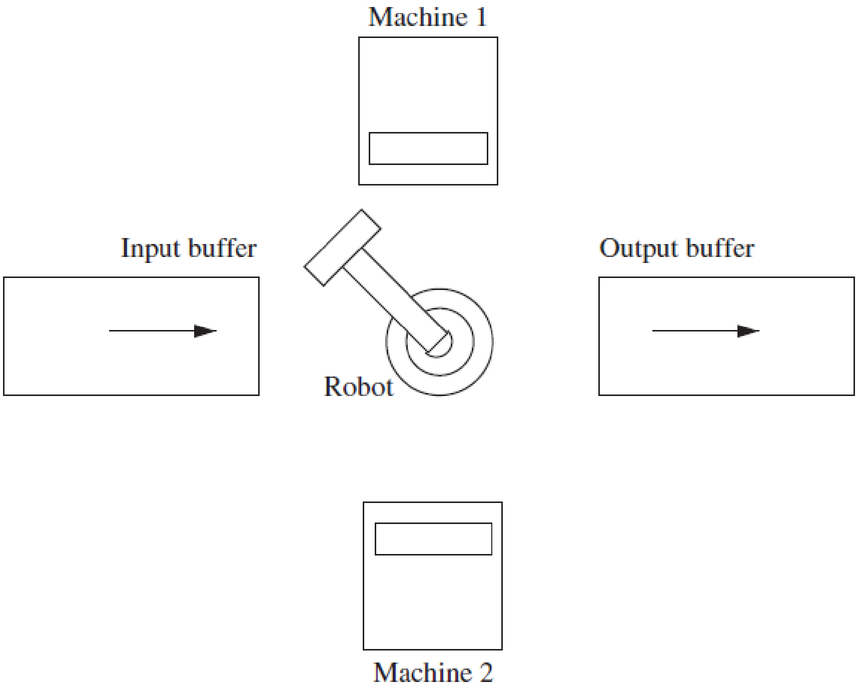


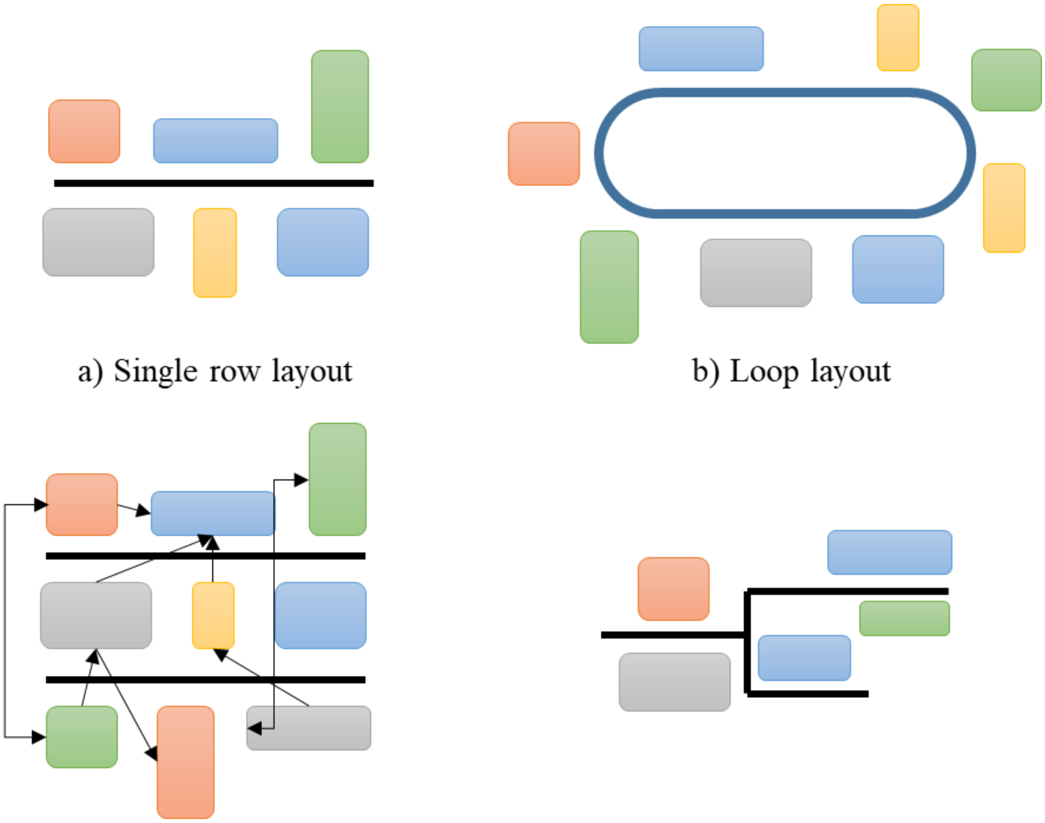
Fig. 3.2.2 Robot-centred cell layout [6]

Material handling systems

A material handling system ensures the delivery of material to the appropriate locations. Material handling equipment can be conveyors (belt, roller, and wheel), automated guided vehicles (AGV), robots, etc. [2]. Reference [13] reveals that **20÷50% of the manufacturing costs are due to the handling of parts**.

A good organization of handling devices might **reduce these costs up to 10÷30%** [13]. When dealing with a material handling system, the problem consists in arranging facilities along the material handling path. Two dependent design problems are considered: finding the facility layout and selecting the handling equipment. The type of material-handling device determines the pattern to be used for the layout of machines (Fig. 3.2.3).

Also, the concerned product or family product must be designed to facilitate the manipulation, assembly etc. Product design for automation based robotic cells includes the following criteria: task operations based on robotic cells for specific product families which must be able to manipulate and assemble the variants of these product families using programming, fast changeover from one product to another within a flexible assembly cell, and reuse of standard elements for new assembly tasks.

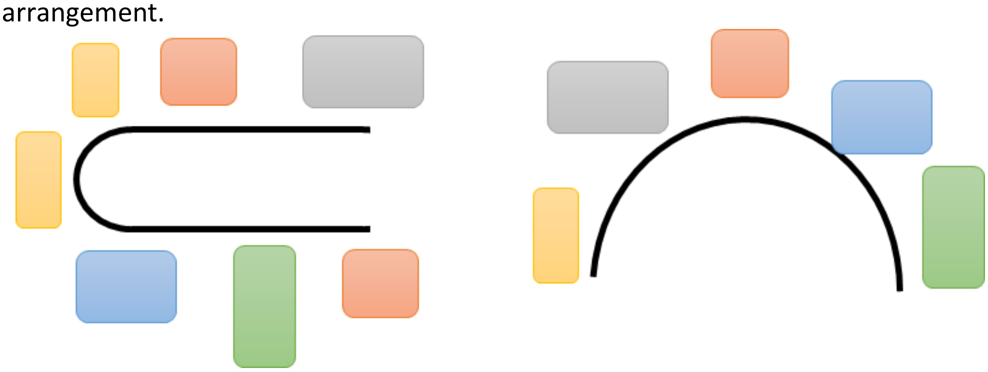


a) Single row layout b) Loop layout

c) Multi-rows layout d) Open-field layout

Fig. 3.2.3. Types of facility layout based on the criteria of material handling rout [5]

The single-row layout (Fig. 3.2.4) includes three shapes such as linear, U-shape and semi-circular. In the linear layout, there may exist bypassing and backtracking, as shown in figure 3.2.5. Backtracking is the movement of some arts from a machine to another machine that precedes it in the sequence of placed machines in a flow line arrangement.



a) U – shape b) semi-circular shape

Fig. 3.2.4. Detaliation of the liniar facility layout – single raw layout [5]

The number of these movements should be minimized. Bypassing occurs when a part skips some machines while it is moving towards the end of a flow line arrangement.

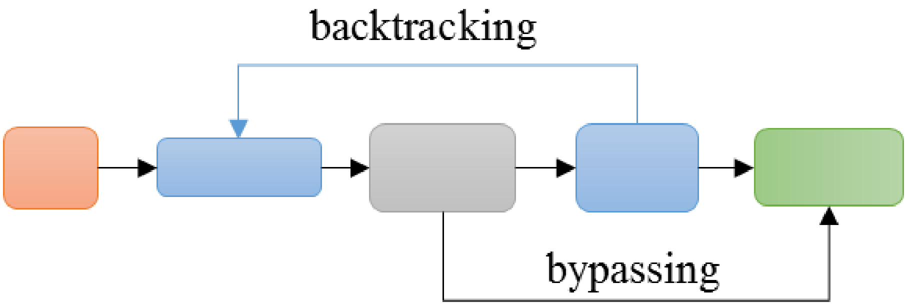


Fig. 3.2.5 Bypassing and backtracking [5]

Table 3.2.1. Advantages and disadvantages of different types of layout [5]

Type of layout	Application	Advantages	Disadvantages
Single row layout	Within robotic cells, in facilities that implement Just in Time method, and sometimes with Flexible Manufacturing Systems	Material flow are moving along the sequence of operations of all the parts; small material handling cost and time; less delays; better operations control; the possibility to use conveyors	When several parts having different sequence of operations are processed, the benefits of a flow line arrangement are reduced since the movement of parts may not be always unidirectional
Multi-rows layout	Suitable for Flexible Manufacturing Systems	Adjacent lines share common equipment; low investment; small space area; high machine utilization rate;	Complicated process management and control; difficulty in coordinating multi-tasks
Loop layout	Used in Flexible Manufacturing Systems	High flexibility in material handling system	Complex in construction; unable to remove disturbances occurring from external sources

Table 3.2.2. Comparison of backtracking and bypassing [5]

	Disadvantages	Objective
Backtracking	Impacts the movement cost and productivity of facility	Should be minimize
Bypassing	Unnecessary travel time and costs	Should be minimize

Within table 3.2.1 there are highlighted the advantages and disadvantages of the four facility layouts (Fig. 3.2.3). Disadvantages of the "backtracking" and "bypassing" strategies are emphasized in table 3.2.2.

Facility shapes, dimensions and the pickup and drop-off locations

Two different facility shapes are often distinguished (Fig. 3.2.4): regular, i.e., generally regular (rectangular) and irregular, i.e., generally polygons containing at least a 270o angle. As mentioned by reference [9] a facility can have given dimensions, defined by a fixed length (Li) and a fixed width (Wi). In this case, the facilities are called fixed or rigid blocks.

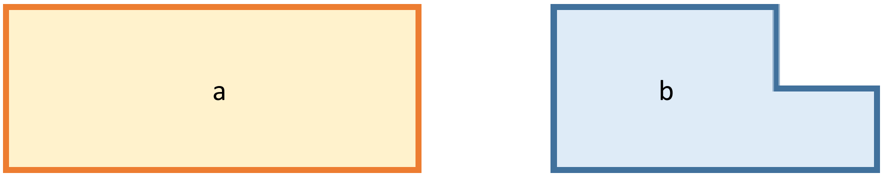


Fig. 3.2.4. Regular (a) and irregular (b) facility shape [5].

Robotic Operational Characteristics: the robot workspace and limits of joints' movements must be considered in early stages of facility layout.

Cycle Time: it is required to find the optimum facility layout and the feasible robot configuration, in such a way that the total cycle time of the robot between all work sites is minimized. For calculating the required cycle time (C) per robot/ workstation/ equipment or per entire production facility it can use the following formula (1). Usually the working time of one shift per day is 8 hours.

$$C = \frac{Production\ time\ per\ day\ (in\ seconds)}{Required\ output\ per\ day\ (in\ units)} \quad (1)$$

Now, it is necessary to determine the **theoretical minimum number of workstations (N_t)** required to satisfy the calculated cycle time (note that this must be rounded up to the next highest integer) using the formula (2):

$$N_t = Sum\ of\ the\ task\ times\ (T) / Cycle\ time\ (C) \quad (2)$$

The next step is to assign the process' tasks to workstations. Assign tasks, one at a time, to the first workstation until the sum of the tasks' times is equal to the workstation cycle time, or no other tasks are feasible because of time or sequence restrictions. Repeat the process for Workstation 2, Workstation 3, and so on, until all process tasks are assigned.

In addition to these factors presented above, two other aspects should be considered in the construction of automated based robotic systems. Firstly, since only a few products are generally suitable for fully automatic handling/assembly, manual working or robotic collaborative processes are often essential with a large number of products. Automation based industrial robotic cells must be constructed so that at any time manual work stations or robotic collaborative stations (Fig. 3.2.6) can be included, following ergonomic principles.

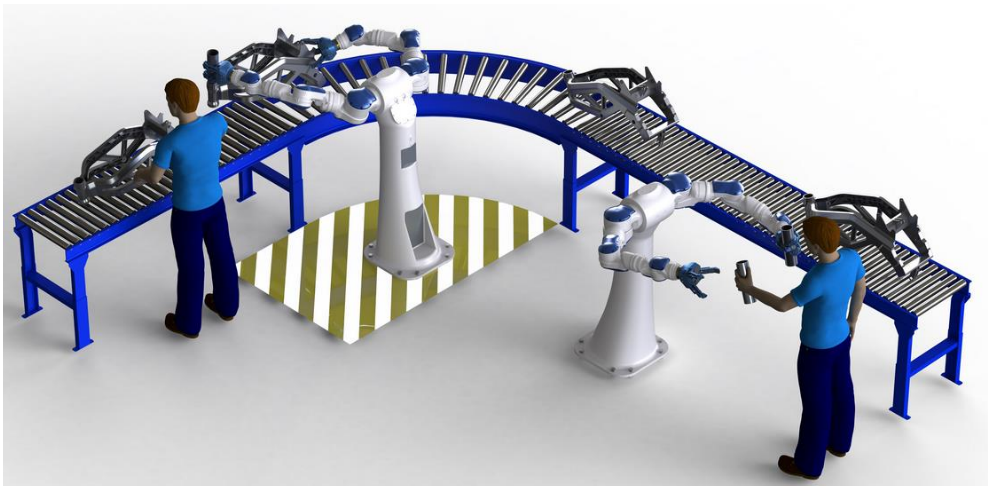


Fig. 3.2.6. Collaborative robots working alongside with human operators (courtesy Yaskawa)

Secondly, since the type-specific peripheral costs will increase in relation to the number of individual parts in the product to be manipulated or assembled, part-specific feeders must be minimized for the economic use of automation based industrial robotic cells.

Evaluation of the generated facility layout

Material handling cost

For manufacturing facilities, *material handling cost* is the most significant criteria for determining the efficiency of a proposed layout. It is determined based on the flows of materials between equipment and the distances between the locations of that equipment. The mathematical formalism to calculate the material handling cost has the following form (3):

$$H_c = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} f_{ij} \, d_{ij}, \qquad \text{i, j = 1,2,3,...n} \qquad (3)$$

Note that H_c is the material handling cost, c_{ij} is the unit cost (the cost to move one-unit load one distance from the equipment *i* to *j*), f_{ij} is the material flow between the equipment *i* and *j* (it is necessary to count how many times a working-object has to pass to an equipment for a new processing or reprocessing; the value for f_{ij} is 1 when the working-object has to pass one time to an equipment and k when the working-object has to pass *k* times to an equipment), d_{ij} is the distance between the centers of equipment *i* and *j*.

Area utilization rate

The area utilization rate of the whole layout is a ratio of total areas required for all workstations/equipment to the smallest possible space (usually the smallest rectangle), which can envelop all the facilities. Hence, the area utilization rate of the generated layout is shown below (4):

$$R_s = \frac{\sum_{i=1}^{n} A_i}{\sum_{i=1}^{n} A_i + \sum_{j=1}^{n} B_j} \times 100\%, \qquad \text{i, j = 1,2,3,...n} \qquad (4)$$

Note that R_s is the "Area utilization rate", A_i is the area of the workstation/equipment *i,* where equipment *i* is sitting, B_j is the remaining blank area of layout. In an ideal facility production layout, the area utilization rate, R_s is 100%. In a real and optimized production facility layout the area utilization rate (R_s) is somewhere in between 75÷100%.

To evaluate the **efficiency of the generated production facility layout,** use the formula (5):

$$Efficiency = \frac{Sum\ of\ the\ task\ times\ (T)}{Actual\ number\ of\ workstations\ (N_a) \times Workstation\ cycle\ time\ (C)} \qquad (5)$$

In the "Efficiency" formula (5) the longest workstation cycle time of the cell is considered. If efficiency is unsatisfactory, regenerate the facility layout using a different approach/rule(s).

3.3 Insights from practitioners regarding facility layout design within automation based robotic systems

There are many tactics that can be used to manipulate a robotic cell layout to reduce footprint, re-route material flow, or provide enhanced accessibility for operators. Some commonly used tactics include:

- Minimizing wasted space in the centre of the robotic cell/production line;
- Exploiting the vertical direction (Z) as much as possible by elevating equipment, robots or conveyors;
- Reducing as much as possible the conveyor widths to fit product or pallet size;
- Provide only the needed level of automation to accomplish the goals of the project;
- Robot control options which allow for safety fencing to be closer to the robot's target points.
- Provide only the needed amount of product or load accumulation to accomplish the goals of the project;
- Use lift gates or embed components into the floor slab to allow additional accessibility.

The first step in laying out a fully functional system is for the design engineers to identify the **available space** and to **understand the product flow requirements**. It is of prime importance to minimize the system footprint while not constricting operator access, forklift travel, material transport, or exit routes. At this stage, the requirements typically take the form of the following:

- Define the product infeed locations;
- Define the raw material delivery locations;
- Establish the forklift travel routs;
- Define the structural obstructions to be avoided;
- Define the desired cell's access points;
- Decide how to integrate into the cell the existing equipment;
- Define the energy drop locations (electrical, air);
- Define height available below the roof's structure, fire protection, piping, mezzanines, etc.

Understanding all these requirements at the beginning of the project will allow the engineers to design an efficient and maintainable robotic cell/robotic line that will meet the expectations of the customer.

There are many software tools that facilitate the representation of the conceptual layout of a proposed automation based robotic system. Some of these tools include: 2-Dimensional CAD; 3D renderings (Fig. 3.3.2, 3.3.3); 3D Dimensional simulations. Depending on the complexity of the system's layout, each of these tools provides a different level of visualization to fully understand the operation and space requirements of a robotic cell. Initial conceptual designs typically begin with a simple 2D layout. This allows for easy manipulation of equipment locations based on discussions with the customer. Once a general acceptable layout has been agreed upon, 3D representations can provide another level of evaluation to give the customer a better idea of how the system will fit into the facility.

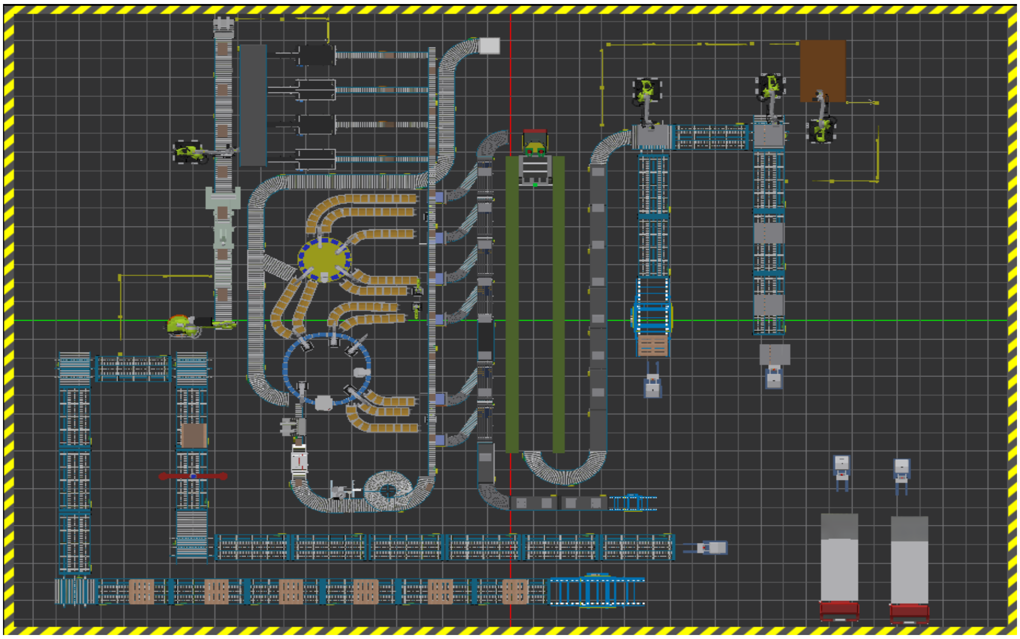


Fig. 3.3.1. 2D drawing of robotic production system layout (Inventor screenshot)

While these initial layout discussions may go smoothly, the inclusion of additional customer representatives to critique the layout can many times add new constraints that must be addressed prior to implementation.

Fig. 3.3.2. 3D virtual prototype of a robotic production system layout (Catia screenshot)

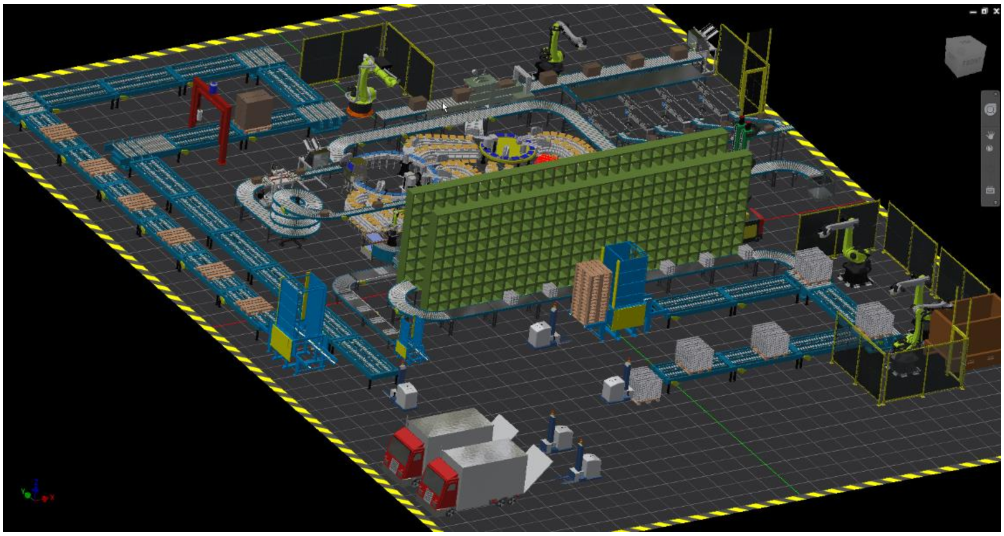


Fig. 3.3.3. 3D virtual prototype of a robotic production system layout (Inventor screenshot)

3.4 Conclusion

Facility Layout Problem in automation based robotic systems requires careful study, planning, designing the robotic solution and implementation. Despite being automated, robotic automation requires manual intervention in:

- Studying and understanding the process and the business's structure
- Selecting the aspects that can be automated
- Selecting the right automation model
- Determining the degree of automation
- Writing codes for robots and PLCs
- Mapping the selected automation model
- Monitoring progress and results
- Optimizing automation for best results

3.5 Recommended readings

1. Andrew Glaser, Industrial Robotics: How to Implement the Right System for Your Plant, 2008;
2. Larry Ross, Stephen Fardo, James Masterson and Robert Towers, Robotics: Theory and Industrial Applications, 2010;
3. Samuel Bouchard, Lean Robotics - A Guide to Making Robots Work in Your Factory, 2017

4. Mocan, B., Timoftei, S., Stan, A., Fulea, M., RobotStudio® - Simulation of industrial automation processes and offline programming of ABBs robots - Practical guide for students - Editura UTPress, Cluj-Napoca, 2017.

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8. Babu, A.J.G., Yao, D., An expert facility layout system: an object-oriented approach. International Journal of Computer Applications in Technology 9 (2-3), pp. 131-143, 1996.
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10. Fulea M., Tanaselea, C., Mocan, B., Murar, M., Algorithm for Automatically Generating the Robot Program for a Reconfigurable Palletising Application, Acta Technica Napocensis, Series: Applied Mathematics, Mechanics and Engineering, vol. 58, Issue IV, pp. 579-584, 2015.
11. Mocan, B., Fulea, M., Olaru, M. and Buchmüller, M., From Intuitive Programming of Robotic Systems to Business Sustainability of Manufacturing SMEs. Amfiteatru Economic, 18(41), pp. 215-231, (IF 0,564), 2016.

Chapter 4: Control system design – exemplified on a robotic manipulation system

Mircea MURAR

Abstract

This chapter presents and discusses the design and development stages required to automate part handling processes within a robotic cell.

4.1. Brief process description

Products that need to be processed are received in a 2x4 matrix type storage organizer. The operator observes if a new storage organizer is received and starts the delivery process by pressing a button on a human machine interface.

An industrial robot equipped with a gripper will move to the storage organizer and pick the first product. After picking the product, the robot moves and places the product on a conveyor belt. Afterwards, the robot moves to its home position and exchanges process related data with the robotic cell's main control unit.

The main control unit drives the conveyor belt towards delivery position. If a product is detected on the delivery position the conveyor belt stops and an operator takes the product for manual packing. After the product was taken by the operator from the conveyor belt, the control system exchanges process related data with the robot's control.

The robot repeats the same procedure for every product from the matrix type storage organizer. After the last product was delivered, the control system will signalize on the HMI that the robotic cell is ready for a new batch.

If during the handling of parts the operator presses the stop button, available on the HMI, the robot delivers the manipulated part to the conveyor belt, the main control unit drives the conveyor belt until that part reaches the delivery position and the process is stopped.

4.2. Control architecture

A generic control architecture and information flow for the robotic cell is graphically represented in figure 4.2.1.

Considering their software and hardware reconfigurability, stability, modularity and interoperability, programable logic controllers are the preferred main control units in robotic cells or automation systems.

The gripper attached to the robot is opened or closed by a pneumatic actuator controlled by the robot's controller. To identify if the attached gripper is in a closed or opened position, two proximity sensors used to detect the gripper's fingers position are mounted on the gripper. As can be observed in figure 4.2.1, pneumatic actuator and proximity sensors are directly wired and controlled by the robot's controller. At certain moments during the manipulating process, the robot's controller exchanges process related information with the main control unit.

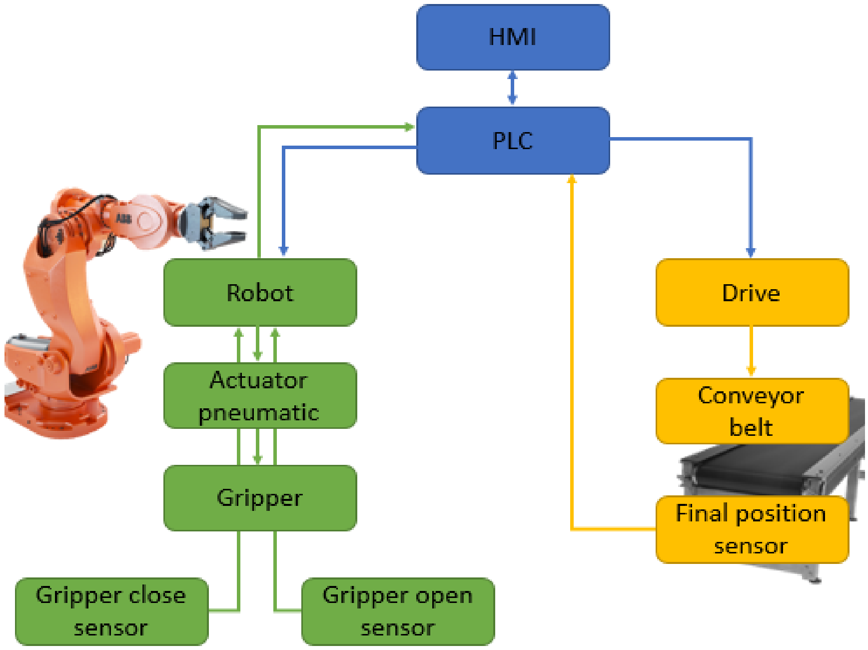


Fig. 4.2.1. Generic control architecture

When considering a medium to high complexity robotic cell, the connection between the robot's controller and the main control system is done using an industrial communication protocol. Since this robotic cell considers a simple task, an industrial communication protocol is not required.

The conveyor's belt is driven by a stepper motor with its own controller which needs to be interfaced with PLC inputs and outputs. A proximity sensor mounted on the conveyor's belt and connected to the PLC will provide the PLC with the required feedback to stop the conveyor when the product arrives to the delivery position.

Figure 4.2.2, presents the product types that are intended to be manipulated. Part 1's dimensions are 460x460x500 mm and its weight is: 125 grams. Part 2's dimensions are 480x330x340 and its weight is: 75 grams. Parts are built out of aluminium.

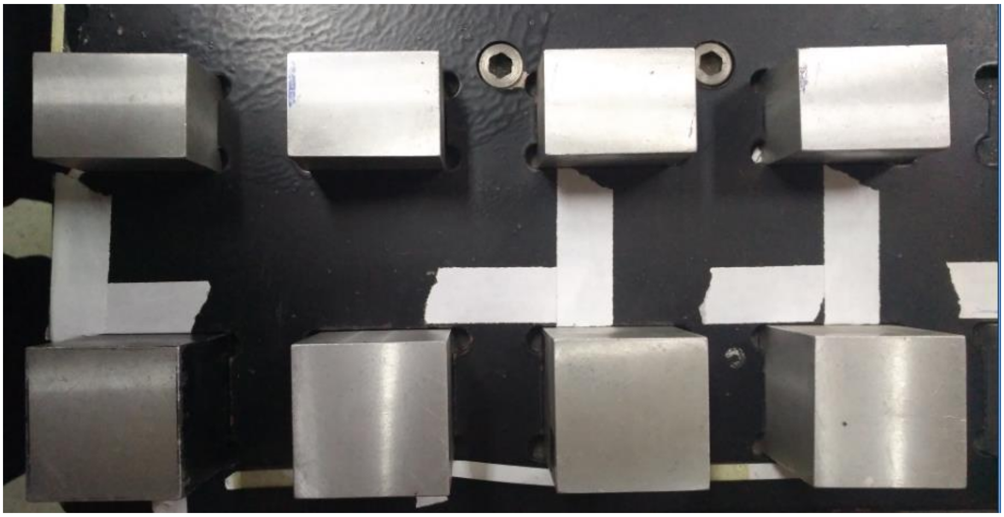


Figure 4.2.2. Product to manipulate

Figure 4.2.3, presents a graphical representation of the most important stages of the process, which will be deployed as control logic in the robot's controller and main control unit to fulfil process requirements.

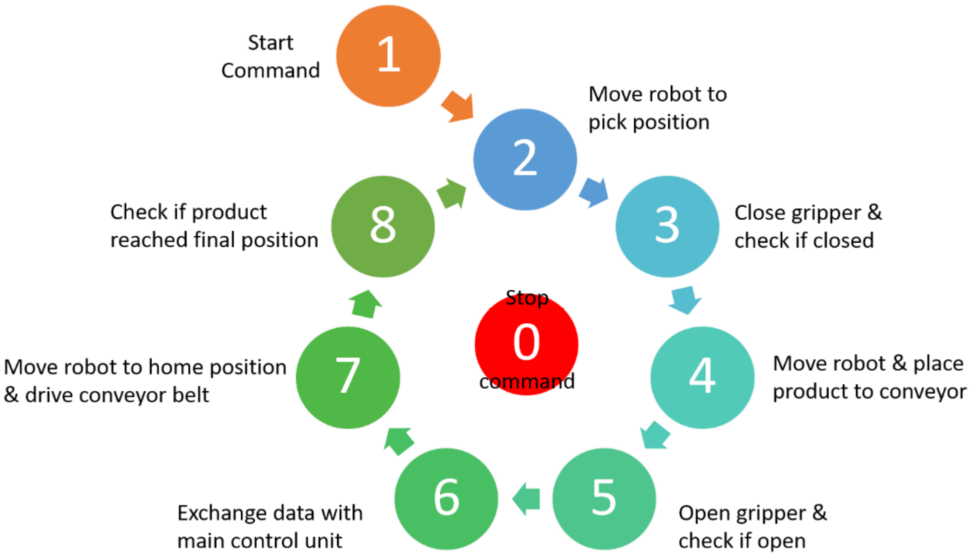


Figure 4.2.3. Graphical representation of most important process stages

Interfacing equipment

A good practice before selecting the equipment and designing the control system is to divide larger systems into smaller functional subsystems to reduce complexity, keep the focus on smaller tasks and identify available equipment requirements. The first subsystem is the industrial robot's controller, the pneumatic actuator, the gripper and gripper's sensors. The second subsystem consists of the main control unit, human machine interface, conveyor control unit, stepper motor and proximity sensor.

Subsystem 1

The industrial robot is equipped with a universal two fingers gripper manufactured by Schunk. The griper's product number is: PGN+ 125/1. The gripper is actuated by a pneumatic oval piston and has two positions: closed or opened. Pneumatic grippers are one of the most used solution for manipulating non-deformable products.

Gripper sensors

One of the simplest and most reliable solution to identify the gripper's position is by using proximity sensors. Proximity sensors are used to detect an object's presence or absence, without having a physical contact with the object.

Since different physics effects can be used to detect objects, a broad range of proximity sensors is available on the market: capacitive sensors, inductive sensors, optical sensors, ultrasonic sensors, magnet sensors and others.

In the described manipulating process, the selection of proximity sensors is based on several aspects:

- The material out of which the gripper is built,
- Sensors' dimensions and mounting possibilities,
- Reliability and complexity,
- The number of wires that need to be routed through the robot's structure,
- Operating voltage and maximum current for the switched load.

The robot's gripper is build out of metal alloys, therefore capacitive sensors cannot be considered since they are used to detect non-metallic objects. Inductive, optical and ultrasonic sensors are using electronic circuitry (e.g. generate magnetic field frequency, modulate light beam) and they might be subject to reliability. A three-wire connection is needed for inductive and ultrasonic sensors. Depending on their working principle, optical sensors might be subject to generate false triggers or not detect the object if unknown objects get in the light beam's path.

For this task, magnet sensors seem to be the appropriate solution. Magnet sensors have a simple construction and operating principle. They are electro-mechanical switches of whose contacts or leads are magnetisable and flexible. When in the proximity of a magnetic field with enough magnetic intensity the leads are magnetized, and the electromagnetic force closes the gap between the leads, it allows the electric signal to pass through.

Therefore, two magnet sensors and one magnet, corresponding to the finger's closed and opened positions will be placed on the gripper's finger and the gripper's body (Fig. 4.2.4). The magnet is placed on the gripper's body and the gripper's sensors are mounted on one of the gripper's fingers so as to be in the proximity of the magnet and to be actuated by the magnet when the gripper's finger is in opened or closed position.

Fig. 4.2.4. Magnetic sensor and magnets mounted on gripper

A two-wire connection will reduce complexity and increase the availability of the robot's IO connectors. Also, considering costs, the following magnetic sensor with LED indicator was selected: PD11S3-BR. Figure 4.2.5 presents the sensors' wiring diagram.

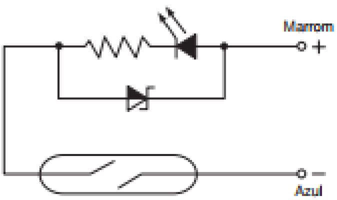


Fig. 4.2.5. PD11S3-BR Magnetic sensor connection diagram

To provide information about gripper's fingers positions, the sensors needs to be wired to robot controller IO system. Usually, digital inputs are 24 VDC rated. Therefore, the brown wire of magnet proximity sensors needs to be connected to a direct current voltage of 24 VDC and the blue wire to one of the robot's controller digital input.

The sensors' wiring to a robot controller is done through a R2CP connector found on the third robot joint. A 24 VDC robot controller internal power supply is used to supply the magnetic sensors. Magnetic sensor power supply will be connected to a terminal pin A of R2CP connector. Magnetic sensors that detect if the gripper's finger is in the opened position is connected to terminal pin B of R2CP and magnetic sensors that detect if the gripper's finger is in a closed position is connected to a terminal pin C of R2CP.

Pneumatic actuator

The available gripper is actuated by a pneumatic piston. A pneumatic actuator closed on the middle position and with two separate pneumatic circuits for closing and opening the griper's fingers will ensure the gripper's main tasks. Since the gripper is connected and controlled by the robot's controller, the pneumatic actuator must be equipped with solenoids for switching between the desired pneumatic circuits. One possible solution for a pneumatic actuator is presented in figure 4.2.6.

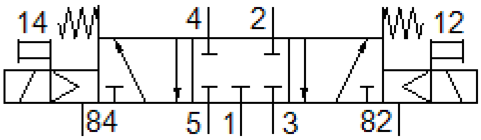


Fig. 4.2.6. Pneumatic diagram of actuator when solenoids are not energized

Figure 4.2.7 shows the pneumatic actuator's behaviour and how pneumatic circuits are connected when solenoids 1 and 2 are energized. The pneumatic actuator is supplied with compressed air on inlet 1. Solenoid 1 control is done using electrical connections 12 and 82, while solenoid 2 is using connections 14 and 84.

When solenoid 1 is energized, the pneumatic actuator will connect the compressed air inlet 1 to outlet 2 and outlet 4 to outlet 5. When solenoid 1 is de-energized, the mechanical spring will bring the pneumatic actuator to the middle position, see figure 4.2.6, closing the air circuits to the gripper. When solenoid 2 is energized the pneumatic actuator will connect the compressed air inlet 1 to outlet 4 and outlet 2 to outlet 3. Therefore, air outlets 2 and 4 will be connected to the pneumatic gripper's connections. Depending on which solenoid is energized they can be used as air inlet to the gripper's piston or air outlet from gripper.

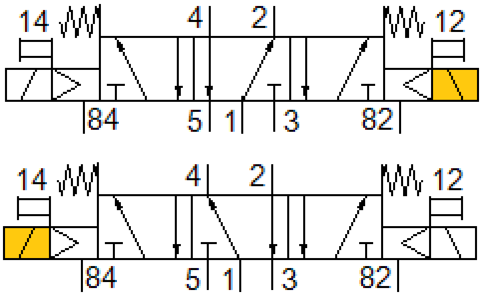


Fig. 4.2.7. Pneumatic actuator behaviour when energized

A pneumatic actuator with presented behaviour is the CPE18-M1H-5/3G-1/4 from Festo, see figure 4.2.8.

Fig. 4.2.8. Pneumatic actuator

To control the pneumatic actuator, its solenoids will be wired to a robot controller IO system. Usually, digital outputs are 24 VDC rated. If different voltage levels are required to control other equipment, additional interfacing equipment capable to support the required voltages will be considered. To reduce costs and number of interfacing equipment the pneumatic actuator solenoids will work on 24 VDC. Therefore, direct connection between the robot controller's digital outputs and the pneumatic actuator's solenoids can be implemented.

The pneumatic actuator's solenoids will be energized by the robot controller's digital outputs to drive the gripper in opened or closed position. The solenoids wiring to the robot's controller is done through R2CP connector found on the third robot's joint. Solenoid 1's positive terminal (white wire) will be connected to the terminal pin H of R2CP and solenoid 2's positive terminal (white wire) to K of R2CP. Negative terminals of solenoid 1 and 2 (brown wires) will be connected to terminal pins D and E of R2CP.

Robot controller IO system

The structure of the ABB robot controller's IO system is organized on several layers, which are presented in figure 4.2.9. The ABB robot controller uses an industrial communication protocol to connect to IO modules or other equipment.

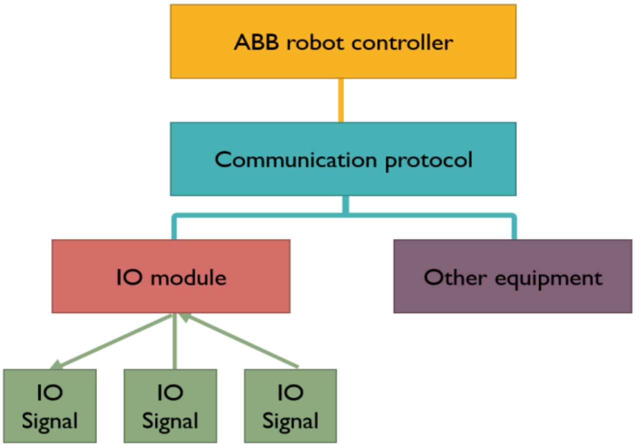


Fig. 4.2.9. ABB controller IO system

DeviceNET is one of the most used communication protocols of the ABB robot's controllers. Connected IO modules or other equipment must have DeviceNET communication protocol implemented to efficiently exchange data with the robot's controller. Also, the manufacturer will provide a software library which describes how product works.

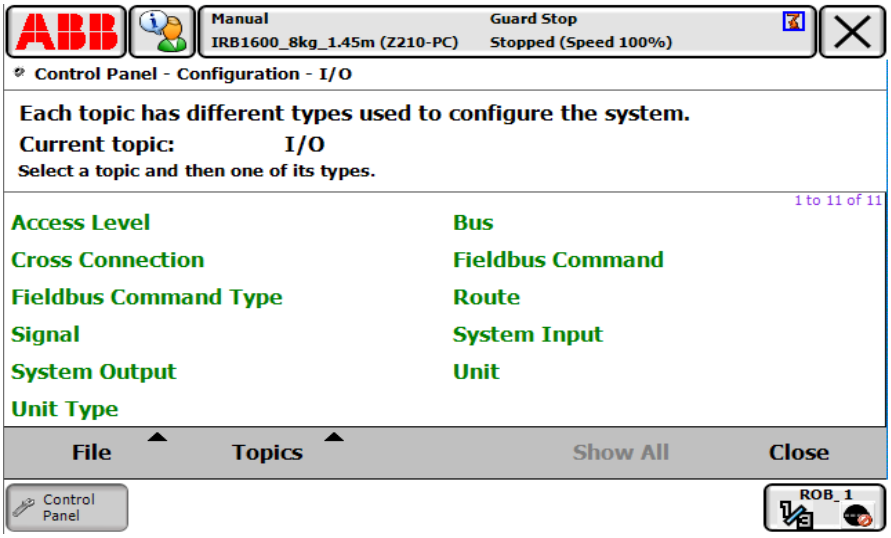


Fig. 4.2.10. ABB robot flex pendant Configuration menu

Before defining and using IO signals, the communication protocol and IO module need to be defined and configured on a robot's controller using robot flex pendent.

Bus section (aka Communication protocols) provides information related to already defined communication protocols and allows to remove, edit or define virtual protocols models for available physical communication boards.

Accessing Bus section is done via the following menu path: ABB Menu → Control Panel → Configuration → Bus (Fig. 4.2.10).

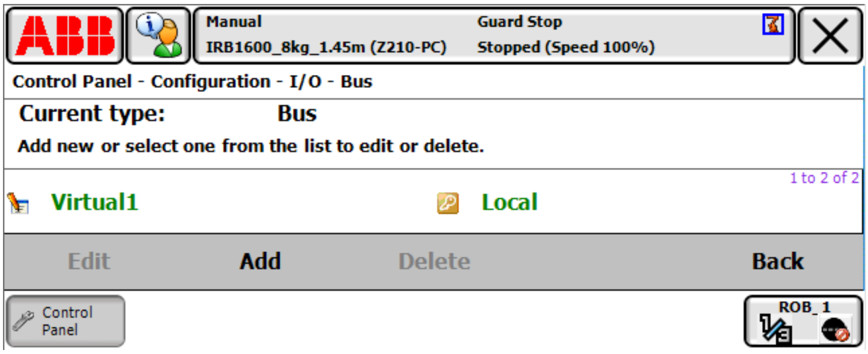


Fig. 4.2.11. ABB robot flex pendant Bus section

Within Bus section we have the option to add and define a new communication protocol by pressing the Add button (Fig. 4.2.11). The virtual model of a new DeviceNET communication protocol contains the following important properties that must be configured (Fig. 4.2.12):

- Board number – is the slot number in the robot control's computer unit where the DeviceNET board is inserted.
- DeviceNET Master Address – this is the communication protocol address where the robot's controller can be accessed.
- DeviceNET Communication Speed – this is the speed at which data is sent and received.

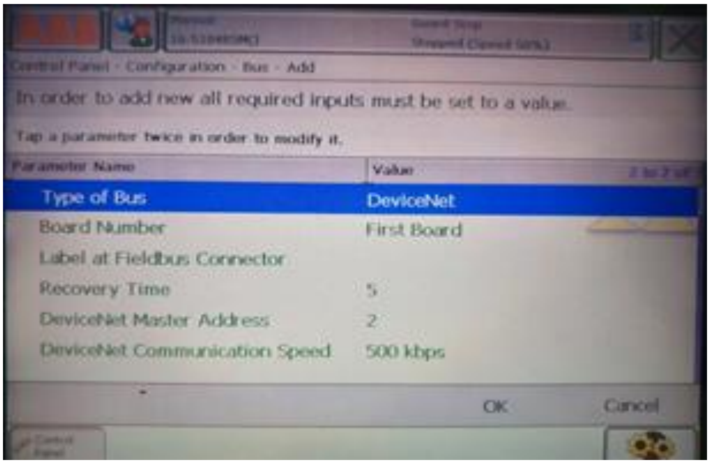


Fig. 4.2.12. DeviceNET communication protocol properties

Warm restart of the robot's controller is required for communication protocol updates to take effect. The robot's controller will ask for restart after communication protocol properties are confirmed, by pressing the OK button, as seen in figure 4.2.12.

After the robot's controller starts-up we need to add and define an IO module to provide connectivity to the gripper's sensors and the pneumatic actuator's solenoids. Since sensors are digital inputs and solenoid are digital outputs for the robot's controller, a mixt IO module is required. The following IO modules supporting DeviceNET are available on the market:

- DSQC 355A – analogic inputs and outputs,
- DSQC 623 – digital inputs and relay based outputs,
- DSQC 651 – analogic and digital inputs,
- DSQC 652 – digital inputs and outputs.

DSQC 623 and DSQC 652 can be used for our application. According to DSQC 652 datasheet and pneumatic actuator datasheet, DSQC 652 digital outputs are capable to source the required current to energize the pneumatic actuator's solenoids. Further after, we will add a DSQC 652 IO unit to the robot's controller and define its properties.

Unit section (aka IO modules) provides information related to already defined IO modules and allows to remove, edit or define virtual IO unit models for available physical IO units.

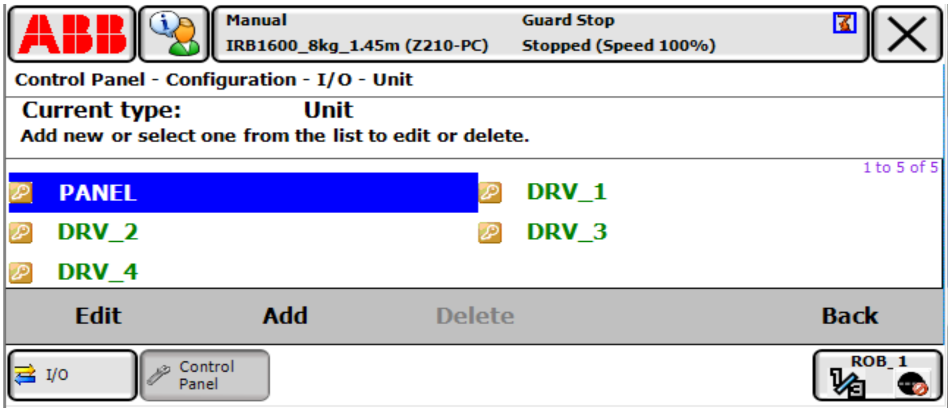


Fig. 4.2.13. ABB robot flex pendant Unit section

Accessing Unit section is done via the following menu path: ABB Menu → Control Panel → Configuration → Unit as seen in figure 4.2.10.

Like adding a communication protocol, in Unit section we have the option to add a new IO module by pressing the Add button, as seen in figure 4.2.13.

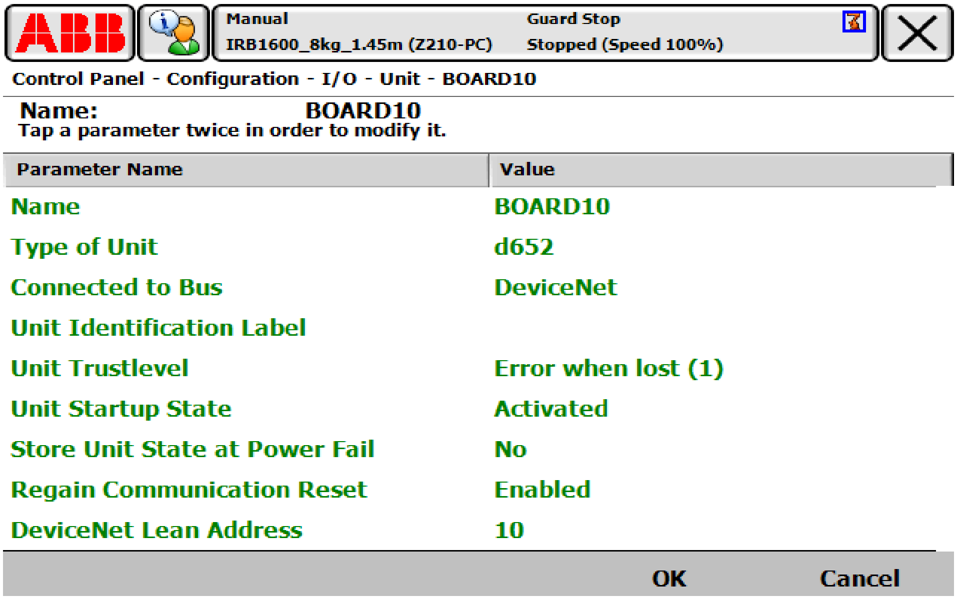


Fig. 4.2.14. IO Unit properties

The virtual model of a new IO module contains the following important properties that must be configured, as seen in figure 4.2.14:

- Name – is the name with which the IO unit will be referred at in the robot controller's application programs.
- Type of Unit – represents the type of connected unit. It contains the virtual model of the connected unit in a format understandable by the robot's controller. Unit type is selectable from a list of virtual models, previously defined in the robot's controller.
- Connected to Bus – the communication protocol to which IO unit is connected.
- Store Unit State at Power Fail – option to memorize IO unit status in case of power failure.
- DeviceNET Address – this address must be the same with the hardware address configured on the IO unit.

Setting the hardware address on DSQC 652 module is done on a X5 connector, using IO unit address jumpers. The address is built by adding the numbers associated to the jumpers, which are not connected to an IO module ground. For example, in figure 4.2.15, jumpers 2 and 8, are not connected to the ground, resulting in address 10.

Warm restart of the robot's controller is required for IO Unit section updates to take effect. Robot controller will ask for a restart after communication protocol properties are confirmed by pressing the OK button (Fig. 4.2.14).

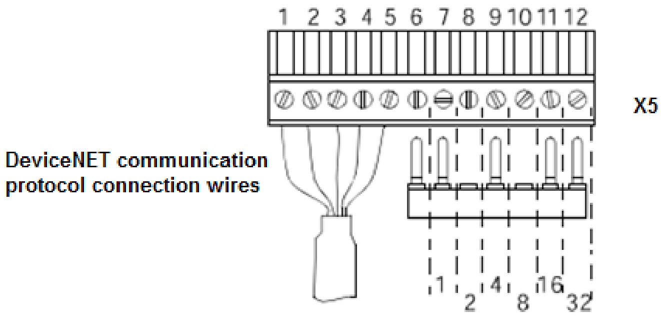


Fig. 4.2.15. IO Unit properties

After the robot's controller starts-up we need to define two digital inputs and two digital outputs to assign to DSQC 652 IO module to ensure connectivity to the gripper's opened and closed sensors and pneumatic actuator solenoids.

Signal section (aka IO signals) provides information related to already defined IO signals and allows to remove, edit, define and assign IO signals to an available physical IO Unit. Also, virtual IO signals can be defined.

Accessing Signal section is done via the following menu path: ABB Menu → Control Panel → Configuration → Signal (Fig. 4.2.10).

Like adding a communication protocol or an IO module, in Signal section we have the option to edit available IO signals, delete or add new IO signal by pressing the Add button (Fig. 4.2.16).

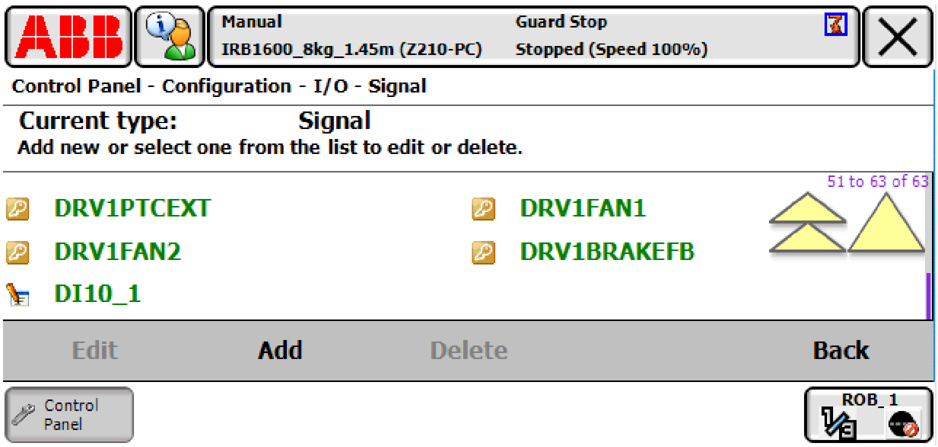


Fig. 4.2.16. ABB robot flex pendant Signals section

The virtual model of a new IO signal contains the following important properties that must be configured (Fig. 4.2.17):

- Name – is the name of the IO signal, as it will be referred to in the robot's application program.

- Type of signal – signal's type digital or analogic and input or output. The signal's type must be selected with respect to available physical properties of the IO unit.
- Assigned to Unit – IO unit of defined IO signal. The IO unit to whom defined signal is assigned.
- Unit Mapping – represents the physical pin on IO unit connectors where this signal can be interfaced to other equipment. If unit mapping is 1, it means that DO signal can be interfaced on terminal pin 1 of connector X1, see figure 4.2.17.
- Access Level – which robot's jobs can make use of the defined IO signal.
- Default value – is the value the signal will have after the controller has started.
- Signal Value at System Failure – is the value that the signal will have if major failure is detected (e.g. communication protocol is no longer connected or an equipment with the same address was connected). When defining the value of this signal, one must consider the effects on interconnected robotic cell equipment.
- Store Signal Value at Power Fail – if this option is enabled, the signal value will be saved in case of power failure. After power-up, the signal will regain the value before power failure.
- Invert Physical Value – if this option is enabled, the value of a signal from the robot's application programs will be inverted. This option is useful when an equipment is replaced with another one with a different control logic.

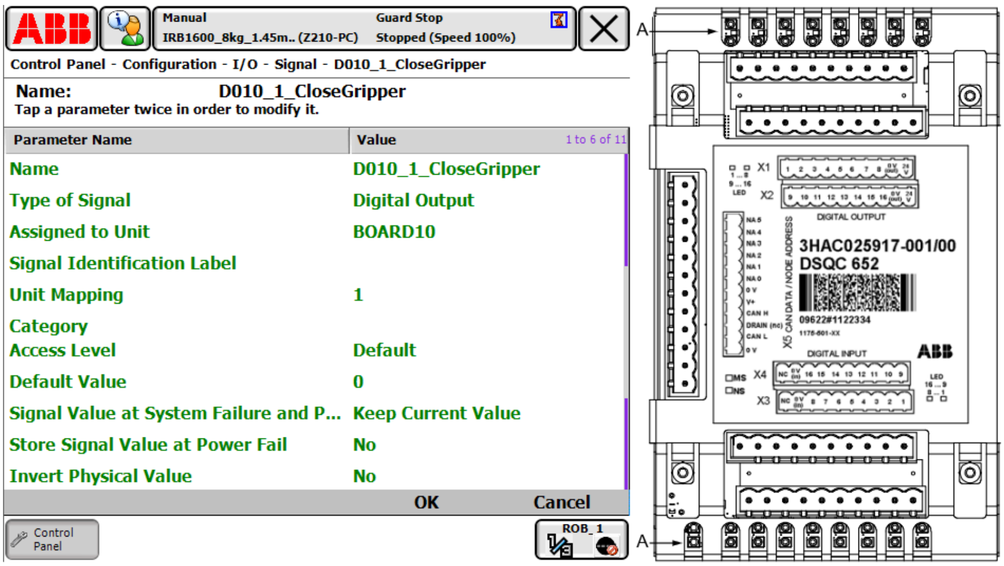


Fig. 4.2.17. IO Signal properties and IO unit connectors

Figure 4.2.17 presents the properties of the digital output signal connected to the pneumatic actuator's solenoids, used to close the gripper and IO signals mapping.

Equipment interconnecting

This subchapter's goal is to explain how different equipment is supplied with electric power and interconnected to achieve subsystem 1's goals: close and open commands and receiving the gripper's position feedback to the robot's controller.

Supplying DSQC 652 IO unit digital inputs and outputs electronics circuitry is done on X1 and X2 connectors for Digital Outputs and on X3 and X4 connectors for Digital Inputs.

The robot's controller 24 VDC internal power supply is used to power DSQC 652 IO unit control logic, digital inputs and digital outputs circuitry. The 24 VDC line is connected through a 500 milliamperes fuse to 24 VDC pins of X1 and X2 connectors. The 0 VDC line is connected to 0 VDC pin of X1, X2, X3 and X4 connector, see figure 4.2.18.

Connecting the gripper's proximity sensors to DSQC 652 IO digital inputs and the pneumatic actuator to DSQC 652 IO digital outputs is done as describe bellow and presented in figure 4.2.18.

The robot's controller 24 VDC internal power supply line is connected to pin 1 of XT6 controller. XT6 pin 1 is wired to terminal pin A of R2CP connector on the third robot joint. Robot controller 0 VDC internet power supply line is connected to pin 4 of XT6 controller. XT6 pin 4 is wired to the terminal pin D of R2CP connector on the third robot joint.

Both proximity sensors are supplied from pin A of R2CP which is connected to the robot's controller 24 VDC internal power supply line. The output of the gripper's opened proximity sensor is connected to pin B of R2CP and to DSQC 652 digital input 2 via pin 2 of XT6 connector. The output of the gripper's closed proximity sensor is connected to pin C of R2CP and to DSQC 652 digital input 1 via pin 3 of XT6 connector.

Solenoids are controlled using separate digital outputs. Controlling the solenoid which opens the pneumatic gripper is done using digital output 1. Digital output 1 is connected through pin 8 of XT6 and pin H of R2CP robot join connector to the positive terminal of the pneumatic actuator solenoid.

Controlling the solenoid, which closes the pneumatic gripper, is done using digital output 2. Digital output 2 is connected through pin 9 of XT6 and pin K of R2CP robot join connector to the positive terminal of the pneumatic actuator's solenoid.

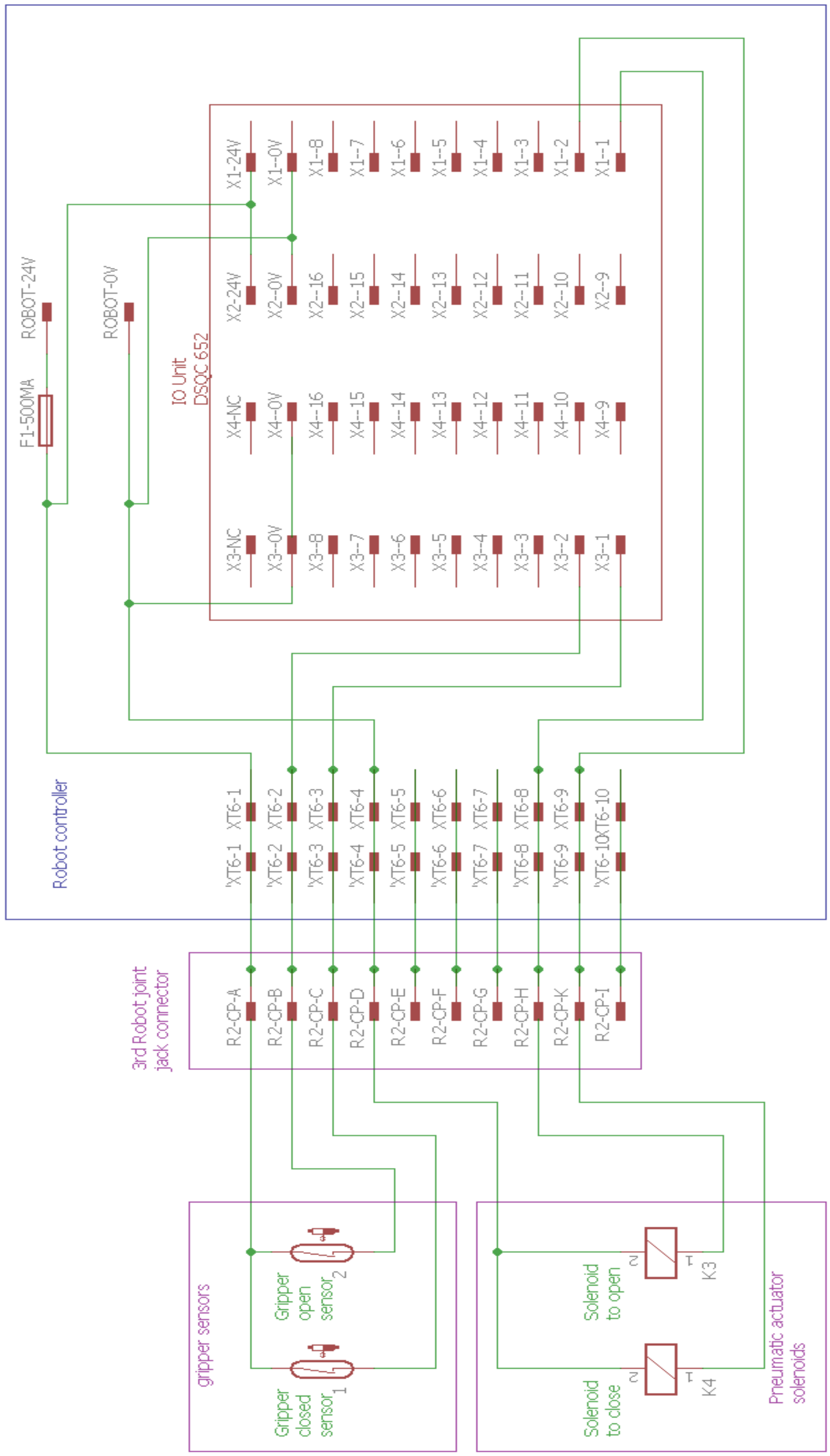


Fig. 4.2.18. Sensors and solenoids wiring to ABB robot DSQC 652 board

The negative terminals of solenoids are connected to terminal pin D of R2CP robot joint connector which is connected to the robot's controller 0 VDC internal power supply line.

As can be observed in figure 4.2.18, DSQC 652 digital inputs and outputs are connected to an internal connector with two rows internally connected and marked as XT6. XT6 pins are connected through the industrial robot's structure to the third joint jack connectors: R2-CP, see figure 4.2.19.

Fig. 4.2.19. Third robot joint with R2-CP and R2-CS jack connectors

Following the procedure for defining and parametrizing the IO signals presented in figure 4.2.16, 4.2.17 and associated procedures, additional digital IO signals will be defined, in accordance with figure 4.2.20:

- digital output signal intended to open the gripper,
- digital input signal used to signalize the close state of gripper,
- digital input signal used to signalize the open state of gripper.

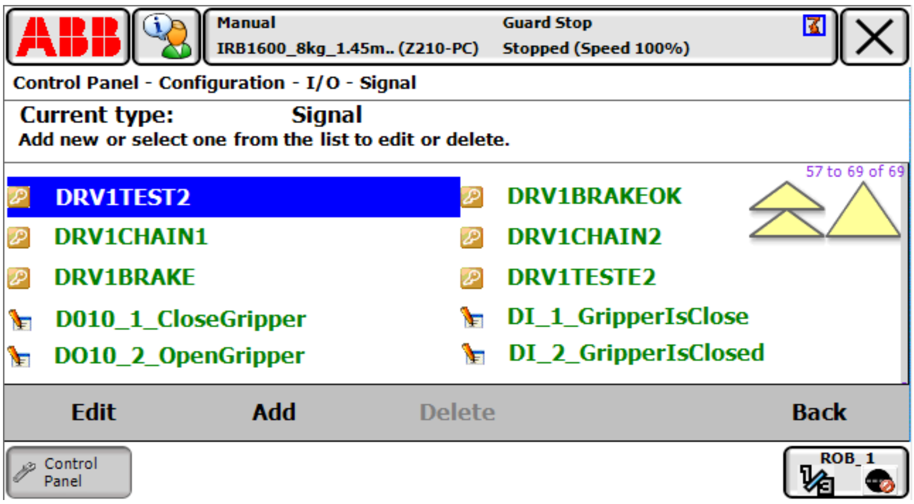


Fig. 4.2.20. Subsystem 1 IO signals

Commissioning

During commissioning, the communication protocol and IO unit's availability will be checked and their functionality validated. Also, IO unit signals will be checked and their effect tested.

Checking if the robot's controller detects the configured IO unit is done via the following path: ABB Menu → Inputs and Outputs. For a better visibility, I/O Units option will enable to be displayed in the Inputs and Outputs section. Figure 4.2.21, presents all the detected I/O Units and their properties.

It can be confirmed that the configured virtual model of DSQC 652 matches the physical IO unit configuration. Its DeviceNET address is 10, it is running and its associated IO signals can be used in a robot's jobs, if defined correctly.

Checking if IO unit signals were wired correctly can be done via the following path: ABB Menu → Inputs and Outputs. For a better visibility, All Signals option will be enabled to be displayed in Inputs and Outputs section. Figure 4.2.22 presents all the detected I/O Units signals, their type and value.

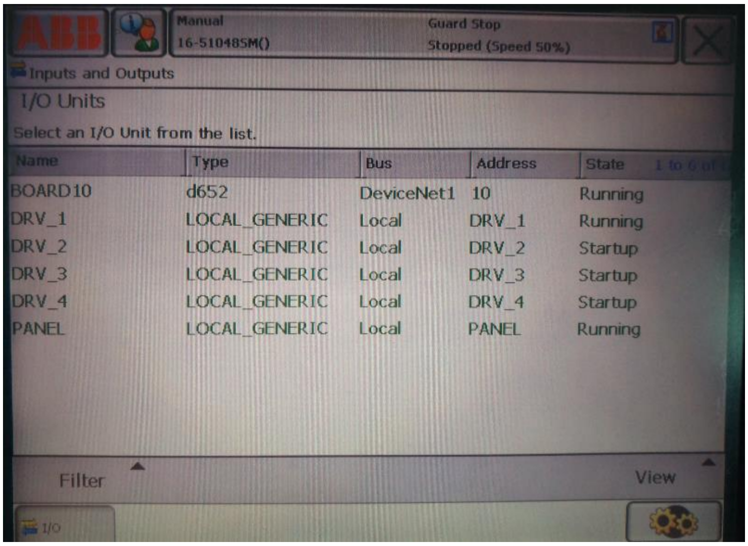


Figure 4.2.21. Detected I/O units, their address, connection bus and status

Energizing pneumatic valve solenoids can be done by selecting the signal that is desired to be simulated and changing its actual value using the options from the bottom. If compressed air is available, energizing gripper solenoids will open or close the gripper. Simulating IO signal value to Logic 0 (eq. 0VDC) or Logic 1 (eq. 24 VDC) is presented in figure 4.2.23.

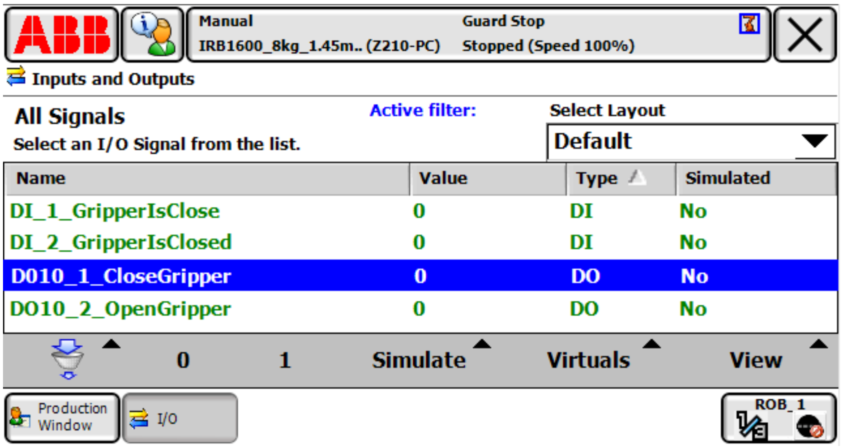


Fig. 4.2.22. Defined I/O unit signals, their value and type

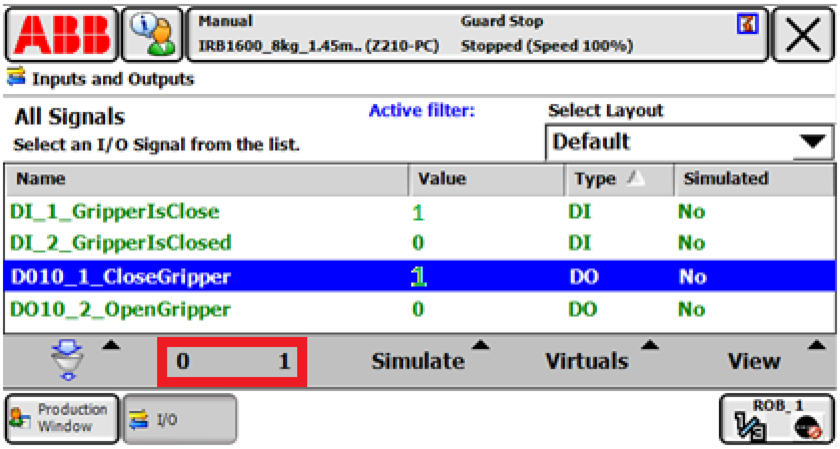


Fig. 4.2.23. Simulating DO signal value and monitoring DI signals

Feedback from opened or closed position will be received if the electrical wiring of the sensors was properly done. Observing the digital inputs' status related to the gripper's position can be observed in Inputs and Outputs, by modifying the filter to All Signals, as in figure 4.2.22, or to Digital Inputs.

Subsystem 2

The main control's unit is informed by the robot's controller after manipulated product is placed on the conveyor belt and the robot is positioned back to the home position. Afterwards, the conveyor belt will be started by the main control unit. If the product reaches the destination position, the conveyor belt's proximity sensor will detect the part, and the main control unit will stop the conveyor belt.

Conveyor sensor

One of the simplest and most used solution to detect objects' presence or absence is by using a proximity sensor. In the described process stage, the selection of proximity sensors is based on several aspects:

- The material out of which the product is built,
- Maximum sensing distance,
- Sensors' dimensions and mounting possibilities,
- Reliability and complexity,
- The number of wires that need to be connected to the main control unit,
- Operating voltage and maximum current for the switched load.

The product to be detected is built out of aluminium and is placed on a conveyor with a width of 240 mm, out of which, the transportation belt's width is 175 mm. Capacitive proximity sensors cannot be considered, since they are used to detect non-metallic objects. Since aluminium is a material with a low magnetic permeability, inductive proximity sensors cannot be used. Magnet sensors have a small operating range and attaching magnets to an aluminium part is not possible.

Optical and ultrasonic proximity sensors are subject to generate false triggers if an unknown object gets in the path of reflected light or ultrasonic beam. Considering costs and complexity, optical sensors seem to be the appropriate solution for this task.

Optical proximity sensors are built out of a transmitter and a receiver. The transmitter sends a modulated beam light to the receiver. Optical proximity sensors can be found in three major construction types: barrier, beam reflection and diffuse reflection.

Barrier type optical proximity sensors have a transmitter and a receiver in different housings and can be used for all types of object detection applications. Beam reflection sensors have the transmitter and receiver in the same housing and they need an additional element to reflect the optical beam back to the receiver, if no object is detected. Diffuse reflection sensors' detection principle is based on the reflection of the light beam by the product to be detected, within its working range.

As can be observed in figure 4.2.2, the product that needs to be detected has a reflective body. One optical proximity sensor based on diffuse reflection seems to be the appropriate solution. Having the transmitter and receiver in the same housing will reduce the number of mounting elements and wiring complexity.

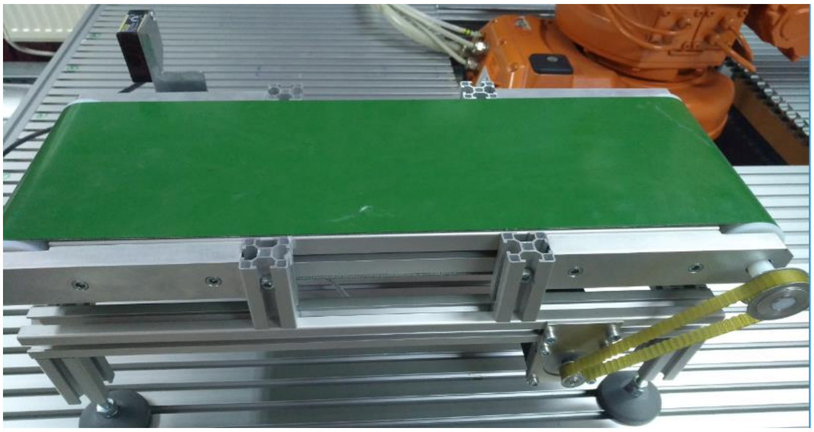


Fig. 4.2.24. Diffuse reflective optical proximity sensor mounted on conveyor belt

For this task one Omron E3JK-DS30M1 diffuse reflection optical proximity sensor with a configurable working rage up to 300 mm was mounted on the conveyor belt structure, where destination position is considered, as in figure 4.2.24.

The sensor uses a relay with two contacts (NC and NO) to signalize object detection. If a Logic 1 is desired when object is detected, we need to connect the main control unit's digital input to Black wire the sensor. If a Logic 0 is desired when an object is detected, we need to connect the main control unit's digital input to the Gray wire of the sensor, see figure 4.2.25.

Since, signalizing object detection with a Logic 0 can generate false triggers in case of a wire break, in most of the cases Logic 1 will be used to signalize object detection. A good process control design would consider both signals to be connected to the main control unit.

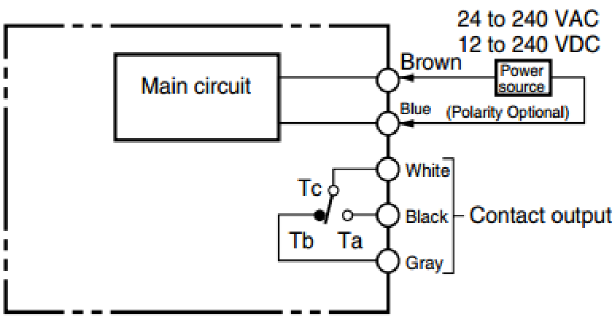


Fig. 4.2.25. E3JK-DS30M1 Optical proximity sensor connection diagram

Conveyor control unit

Depending on many aspects (e.g. application type, power requirements) manufacturing equipment is driven by different types of actuators (e.g. electric motors, pneumatic devices).

A small conveyor belt driven by a stepper motor is considered for this task. The motor's type, the step's angle and the required current are among the most important motor characteristics. Conveyor belt motor is a NEMA 23 bipolar stepper with an 1.8° step angle which requires a current of 2.0 amperes to rotate one step.

Dedicated control units are used to achieve the desired behaviour and optimum control of stepper motors. A stepper motor's control unit is capable to control a broad range of stepper motors. Since bipolar stepper motors can be connected also as unipolar motors, and considering stepper motor technical characteristics, the 2M542 control unit is used.

Since control units are designed to control a broad range of stepper motors, a configuration procedure is required for the control unit to match it to the motor's requirements and achieve optimum stepper motor control. Control unit configuration is done using available micro switches. As can be observed in figure 4.2.26, first three micro switches are used to select the current injected in stepper motor windings. Last four micro switches are used to select the number of micro steps generated by the control unit to make the motor's shaft to rotate one revolution.

According to the conveyor belt's motor current, the following micro switches configuration is required: SW1 – OFF, SW2 – OFF and SW3 – ON. By configuring a small number of steps per revolution, a faster but more rough motion will be obtained. A high number of steps per revolution will generate a slower but smoother motion.

SW **1**	SW **2**	SW **3**	Current (A_{rms})
ON	***ON***	***ON***	1.00 A
OFF	***ON***	***ON***	1.46 A
ON	OFF	***ON***	1.91 A
OFF	OFF	***ON***	2.37 A
ON	***ON***	OFF	2.84 A
OFF	***ON***	OFF	3.31 A
ON	OFF	OFF	3.76 A
OFF	OFF	OFF	4.20 A

SW **5**	SW **6**	SW **7**	SW **8**	Steps/Rev
ON	OFF	***ON***	***ON***	800
OFF	OFF	***ON***	***ON***	1600
ON	***ON***	OFF	***ON***	3200
OFF	***ON***	***ON***	***ON***	6400
ON	OFF	OFF	***ON***	12800
OFF	OFF	OFF	***ON***	25600
ON	***ON***	***ON***	OFF	1000
OFF	***ON***	***ON***	OFF	2000
ON	OFF	***ON***	OFF	4000
OFF	OFF	***ON***	OFF	5000
ON	***ON***	OFF	OFF	8000
OFF	***ON***	OFF	OFF	10000
ON	OFF	OFF	OFF	20000
OFF	OFF	OFF	OFF	25000

Fig. 4.2.26. Control unit configuration options

When selecting the right number of steps per revolution one should take into consideration the following aspects:

- Required moving speed,
- Transported product type,
- Motor pull out torque curve,
- Maximum pulse frequency which can be generated by the main control unit,
- Maximum pulse frequency which can be accepted by the stepper motor.

Figure 4.2.27, presents how the motor pulls out torque changes with respect to pulses' frequency. The maximum number of pulses supported by the motor to generate motor angular steps can be identified in figure 4.2.27. A good approach for heavy parts must consider starting and stopping the conveyor belt using a ramp and cost pattern, by increasing and decreasing the number of pulses per seconds.

Since, manipulated parts have a weight of up to 150 grams, the conveyor belt motor torque is enough on the entire pulse frequency range. Considering that manipulated parts are not easily damageable, a higher speed and rough motion is selected.

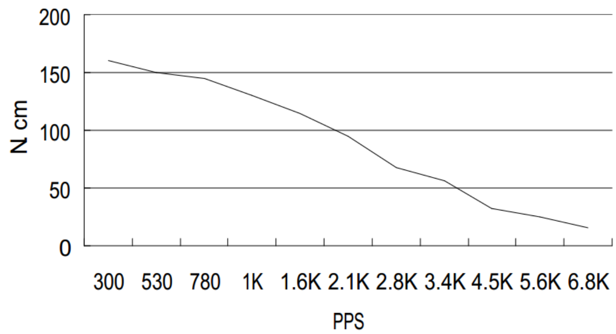


Fig.4.2.27. Motor torque versus pulses frequency

To achieve high motor speed, the main control unit will generate pulses with a frequency from the top of the motor's supported frequency range (e.g. 3.4k, 5.6k or above). Also, the conveyor belt's motor control unit will be configured to control the motor so that it makes a complete revolution in fewer steps (e.g. 8000, 6400 or below). A number of 6400 steps per a complete revolution of the motor's rotor is configured by switches SW5 – OFF, SW6 – ON, SW7 – ON and SW8 – ON.

The conveyor belt stepper motor windings and power supply must be connected to a 2M542 control unit connector, according to the schematics presented in figure 4.2.28. As in 2M542 datasheet, the accepted power supply voltage range is between 24 to 50 VDC.

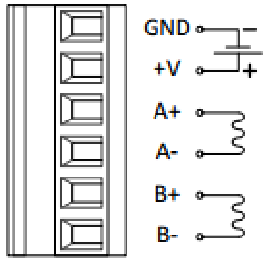


Fig. 4.2.28. Stepper motor control unit power supply and motor windings connections

Controlling stepper motor control unit is done by connecting and activating or deactivating three opto-isolated signals: pulse, direction and enabling by main control unit, see figure 4.2.29.

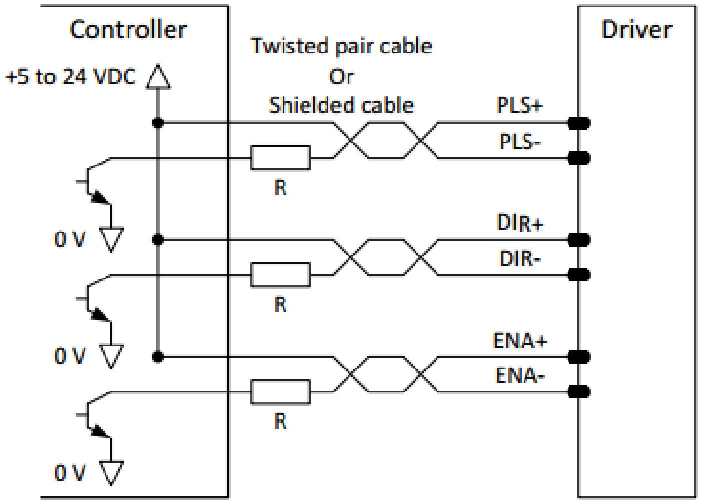


Fig. 4.2.29. Stepper motor control unit control signals connections

If the Pulse (PLS) signal is enabled, the motor will move one micro-step. According to the number of steps per configured revolution, the motor will shift a specific angular distance. The direction (DIR) signal is used to select the rotation's direction. When the Enable (ENA) signal is activated, the 2M542 control unit will shut off the output current and the stepper motor will lose torque. As in 2M542 datasheet, control signals must have a width of at least 2.5 microseconds to have effect on the control unit side.

When sizing and selecting the resistor for control signals must consider the voltage amplitude of main control unit signals connected to 2M542 control unit so as to obtain the current required to activate the 2M542 optocouplers. Usually, a current between 10 and 20 milliamps is enough.

Main control unit

A programmable logic controller (PLC) will be considered as the main control unit in this application. Even though most of the PLCs available on the market have a modular structure, before selecting a PLC and its modules, the number of inputs/outputs and their type must be identified.

Table 4.2.1. Main control unit input and outputs overview

No.	Signal description	Signal type	Observations
1	Conveyor belt proximity sensor NC contact	Digital input	
2	Conveyor belt proximity sensor NO contact	Digital input	
3	Conveyor belt control unit Pulse signal	Digital output	High frequency pulses are required
4	Conveyor belt control unit Direction signal	Digital output	
5	Conveyor belt control unit Enable signal	Digital output	
6	Robot controller input 1	Digital output	Multiplexed IO signals used to trigger specific actions on the robot's controller or the main control unit's side.
7	Robot controller input 2	Digital output	
8	Robot controller input 3	Digital output	
9	Robot controller output 1	Digital input	
10	Robot controller output 2	Digital input	
11	Robot controller output 3	Digital input	

Table 4.2.1 presents an overview of IO signals that need to be considered for connecting with the proximity sensor, the conveyor's control unit and the industrial robot's controller.

A number of 5 digital inputs and 6 digital outputs are the minimum requirements of the main control's unit in terms of IO signals out of which one high frequency digital output.

A good practice in automation systems is to consider a higher number of inputs and outputs than the minimum with at least 20% for further system developments. Therefore, an ideal main control unit should have 6 digital inputs, 6 digital outputs and 1 high frequency digital output.

Finding PLCs with the required resources in terms of IO signals for a proposed task within Siemens product portfolio can be done using the TIA Selection tool. The TIA Selection tool is a free software product which can be downloaded or used online (https://mall.industry.siemens.com/spice/TSTWeb/#/Start/).

According to the TIA Selection tool, any basic PLC from S7-1212, S7-1213, S7-1214, S7-1215 and S7-1217 can be selected since they provide enough IO signals for the proposed task. Additionally, a signal board capable to generate high frequency pulses is needed.

Using the TIA Selection tool, the following equipment were selected:

- S7-1217C (e.g. 6ES7 217-1AG40-0XB0) as the main control unit
- SB 1223 (e.g. 6ES7223-3BD30-0XB0) a signal board which must be mounted on the main control unit and is capable to generate digital output pulses at a frequency of 200 kHz.

Equipment interconnecting

This subchapter's goal is to explain how subsystem 2's equipment is supplied with electric energy and interconnected to achieve its goals: control the conveyor belt and detect if the manipulated part reached the destination position.

A 24 VDC power supply capable to deliver a current of maximum 5 amperes is selected to supply with power the programmable logic control, the human machine and the conveyor belt motor's control unit.

Selecting the electrical protection fuse rating for the main control unit is based on technical characteristics of the PLC and the interfaced equipment. According to S7-1217 PLC and SB 1223 the signal board's technical data an input current of 600 milliamperes and is required to power up the PLC CPU and a current of 35 milliamperes for SB.

Every PLC digital input will sink a current of 4 milliamperes. Even if, according to the table 1, we use only 5 digital inputs, we will foresee current requirement for all digital inputs for further development. Therefore, a total of 40 milliamperes is required for the 10 digital inputs available on PLC.

PLC Digital outputs are capable to source a current of maximum 500 milliamperes. Two outputs that are going to be connected from the PLC to the conveyor belt motor's control unit will be interfaced with optocouplers associated to direction and enable signals, see figure 4.2.29. To activate an optocoupler, the requirements in terms of current are up to 10 milliamperes. Therefore, 2 digital outputs connected from the PLC to the optocouplers will require 20 milliamperes. The three outputs used to exchange data with the robot's controller will be interfaced with Phoenix

Contact PLC-RSC-24DV/21 interfacing relays. Selected interfacing relay solenoid requires a current of 10 milliamperes at 24 VDC. Therefore, 3 digital outputs connected from the PLC to the interfacing relays will require 30 milliamperes. Also, the current requirements for the unused digital outputs were considered as if they were to be connected through interfacing relays.

Even if the SB digital inputs are not used, required sink current of 7 milliamperes per input must be consider for further development. Therefore, a current of 14 milliamperes is required.

The SB digital outputs are capable to source a current of maximum 100 milliamperes. One output is going to be connected from the SB to conveyor belt motor's control unit and interfaced with the optocoupler associated to pulse signal, see figure 4.2.29. Also, the current requirements for the unused digital output were considered, as if they were to be connected through an interfacing relay. Therefore, a current of 30 milliamperes is needed by the unused SB digital output.

A total of 769 milliamperes is required to power the main control unit in order for it to be able to achieve its tasks, while allowing further development options. A coefficient of 1.25 is used for selecting the fuse rated current. Therefore, a normal blow fuse of 1.0 amperes (or following one greater than 1.0 amperes) will be used.

Figure 4.2.30, presents how the PLC, the PLC digital input group, the digital output group and the SB are supplied with electric energy. The positive output of VAC/DC power supply is connected through an external 1000 mA fuse (F1) to:

- PLC
    - L+ terminal,
    - digital outputs group 6L+ terminal,
- SB L+ terminal.

The negative output of VAC/DC power supply is connected to:

- PLC
    - M terminal,
    - digital inputs 1M terminal,
    - digital outputs 6M terminal,
- SB M terminal.

Figure 4.2.31, presents how the conveyor belt's proximity sensor is connected to the power supply and to two of the programmable logic controller's digital inputs. Since the sensor's internal circuitry needs a current of 30 milliamperes, it will be connected to the output from fuse F1. The positive output of VAC/DC's power supply is connected to the positive (+) sensor's supply terminal and the negative line is connected to negative (-) sensor's supply terminal.

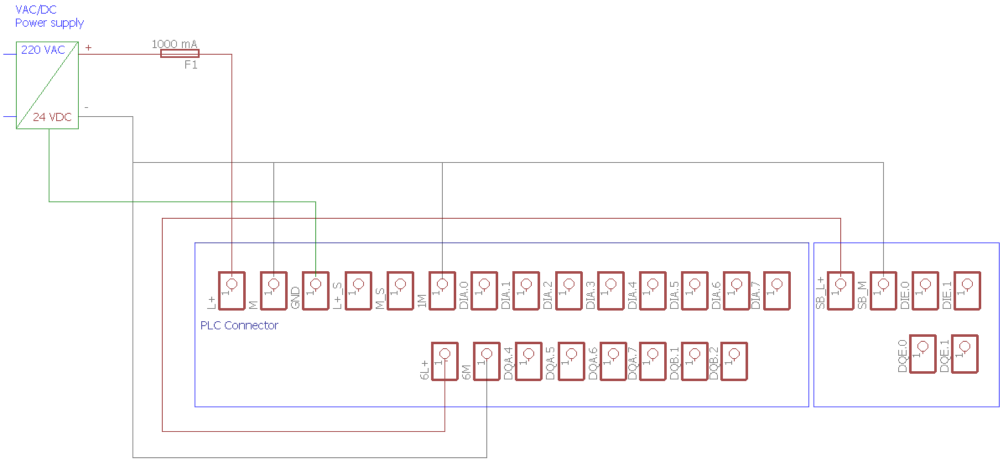


Fig. 4.2.30. Supplying with energy the PLC and SB

If an object is detected, the internal sensor circuitry switches the internal signal relay contacts. Since PLC inputs are rated for 24 VDC, the output from fuse F1 is connected on the signal relay's common (C) terminal. Relay terminal NC is connected to the PLC's digital input 0 and relay's terminal NO is connected to the PLC digital input 1. Both terminals will change their state when an object is detected and the relay coil is energized.

In order for the PLC's internal circuitry to detect the voltage levels received from the proximity sensor to its inputs, a common reference point between the PLC CPU and the PLC digital inputs group is required. This is the reason why the digital inputs common (1M) is connected to the negative output of VAC/DC.

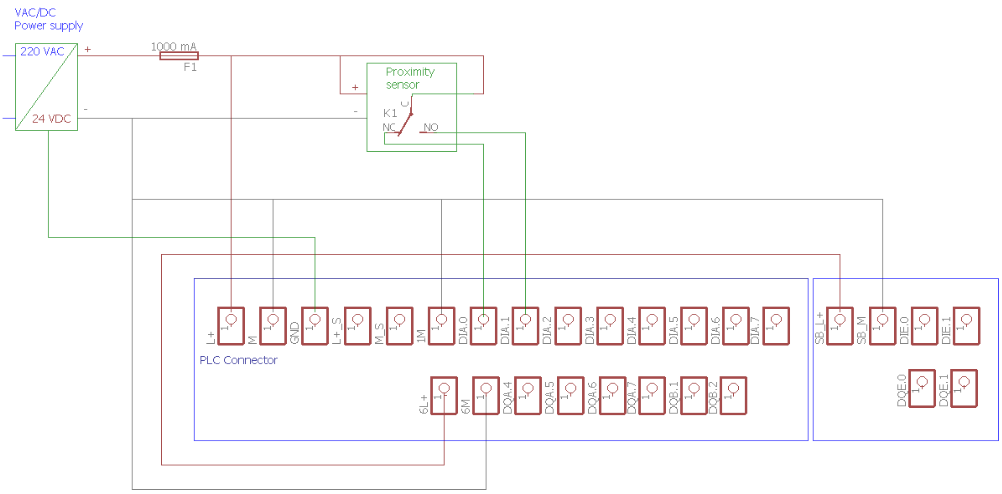


Fig. 4.2.31. Connecting conveyor proximity sensor to power supply and PLC

Selecting the electrical protection fuse's rating for the conveyor belt's control unit is based on the stepper motor's technical characteristics and the control unit's requirements. According to the stepper motor's technical datasheet, if connected as a unipolar motor, a current of 2.8 Amperes is required. Since surge currents might be experienced when energizing the motor's windings, a factor of 1.25 is used for selecting the fuse's rated current for the motor. The stepper motor's control unit technical data specifies that a current of 100 mA is required for the motor control unit's internal logic. Therefore, a slow blow fuse of 3.5 Amperes or first greeter than 3.5 Amperes will be used.

Supplying the conveyor belt motor's control unit with electrical energy is straightforward and presented in figure 4.2.32. The positive output of the VAC/DC power supply is connected through an external 3500 mA fuse (F2) to the main control unit +V terminal, while the negative output of the VAC/DC power supply is connected to the GND terminal.

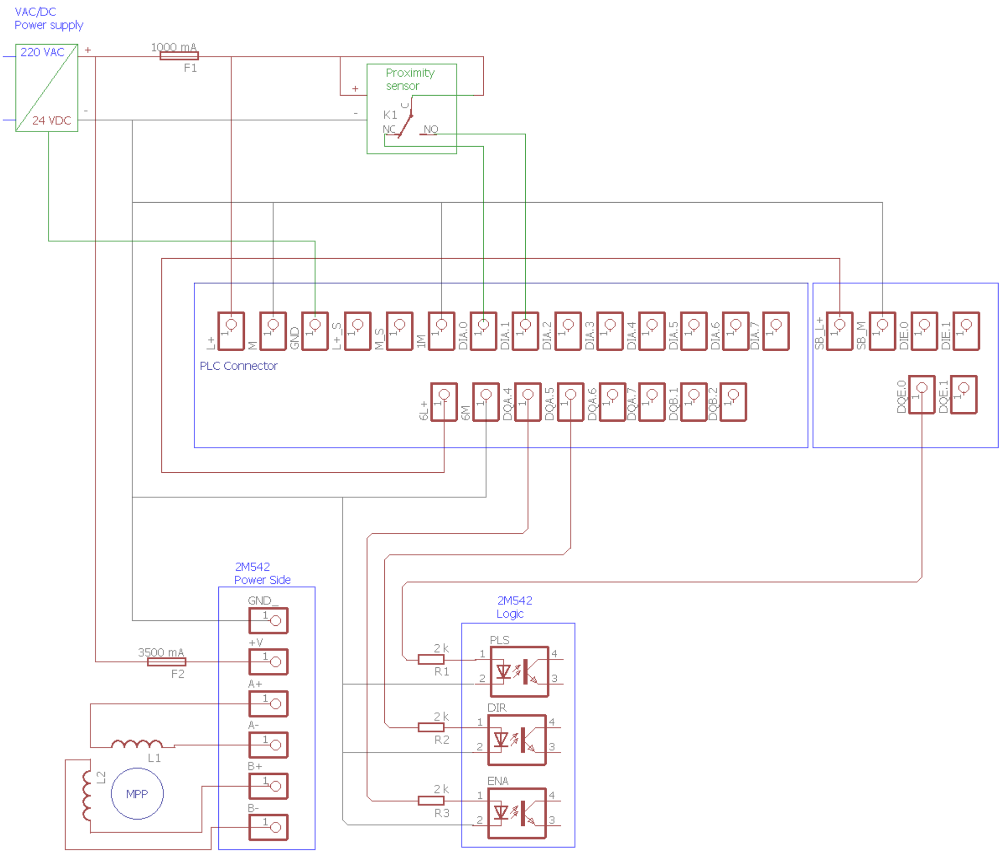


Fig. 4.2.32. Connecting conveyor belt main control unit to power supply and interfacing with PLC digital outputs

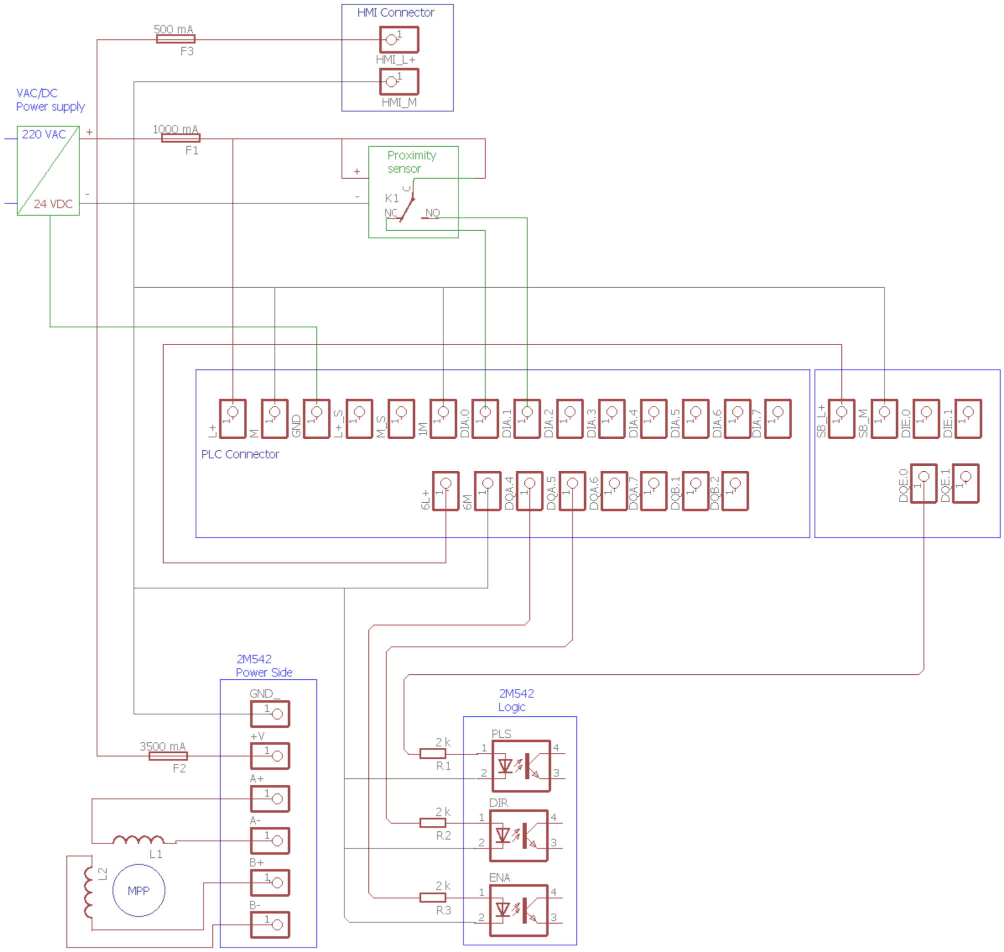


Fig. 4.2.33. Connecting HMI to power supply

According to the stepper motor's datasheet, connecting the stepper motor in a unipolar connection to the motor's control unit is done by wiring the red and black wires of the first winding to A+ and A- control unit's terminals and by wiring the white and green wires of the second winding to B+ and B- control unit's terminals.

Interfacing the motor's control unit with the main control unit is also presented in figure 4.2.32. The high speed digital output (DQE.0) available on the main control unit's signal board is wired to the PLS+ optocoupler on the motor control unit's side through a 2 kilo-ohms resistance. As already stated, this output is used to trigger step movements of the motor. Digital outputs DQA.4 and DQA.5 on PLC used to select the motor's movement direction and to enable or disable the motor's control unit are connected to DIR and ENA optocouplers through 2 kilo-ohms resistances.

Selecting the electrical protection fuse rating for human machine interface is based on technical characteristics of the HMI. According to KTP400 Basic Mono PN HMI an input current of 500 milliamperes is required to power up and run the HMI. Therefore, a normal blow fuse of 0.5 Amperes (or the following greater than 0.5 Amperes) will be used.

Supplying HMI with energy is presented in figure 4.2.33. The positive output of the VAC/DC's power supply is connected through an external 500 mA fuse (F3) to the main control unit's +V terminal, while the negative output of the VAC/DC power supply is connected to the GND terminal.

Commissioning

During commissioning, PLC hardware configuration must be checked and validated in TIA Portal, proximity sensor's functionality and electrical connections will be checked and their functionality validated. Also, the PLC digital inputs and outputs will be checked and their effect tested.

Before checking equipment functionalities, a new automation project named *Robotic_Cell* is created in TIA Portal, see figure 4.2.34. The following automation equipment which is used in the robotic cell is introduced in the hardware configuration of the project, see figure 4.2.35:

- S7-1217C (e.g. 6ES7 217-1AG40-0XB0) - main control unit
    - SB 1223 (e.g. 6ES7 223-3BD30-0XB0) - signal board
- KTP 400 Mono (e.g. 6AV6 647-0AA11-3AX0) – human machine interface

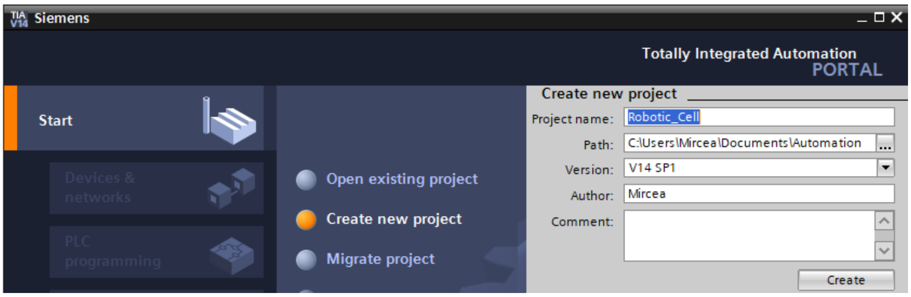


Fig. 4.2.34. Creating a new project in TIA Portal V14 SP1

The following basic configuration will be considered for the introduced PLC:

- Ethernet address: 192.168.50.100 and Subnet mask: 255.255.255.0
- Digital inputs start address: 0 and digital outputs start address: 0
- Start-up after Power on: Warm-restart – RUN
- Enable system memory byte at MB200 and clock memory byte at MB201.
- Time of day: UTC +2.0 Bucharest

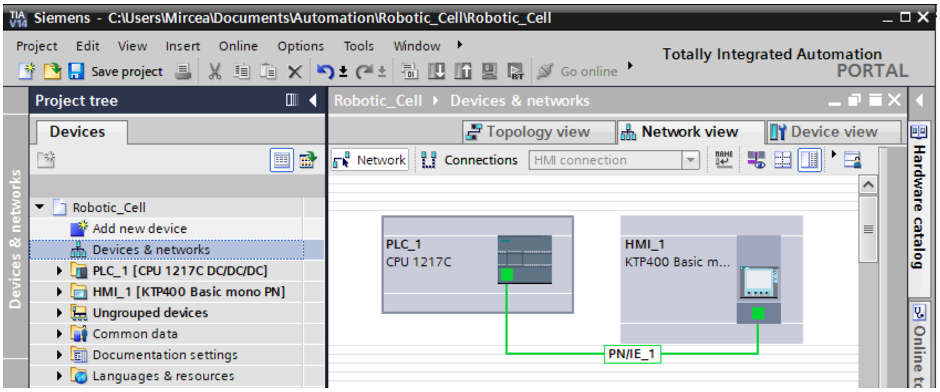


Fig. 4.2.35. Hardware configuration layout

The following basic configuration will be considered for the SB mounted on the introduced PLC:

- Digital inputs start address: 2 and digital outputs start address: 2

The following basic configuration will be considered for the introduced HMI:

- Ethernet address: 192.168.50.105 and Subnet mask: 255.255.255.0

According to table 4.2.1 and figure 4.2.33, the following tags must be defined for the PLC digital inputs and outputs (Fig. 4.2.36).

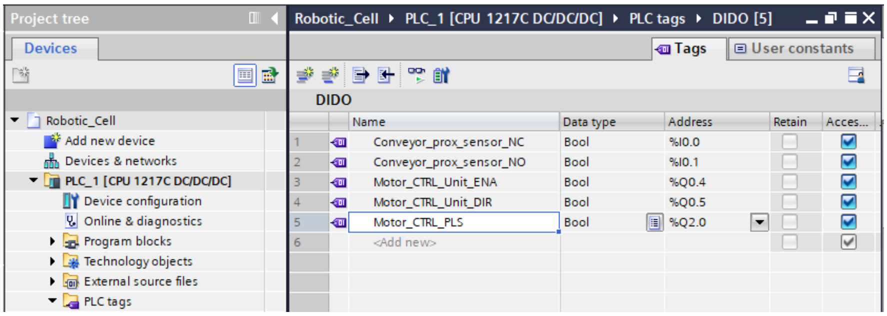


Fig. 4.2.36. PLC defined tags and their addresses

Further after, the hardware configuration of the PLC is compiled and downloaded to the PLC, see figure 4.2.37 and 4.2.38. The same procedure is followed for software developments.

Checking the conveyor belt's proximity sensor, monitoring mode for the created tags will be activated after hardware and software configurations are compiled and downloaded to the PLC, see figure 4.2.39.

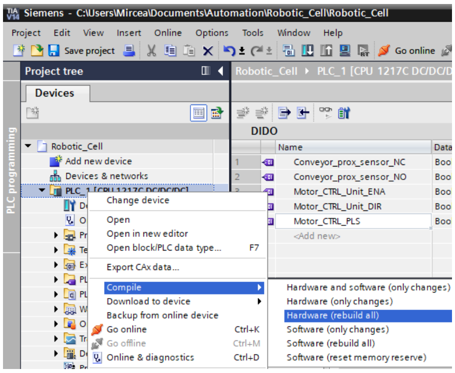


Fig. 4.2.37. Compiling hardware configuration

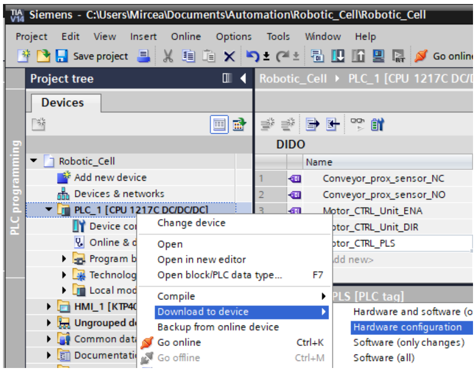


Fig. 4.2.38. Downloading hardware configuration

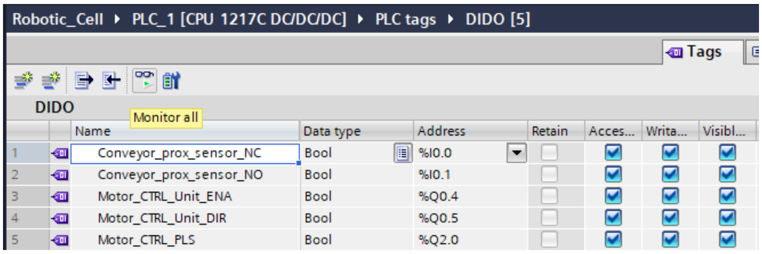


Fig. 4.2.39. Enabling monitoring mode for created tags

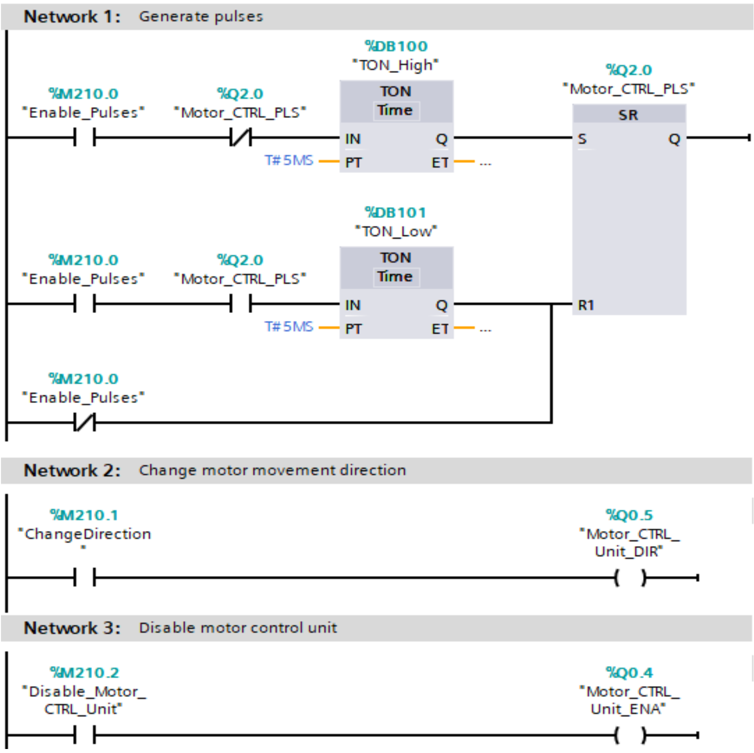


Fig. 4.2.40. Control logic to check motor control functionalities

If the proximity sensor was wired accordingly to figure 4.2.31 and its related instructions, digital inputs %I0.0 and %I0.1 must have the following values when a part is or is not detected:

- Part not detected: %I0.0 – True and %I0.1 – False,
- Part detected: %I0.0 – False and %I0.1 – True.

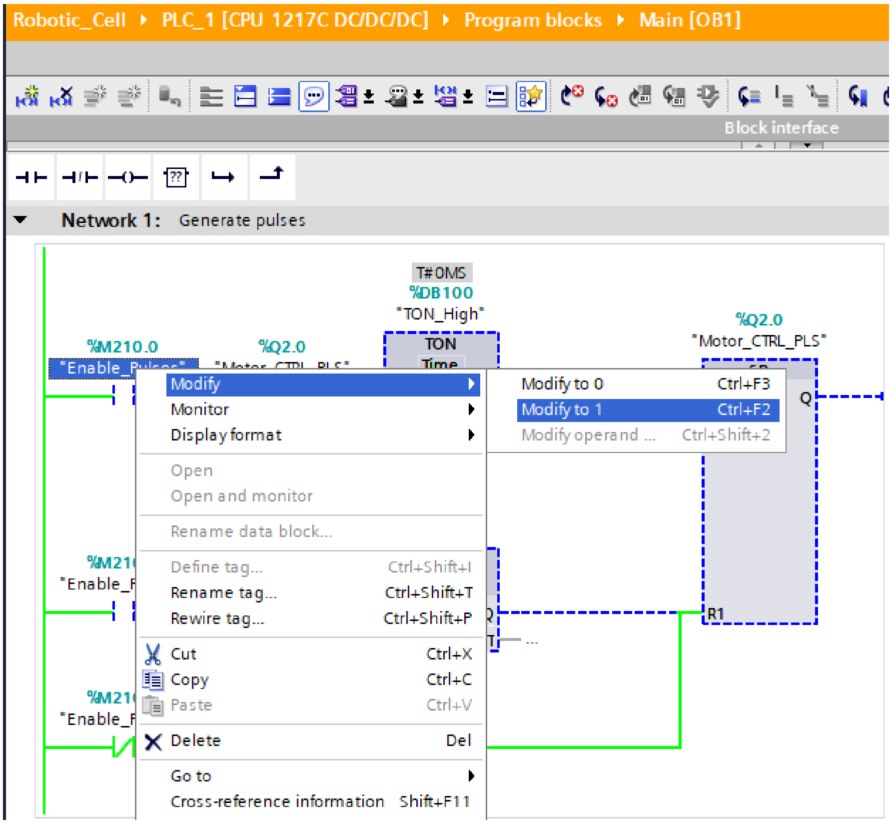


Fig. 4.2.41. Trigger 100 Hz pulses

A simple ladder logic is developed in the main program (e.g. OB1) block of the PLC to check the conveyor belt's motor control, see figure 4.2.40. Developed logic considers the M210.0 memory zone to enable or disable the high frequency toggling. If memory zone M210.0 is active, pulses having a frequency of 100 Hz are generated on the digital output Q2.0, which is connected to the motor control unit's PLS input.

In network 2 and 3 of developed control logic, presented in figure 4.2.40, there are two memory zones, M210.1 and M210.2, used to modify the state of digital outputs which will change the motor's movement direction or disable the motor's control unit.

Before testing the developed control logic, it needs to be compiled and loaded to the PLC memory. Connecting to the PLC, there is the possibility to change the memory zones to trigger specific testing functionalities (Fig. 4.2.41).

By changing the M210.0's memory zone to 1 (aka Logic 1 or High) the PLC's control logic will trigger pulses on digital output Q2.0. If the motor's control unit is not disabled, the motor will rotate. If the memory zone is switched back to 0 (aka Logic 0 or Low) the PLC's control logic will stop triggering pulses on the digital output Q2.0.

Changing the motor's rotating direction is done by modifying M210.1 memory zone to 1. Disabling the motor's control is done by modifying M210.2 memory zone to 1.

Interfacing system 1 and 2

Triggering specific actions from the robot's controller to the PLC and vice-versa is done using three digital outputs and three digital inputs from the robot controller's DSQC 652 IO unit, which are interfaced with the PLC using relays (e.g. RO1, RO2, RO3, RI1, RI2, RI3).
Figure 4.2.42 presents how relays RO1, RO2 and RO3 coils are connected to the robot controller's IO unit digital outputs 9, 10, 11 on connector X2 and how relays RO1, RO2 and RO3 contacts are connected to the PLC's digital inputs I0.2, I0.3 and I0.4.

The operating principle is very simple, when digital output 9 of the robot controller 's IO unit is activated, RO1 coil is energized and its contact closes. Then, a 24 VDC voltage is connected to the PLC's digital input I0.2. The PLC detects a signal change and triggers the action developed and associated in the control logic.

In the same figure, it is presented how relays RO6, RO7 and RO10 coils are connected to the PLC's digital outputs DQ0.6, DQ0.7, DQ1.0 and how relays RO6, RO7 and RO10 contacts are connected to the robot controller's IO unit digital inputs 6, 7 and 8 on connector X3. The operating principle is very simple, when digital output 6 of PLC is activated, the RO6 coil is energized and its contact closes. Then, a 24 VDC voltage is connected to the robot controller's DSQC 652 IO digital input 6. The robot's job will detect a signal change and trigger the action developed in the robot job's control logic.

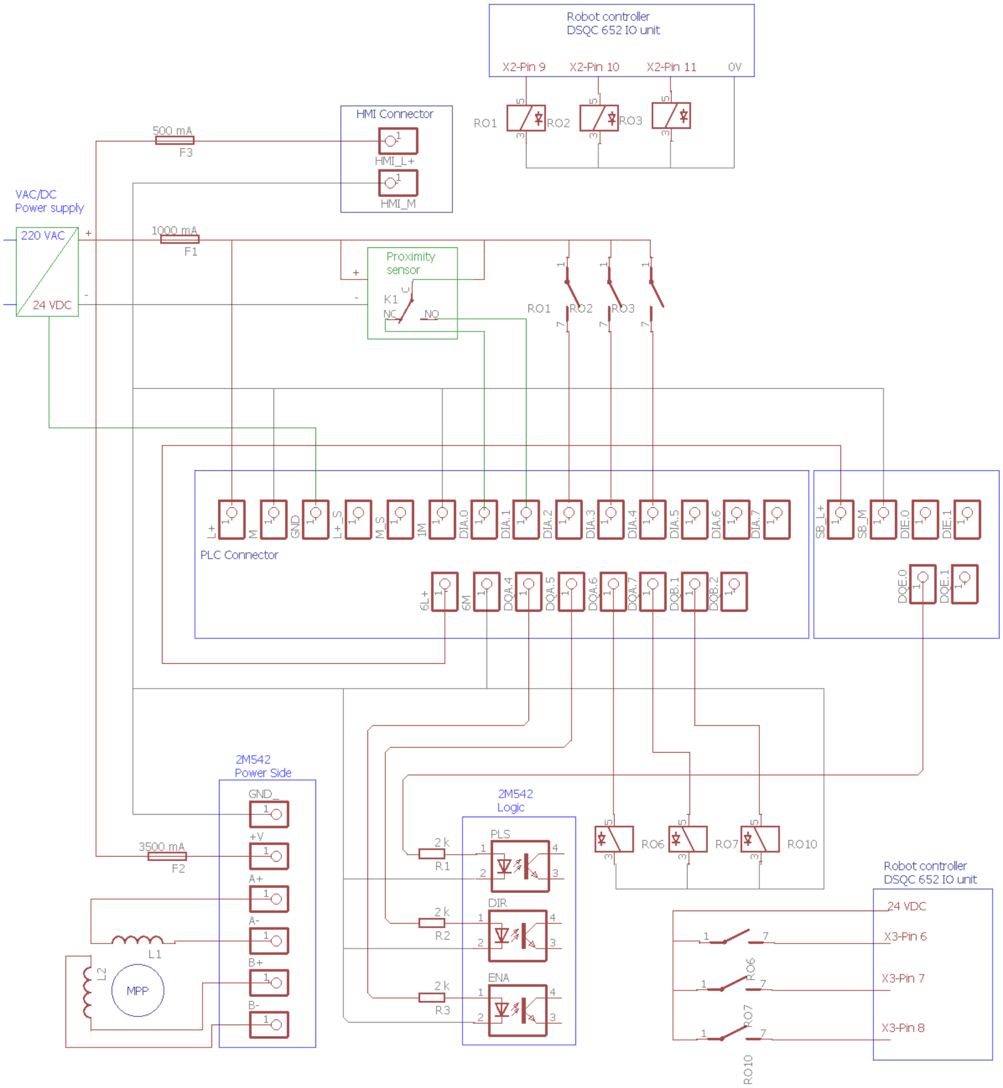
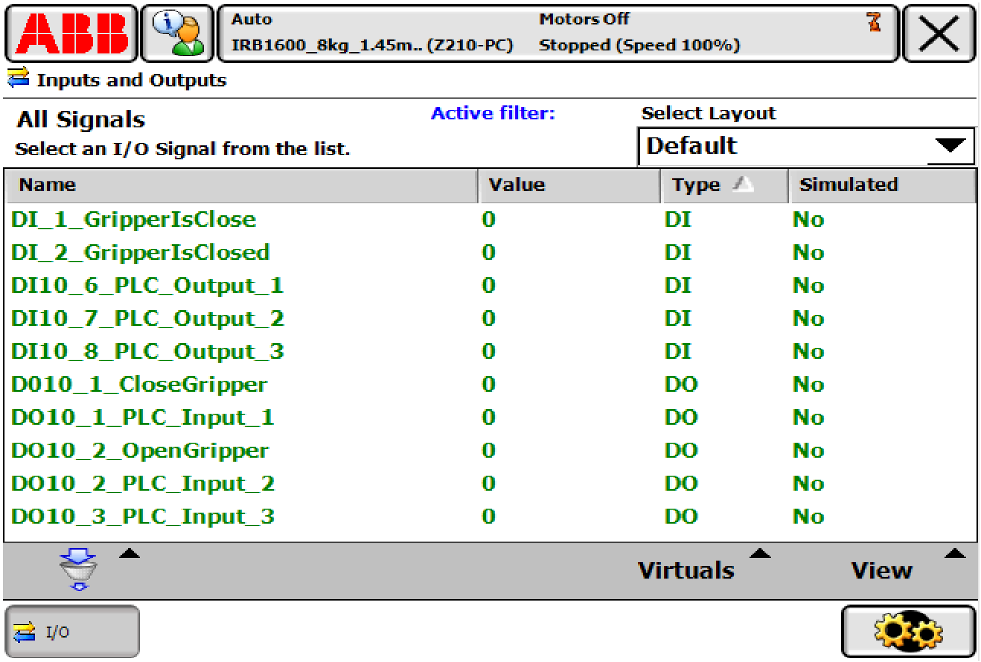


Fig. 4.2.42. Interconnecting system 1 and system 2

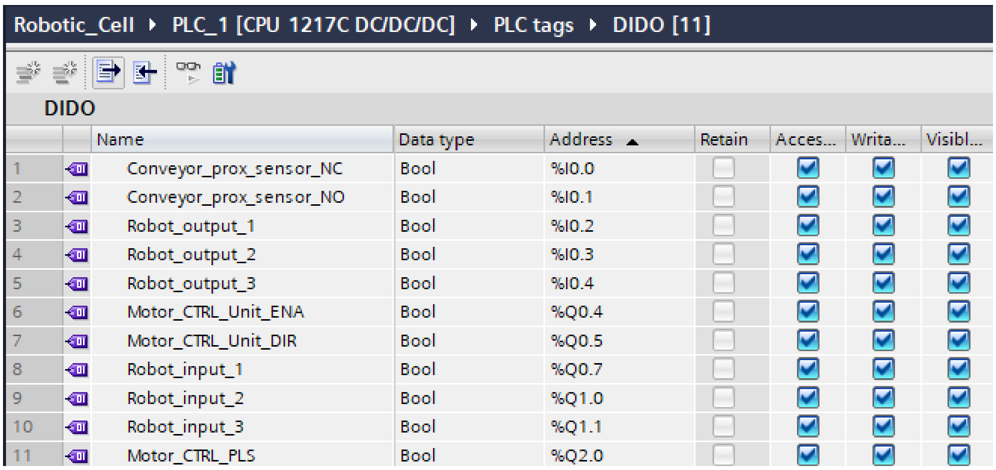
Updating signals

After interfacing both systems, according to the electrical wirings, the exchanged signals must be defined on the robot's controller and on the main control unit, see figure 4.2.43 for the robot's controller and figure 4.2.44 for the main control unit.



Name	Value	Type	Simulated
DI_1_GripperIsClose	0	DI	No
DI_2_GripperIsClosed	0	DI	No
DI10_6_PLC_Output_1	0	DI	No
DI10_7_PLC_Output_2	0	DI	No
DI10_8_PLC_Output_3	0	DI	No
D010_1_CloseGripper	0	DO	No
DO10_1_PLC_Input_1	0	DO	No
DO10_2_OpenGripper	0	DO	No
DO10_2_PLC_Input_2	0	DO	No
DO10_3_PLC_Input_3	0	DO	No

Fig. 4.2.43. Updated list of IOs for robot controller



	Name	Data type	Address	Retain	Acces...	Writa...	Visibl...
1	Conveyor_prox_sensor_NC	Bool	%I0.0	☐	☑	☑	☑
2	Conveyor_prox_sensor_NO	Bool	%I0.1	☐	☑	☑	☑
3	Robot_output_1	Bool	%I0.2	☐	☑	☑	☑
4	Robot_output_2	Bool	%I0.3	☐	☑	☑	☑
5	Robot_output_3	Bool	%I0.4	☐	☑	☑	☑
6	Motor_CTRL_Unit_ENA	Bool	%Q0.4	☐	☑	☑	☑
7	Motor_CTRL_Unit_DIR	Bool	%Q0.5	☐	☑	☑	☑
8	Robot_input_1	Bool	%Q0.7	☐	☑	☑	☑
9	Robot_input_2	Bool	%Q1.0	☐	☑	☑	☑
10	Robot_input_3	Bool	%Q1.1	☐	☑	☑	☑
11	Motor_CTRL_PLS	Bool	%Q2.0	☐	☑	☑	☑

Fig. 4.2.44. Updated list of IOs for main control unit

Commissioning

Subsystem's 1 and 2 commissioning is required to check if exchanged signals between the main control unit and the robot's controller are received correctly:

- If PLC digital output Robot_input_1 (%Q1.0) is enabled, the robot controller's digital input DI10_6_PLC_Output_1 will be activated.
- If PLC digital output Robot_input_2 (%Q1.1) is enabled, the robot controller's digital input DI10_7_PLC_Output_2 will be activated.

- If PLC digital output Robot_input_3 (%Q1.2) is enabled, the robot controller's digital input DI10_8_PLC_Output_3 will be activated.
- If robot controller digital output DO10_1_PLC_Input_1 is enabled, the PLC digital input Robot_output_1 (%I0.2) will be activated.
- If robot controller digital output DO10_2_PLC_Input_2 is enabled, the PLC digital input Robot_output_2 (%I0.3) will be activated.
- If robot controller digital output DO10_3_PLC_Input_3 is enabled, the PLC digital input Robot_output_3 (%I0.4) will be activated.

Control logic development

Since in commissioning phases, the manufacturing equipment is briefly tested and its functionalities validated, the control logic to achieve application goals needs to be developed.

A simplistic approach of the control logic, in order to keep the developed program easy to present and follow, will be implemented in the following subchapters, for the main control unit and the robot's controller.

Main control unit

First step towards the control logic's development consists in generating pulses with high frequency for the stepper motor's control unit. Therefore, one of the main control unit's pulse generators needs to be enabled and configured to trigger pulses on Motor_CTRL_PLS (e.g. Q2.0) digital output.

To achieve this, PLC hardware configuration needs to be adjusted. Still, the maximum number of pulses per second that can be received by the motor must not be exceeded (Fig. 4.2.27). Enabling and configuring pulse generator functionality for a main control unit to be able to trigger pulses at a frequency of 5kHz (e.g. 200 µsec) and a pulse duration of 50% is detailed in figure 4.2.45.

By default, process image of inputs and outputs is read and written to physical inputs and outputs every PLC cycle. Usually, the application's software has PLC cycles greater than 5 milliseconds. Such a PLC cycle is greater than the required pulse frequency for controlling the motor's control unit and for achieving a moderate conveyor belt's speed. This signifies that the outputs will be updated with a time frequency of 5 milliseconds at best.

To allow the configured pulse generator functionality to trigger pulses on Motor_CTRL_PLS's (e.g. Q2.0) digital output at a frequency of 5Khz, the updating of physical outputs on the PLC's cycle must be disabled, see *Output addresses* section in figure 4.2.45, and enable a hardware asynchronous functionality for pulse generating.

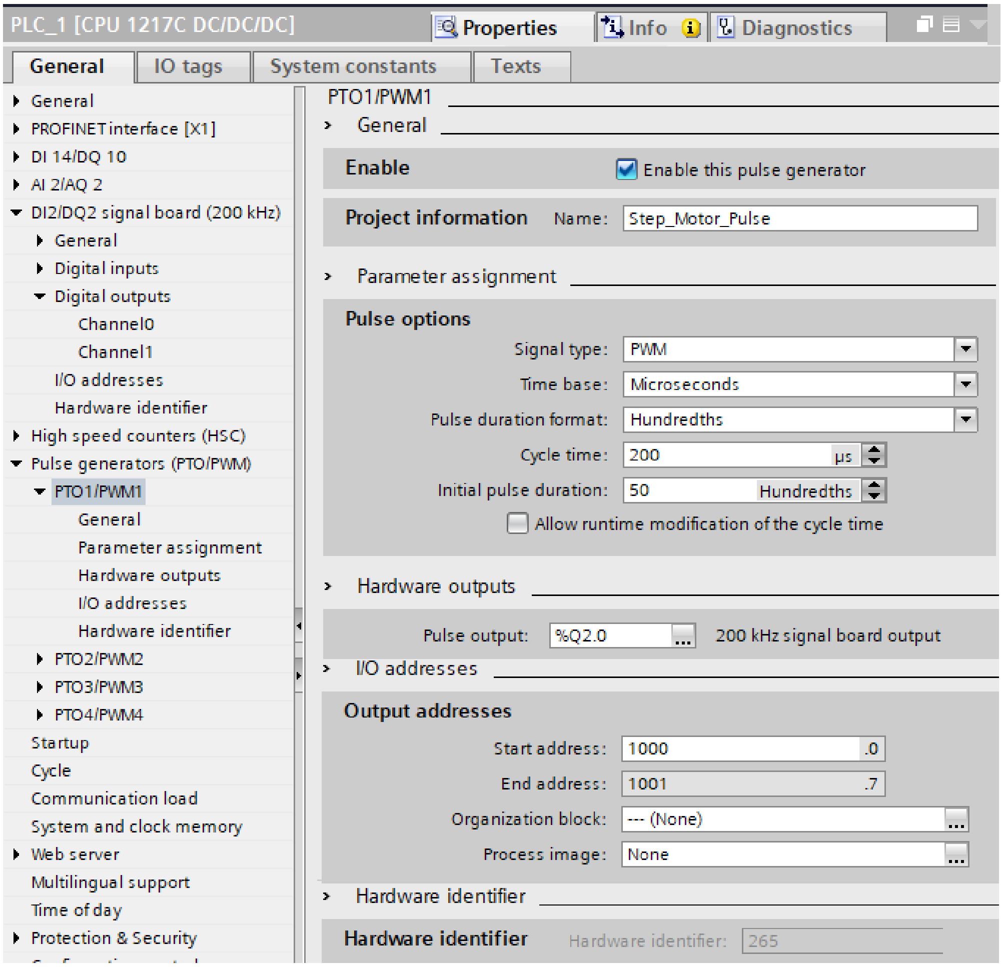


Fig. 4.2.45. Enable and configure main control unit pulse generator 1

Since high frequency output Q2.0 will be controlled by the configured pulse generator, the usage of %Q2.0 in the application program will be avoided and the defined tag (e.g. Motor_CTRL_PLS) needs to be deleted from the tag table where it was defined, see figure 4.2.39.

First network of the developed control logic for testing, see figure 4.2.40, will be modified in accordance with figure 4.2.46. Controlling the pulse generator's functionality is done by parametrizing and using the CTRL_PWM programming instruction. The configured pulse generator will be linked to the PWM input of the CTRL_PWM. The Enable input of CTRL_PWM is activated if the following conditions are active:

- Start signal received from HMI,
- Enable pulses memory zone is Logic 1.

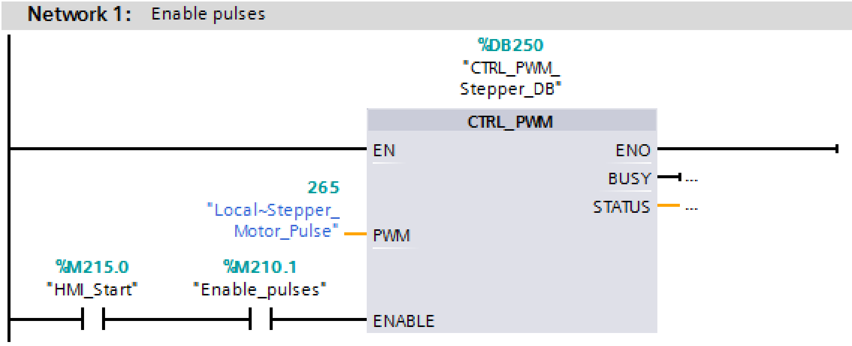


Fig. 4.2.46. Parametrizing and using CTRL_PWM instruction to generate pulses

Enable the pulses' memory zone (e.g. M210.1) is set to Logic 1 if

- Start signal received from HMI,
- Robot output 1 is ON, Robot output 2 is OFF and Robot output 3 is OFF – activated by the robot's controller to signalize that part was placed on the conveyor belt and the robot is in home position.
- Part is not detected by the conveyor belt's sensor.

Enable pulses' memory zone (e.g. M210.1) is reset to Logic 0 if

- Part is detected by the conveyor belt's sensor.

Figure 4.2.47 presents the control logic that is intended to set or reset the memory zone M210.1, which enables pulse generation. The three robot outputs are multiplexed signals able to signalize seven specific robot states. In the same manner, the main control unit will use three outputs to signalize its state to the robot's controller.

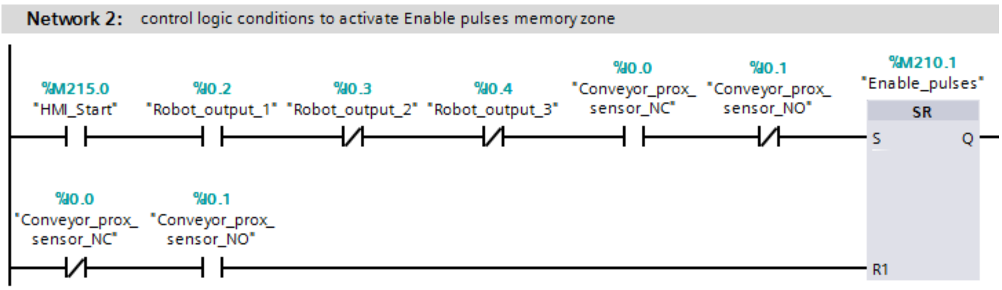


Fig. 4.2.47. Enable pulses memory zone to set/reset

According to the graphical representation of the process's stages, presented in figure 4.3.3, a start signal from HMI will trigger the robot's job. Therefore, a new network will be defined to activate one of the robot's digital inputs, see figure 4.2.48. Activated input must be processed in the robot's job accordingly.

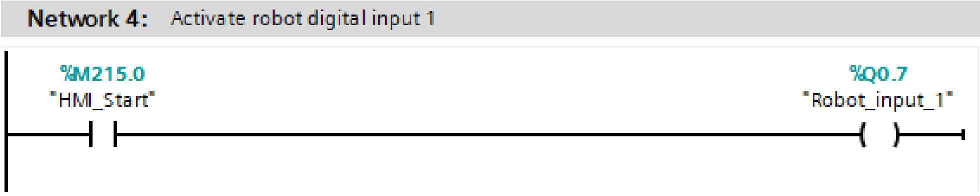


Fig. 4.2.48. Activating robot digital input 1 to start robot job.

To make the robot manipulate the next part, the control logic developed in the PLC detects when *Enable_pulses (%M210.1)* memory zone is reset by using a negative edge detection instruction. The output of negative edge instruction is available only for one PLC cycle, therefore, a timer off programming instruction to generate a 500 milliseconds pulse on the second robot input is used, see figure 4.2.49.

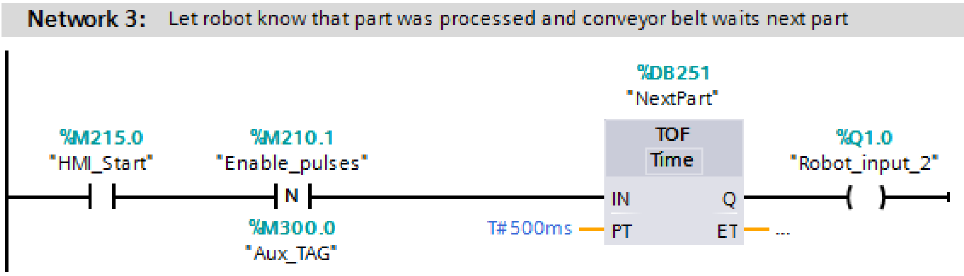


Figure 4.2.49. Activating robot digital input 2 after conveyor belt is stopped by resetting the memory zone which enables pulses generation

After robot job is finished the robot activates all the digital outputs connected to the main control unit to signalize the end of process. This state will reset the HMI Start (%M215.0) command, see figure 4.2.50. HMI Start command will also be resettable from a HMI button.

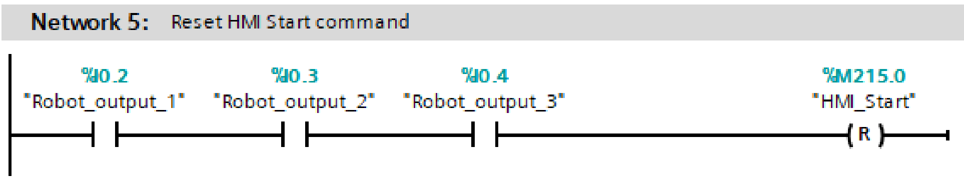


Fig. 4.2.50. Reset start command received from HMI when robot job is finished

Human Machine Interface

In this subchapter, a Human Machine Interface (aka HMI) having two buttons to start or stop the process is about to be developed. Since the HMI was already introduced and configured in the configuration of automation devices in TIA Portal, defining a new page is the next step.

Using the project explorer, the HMI section and, further after, the *Screens* expended section and the option to add a new screen *Add new screen* will be used, see figure

4.2.51. TIA Portal will automatically open the newly created screen in the active window.

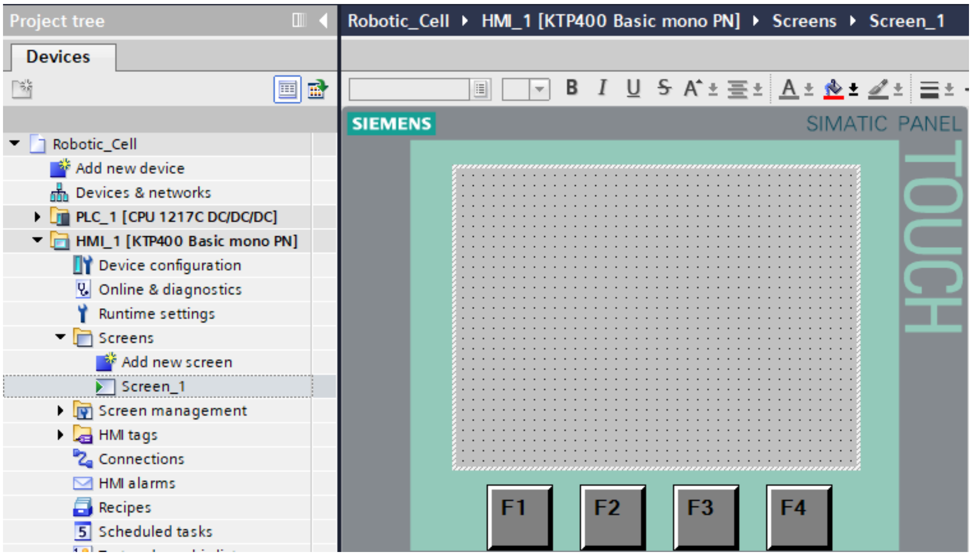


Fig. 4.2.51. Add new screen result

The TIA Portal updates the options available in the toolbox in accordance to which functionalities are opened in the active window. Two virtual buttons from the elements category of the toolbox will be added by drag and drop to the created page, and their appearance cam be personalized from the properties section as in figure 4.2.52.

To obtain an effect on the PLC application software, the two added buttons need to be associated with specific events that can trigger specific functionalities to the PLC's memory zones, when the button is pressed or clicked.

As developed in the PLC application program, see figure 4.2.48, the PLC waits for a HMI command to modify the memory zone *HMI_Start* (e.g. %M215.0) to logic 1 to activate the robot controller's digital input which starts the robot's job.

Therefore, by using the properties of the two buttons, a set and reset action will be added and configured to modify the *HMI_Start* memory zone when a press or click event takes place, see figure 4.2.53, for START button, and figure 4.2.54, for STOP button.

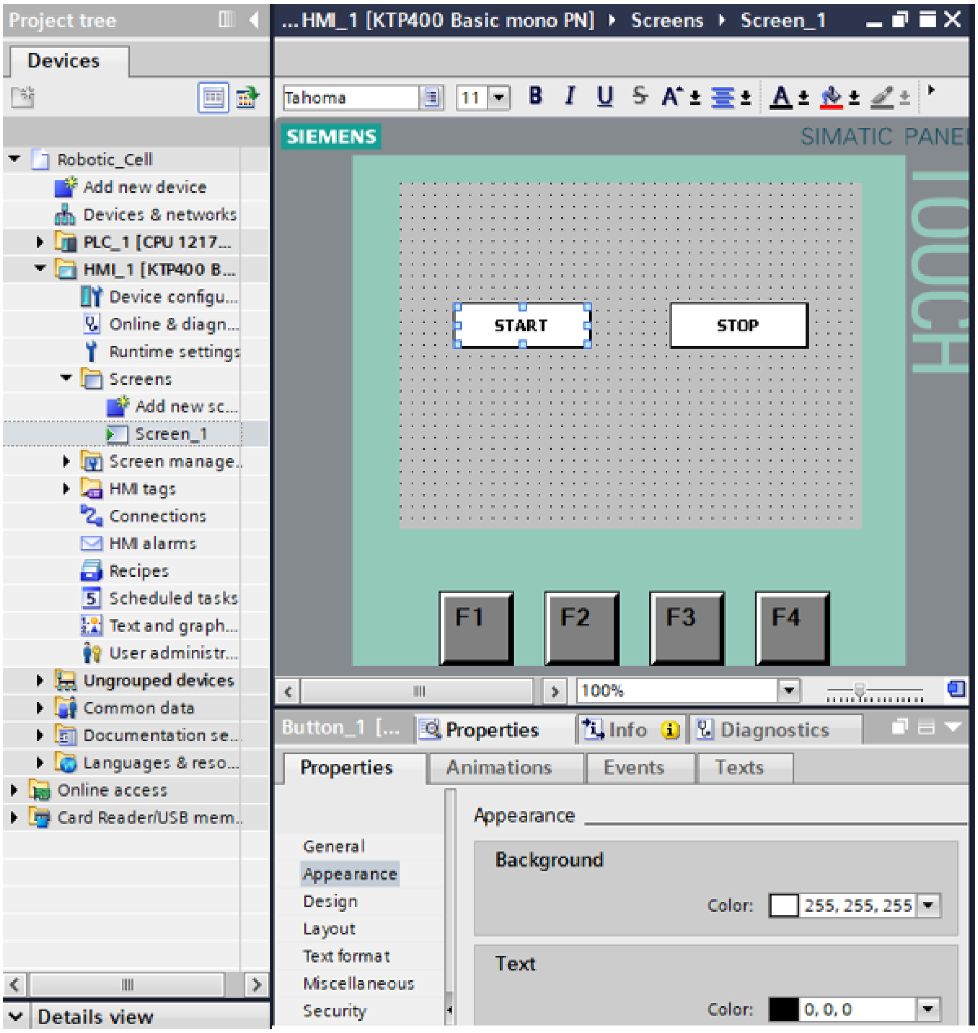


Fig. 4.2.52. Newly developed screen with start and stop buttons

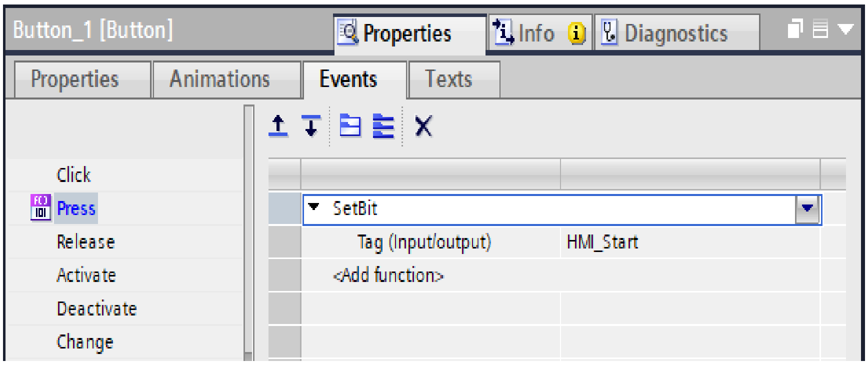


Fig. 4.2.53. Adding a *SetBit* function when a press event on START is identified

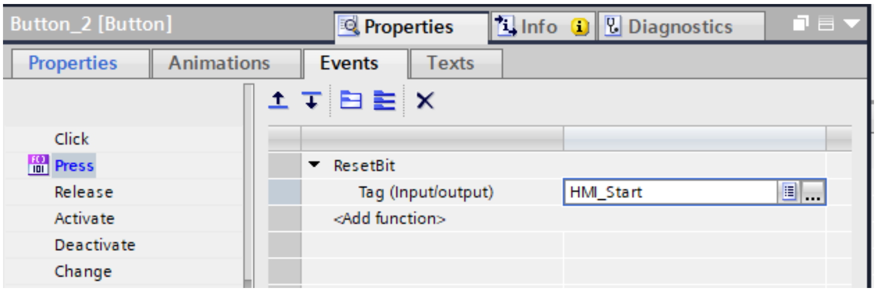


Fig. 4.2.54. Adding a *ResetBit* function when a press event on STOP is identified

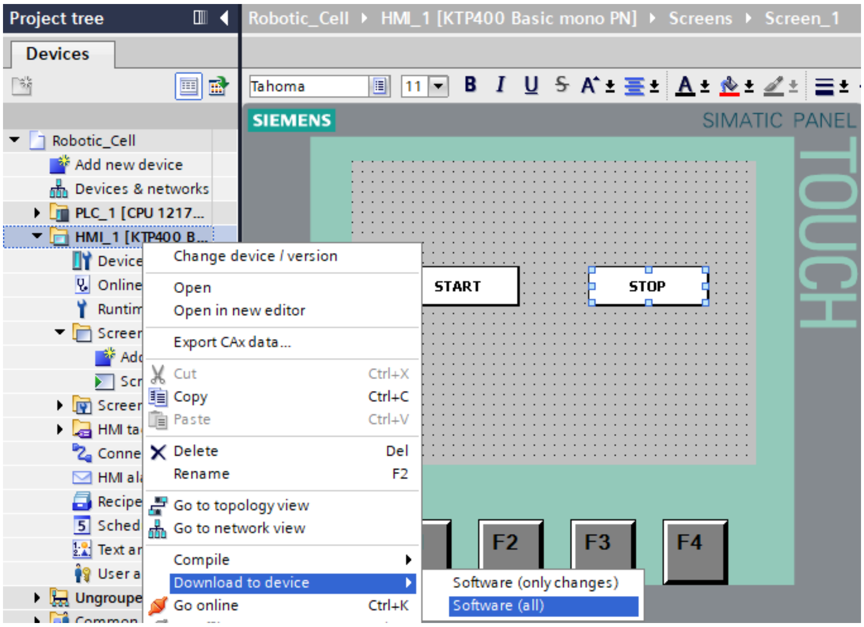


Fig. 4.2.55. Downloading application software to HMI

Further after, the developed application program for the HMI is compiled and downloaded to the HMI, see figure 4.2.55.

Robot controller unit

As presented in figure 4.2.56, the robot controller's application program lines 1 to 6 contain robot targets defined for the home position, a position above the first part from the 2x4 matrix type storage organizer, a pick position for the first part, a position above conveyor belt and a drop position on conveyor belt. All this robot targets are defined as constants.

The last two robot targets: *uAboveDropPosition* and *uDropPosition* will always be the same since the robot will place the part on the same position on the conveyor belt.

```
1  MODULE MainModule
2      CONST robtarget uHomePosition:=[[806.29,0.00,1154.00],[0.5,0,0.866025,0],[0,0,0,0],[9E
3      CONST robtarget uAbovePickPosition:=[[913.87,-122.14,925.07],[0.00216192,-0.066383,-0.
4      CONST robtarget uPickPosition:=[[913.87,-122.14,821.43],[0.00216184,-0.066383,-0.99779
5      CONST robtarget uAboveDropPosition:=[[772.33,375.18,907.07],[0.00675256,-0.635939,0.77
6      CONST robtarget uDropPosition:=[[772.33,375.18,805.89],[0.00675256,-0.635939,0.771708,
7
8      VAR robtarget uDynamicAbovePickPosition;
9      VAR robtarget uDynamicPickPosition;
10
11     VAR num xDistanceBetweenParts:=100;
12     VAR num yDistanceBetweenParts:=200;
13     VAR num collumns:=0;
14     VAR num rows:=0;
15
```

Fig. 4.2.56. Robot job application program snippet 1

Program lines 8 and 9 contain two robot targets defined as variables: *uDynamicAbovePickPosition* and *uDynamicPickPosition*. Considering the matrix type storage's number of lines and columns, distance between parts on the same column (line 11) and distance between lines (line 12) the application program will dynamically build a variable robot target able to come over the storage and survey the positions of the parts and pick position for every part in the matrix type storage considering the position of the first part memorized in robot targets: *uAbovePickPosition* and *uPickPosition*.

Variables defined on program lines 13 and 14 are used by the application program in the iterative programming instruction to cycle through every column of every line in the matrix type storage.

Distances between parts on the same column and distances between matrix type organizer rows are considered as shown in figure 4.2.57.

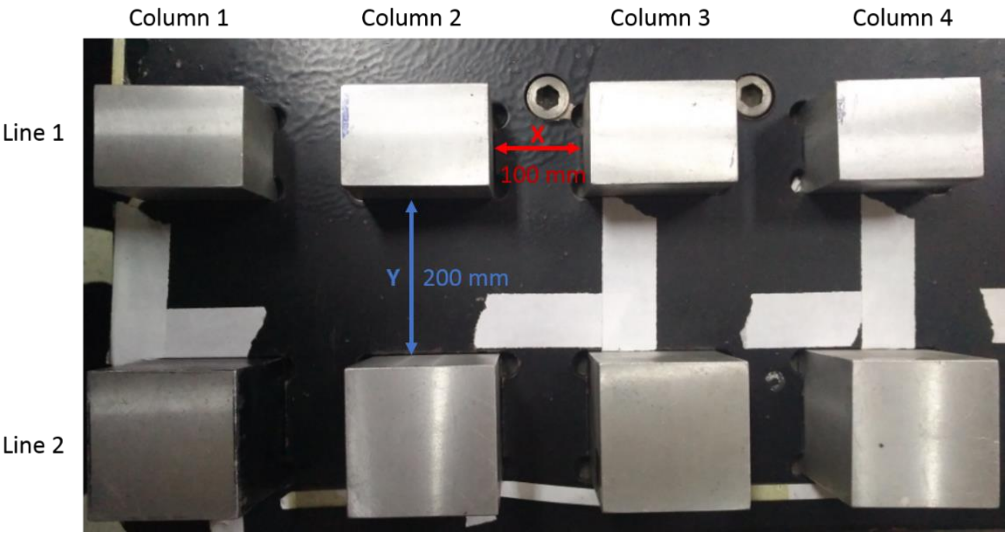


Fig. 4.2.57. Distance between parts on the same and different lines

```
16  PROC main()
17      MoveJ uHomePosition,v1000,z50,tool0;
18      openGripper;
19
20      FOR rows FROM 1 TO 2 DO
21          FOR columns FROM 1 TO 4 DO
22              IF checkPlcCmd() THEN
23
24                  uDynamicAbovePickPosition:=uAbovePickPosition;
25                  uDynamicAbovePickPosition.trans.x:=
26                      uDynamicAbovePickPosition.trans.x+(rows-1)*xDistanceBetweenParts;
27                  uDynamicAbovePickPosition.trans.y:=
28                      uDynamicAbovePickPosition.trans.y+(columns-1)*yDistanceBetweenParts;
29
30                  uDynamicPickPosition:=uPickPosition;
31                  uDynamicPickPosition.trans.x:=
32                      uDynamicPickPosition.trans.x+(rows-1)*xDistanceBetweenParts;
33                  uDynamicPickPosition.trans.y:=
34                      uDynamicPickPosition.trans.y+(columns-1)*yDistanceBetweenParts;
35
36                  MoveJ uDynamicAbovePickPosition,v1000,z50,tool0;
37                  MoveL uDynamicPickPosition,v100,fine,tool0;
38                  closeGripper;
39                  MoveL uDynamicAbovePickPosition,v1000,z50,tool0;
40
41                  MoveJ uAboveDropPosition,v1000,z50,tool0;
42                  MoveL uDropPosition,v100,fine,tool0;
43                  openGripper;
44                  MoveL uAboveDropPosition,v100,fine,tool0;
45                  MoveJ uHomePosition,v1000,z50,tool0;
46
47                  PulseDO\High,\PLength:=0.5,DO10_1_PLC_Input_1;
48                  WaitDI DI10_7_PLC_Output_2,high;
49              ENDIF
50          ENDFOR
51      ENDFOR
52      IF checkPlcCmd() THEN
53          SetDO DO10_1_PLC_Input_1, high;
54          SetDO DO10_2_PLC_Input_2, high;
55          SetDO DO10_3_PLC_Input_3, high;
56      ELSEIF checkPlcCmd() = FALSE THEN
57          SetDO DO10_1_PLC_Input_1, low;
58          SetDO DO10_2_PLC_Input_2, low;
59          SetDO DO10_3_PLC_Input_3, low;
60      ELSE
61      ENDIF
62  ENDPROC
```

Fig. 4.2.58. Robot job application program snippet 2

The main robot's job application procedure is presented in figure 4.2.58. First instruction is intended to bring the robot into the position defined as the home position (line 17). Before moving towards matrix type organizer, we will ensure that the gripper is open. Opening the gripper is done using the *openGripper* procedure (line 18). This procedure is detailed later in this subchapter.

Two iterative and imbricated FOR programming instructions (line 20 and 21) are used to cycle through every position of the matrix type storage organizer, if a start job command from the PLC was received. Checking for the start command is done by calling within an IF instruction the function *checkPlcCmd* (line 21). This function returns true if the start command was received or false if not. The start command is multiplexed by means of digital inputs activated by the PLC. This procedure is detailed later in this subchapter.

The first FOR instruction is to select the line and the second is used to cycle through all columns of the selected line. The actual control values of the FOR instructions, *rows* and *columns*' variables, provide information on which line and column the part that is going to be manipulated by the robot can be found. The limits up to which *rows* and *columns* are increased depends on the number of lines and columns of parts organizer, see figure 4.2.58.

Knowing the distance between parts and the part that is going to be manipulated, given by the value of *rows* and *columns* variables, the robot's application programs dynamically builds the above position and the pick position for the specific part.

First the robot position *uAbovePickPosition* is copied to *uDynamicAbovePickPosition* (line 24). Second, the offset on X and Y axes for the specific part is added (lines 25 to 28). The same approach is used to build the robot's pick position: *uDynamicPickPosition* (lines 30 to 34).

After positions are build, the application program moves the robot to the position above the part that is going to be picked (line 36). Afterwards, using a liner motion instruction, with a reduced speed and fly-by, the robot is positioned to the pick position (line 37).

The gripper is closed by calling *closeGripper* procedure after the robot reached the picking position (line 38). This procedure is detailed later in this subchapter. Further after, the robot is moved back to the position above picking point (line 39).

At this point, the part is picked and lifted by the robot above its position. The robot job moves the robot above the drop position (line 41). Afterwards, using a liner motion instruction with a reduced speed and fly-by, the robot is positioned to the drop position (line 42) on the conveyor belt and the gripper is opened by calling *openGripper* procedure (line 43).

After the gripper is opened, the robot moves back to the position above dropping point (line 44) and further after to the home position (line 45). If the robot reached home position the robot's job generates a pulse of 500 milliseconds on the digital output *DO10_7_PLC_Input_1,* connected to PLC (line 47).

On top of other process conditions, when this signal is received by the PLC, the conveyor belt will start, see figures 4.2.47 and 4.2.46. After generating the 500 milliseconds signal to the PLC, the robot waits a signal from the PLC on digital inputs *DI10_7_PLC_Output_2* to continue its job (line 48). The PLC will generate a 500 milliseconds pulse to the robot's input after part is detected and conveyor stops, see figure 4.2.48.

After robot controller receives the signal, it moves forward to the next position, built by the incrementing values of *rows* and *columns'* control variables of FOR instructions. This procedure repeats for all parts.

After *rows* and *columns* control variables of FOR instructions reached their limits, the FOR instructions are terminated. After parts manipulating procedure ends the robot job checks by calling *checkPlcCmd* function if a start command was received. If start command was received and all parts were manipulated, the robot's controller activates digital outputs: *DO10_1_PLC_Inputs_1*, *DO10_2_PLC_Inputs_2* and *DO10_3_PLC_Inputs_3* to signalize the end of the program to the PLC (lines 52 to 55). When these signal pattern are received by the PLC, the start command received from HMI is reset, see figure 4.2.50.

```
    FUNC bool checkPlcCmd()
        IF DI10_6_PLC_Output_1 = high AND
           DI10_7_PLC_Output_2 = low AND
           DI10_8_PLC_Output_3 = low THEN
            RETURN TRUE;
        ENDIF
        RETURN FALSE;
    ENDFUNC

    PROC openGripper()
        WaitTime 1;
        SetDO DO10_1_CloseGripper,low;
        SetDO DO10_2_OpenGripper,high;
        WaitTime 1;
        WaitDI DI_1_GripperIsClose,high;
    ENDPROC

    PROC closeGripper()
        WaitTime 1;
        SetDO DO10_2_OpenGripper,low;
        SetDO DO10_1_CloseGripper,high;
        WaitTime 1;
        WaitDI DI_2_GripperIsClosed,high;
    ENDPROC
ENDMODULE
```

Fig. 4.2.59. Robot job application program snippet 3

If no command from the PLC to start the robot job is received, the robot job deactivates outputs: *DO10_1_PLC_Inputs_1*, *DO10_2_PLC_Inputs_2* and *DO10_3_PLC_Inputs_3*. These signal patterns signalize to the PLC that the robot controller is ready for a new job (lines 56 to 59).

Figure 4.2.59 presents one function and two procedures. *checkPlcCmd()* function returns a True Boolean value if the PLC application software activates the *DI10_6_PLC_Output_1* and deactivates the other two robot controller digital inputs

DI_10_7_PLC_Output_2 and *DI_10_7_PLC_Output_3*. In any other case, the function returns a False. This function will return true when the PLC receives a start command from HMI.

After *openGripper* procedure is called by the main program, a delay of 1 second is used before resetting the output that is intended to energize the solenoid of pneumatic actuator to close the gripper (line 71), set the output that is intended to energize the solenoid of the pneumatic actuator to open the gripper (line 72) and wait another second. The procedure will end only after the digital input *DI_1_GripperIsOpen*, that is connected to the sensors that detect the open state of gripper is activated (line 74).

After *closeGripper* procedure is called by the main program, a delay of 1 second is used before resetting the output that is intended to energize the solenoid of pneumatic actuator to open the gripper (line 79), set the output that is intended to energize the solenoid of pneumatic actuator to close the gripper (line 80) and wait another second. The procedure will end only after the digital input *DI_1_GripperIsClosed*, that is connected to the sensors that detects the close state of gripper is activated (line 82).

Robotic cell tests

After development of PLC, HMI and robot application program, the robotic cell needs to be tested to detect if the process is completed in a safely and reliable way.

During testing procedure, the conveyor belt sensor's accuracy needs to be tested on different detection ranges. Also, identified adjustments, improvements and optimization considering the application programs on the PLC and the robot's controller will be noted and implemented, if feasible.

Since there is no perfect approach in the process of programming the robot, PLC and HMI the author encourages the user to experience more than one method to achieve the goals of the process and test its performance and robustness.

4.3 Recommended readings

1. Simatic S7-1200 Programmable controller – System manual (link: https://support.industry.siemens.com/cs/document/109741593/simatic-s7-s7-1200-programmable-controller?dti=0&lc=en-WW)
2. ABB Robotics, Operating manual RobotStudio (link: https://library.e.abb.com/public/d11e7784c590c24dc1257b5900503e1f/3HAC032104-en.pdf)

3. ABB Robotics, Operating manual – Trouble shooting, IRC5 (link: https://community.plm.automation.siemens.com/siemensplm/attachments/siemensplm/Robotics-Tecnomatix/2730/1/Operating%20manual_Trouble%20shooting_3HAC020738-001_revK_en.pdf)
4. ABB Robotics, Technical reference manual – Rapid Instructions, Functions and Data Types (link: https://library.e.abb.com/public/688894b98123f87bc1257cc50044e809/Technical%20reference%20manual_RAPID_3HAC16581-1_revJ_en.pdf)
5. ABB Robotics, Operating Manual - Introduction to RAPID (link: http://www.oamk.fi/~eeroko/Opetus/Tuotantoautomaatio/Robotiikka/Introduction_to_RAPID_3HAC029364-001_rev-_en.pdf)

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[1] Berger, H. (2013). *Automating with SIMATIC S7-1200: Configuring, Programming and Testing with STEP 7 Basic.* Wiley.

[2] Petruzella, F. (2016). *Programmable Logic Controllers, 5th Edition.* McGraw-Hill Education.

[3] Scherz, P., & Monk, S. (2013). *Practical Electronics for Inventors, 3rd Edition.* McGraw-Hill Education TAB.

Chapter 5: Case studies on multidisciplinary design of industrial robotic automation solutions (robotic cells and production lines)

Anca STAN and Sanda TIMOFTEI

Abstract

This chapter presents several examples of students' semester projects on each of the three case studies. The projects are not presented in detail, each of them highlights various aspects addressed. The three case studies' objectives were intended to develop skills and competencies for our students to be able to design a robotic automation project from A to Z - from mechanical and electrical equipment design to facility layout optimisation, and control design or programming the entire automated system.

5.1. Case studies objectives

5.1.1. Objectives for the first case study

Designing a robotic assembly and palletizing line for the product that is illustrated in figure 5.1.1. The **MINIMUM** configuration of the robotic assembling and palletizing system is:

- a pneumatic feeder,
- two photoelectric sensors,
- a capacitive proximity sensor,
- an inspection system of the assembled products,
- two conveyors,
- an index table,
- a PLC and two industrial robots.

All equipment and devices will be integrated into a single functional robotic system that assembles and packages the product shown in figure 5.1.1, while going through all the steps shown below:

1. *Analysis and planning the assembly performance of the product* illustrated in figure 5.1.1.
2. *Design or selection the necessary equipment and devices*
3. *Sensors and actuators selection. Control system design*

4. *Robotic manufacturing facility layout design*
5. *Economic justification of the designed industrial robotic automation solution*

Fig. 5.1.1. The product required to be assembled by automated system – initial version (upper image) vs. the product required to be palletized (lower image)

Obs.: The Dacia 1300 model is attached to the black pedestal by means of two M3 x 30 screws.

5.1.2. Objectives for the second case study

Designing a robotic assembly and palletizing line for the product that is illustrated in figure 5.1.2. The minimum composition of the robotic assembling and palletizing system is:

- a pneumatic feeder for the product shown in figure 5.1.2,
- two photoelectric sensors,
- two capacitive proximity sensors,
- an inspection system of the assembled products,
- two transfer conveyors,
- An accumulation conveyor,
- an index table,
- a PLC and two robots.

Fig. 5.1.2. The product required to be assembled – initial version
(3 models)

All equipment and devices will be integrated into a single functional robotic system that assembles and packages the product shown in figure 5.1.2, while going through all of the steps shown below:

1. Analysis and planning the assembly performance of a mechatronic product. Equipment and devices selection/ design
2. Sensors and actuators selection. Control system design
3. Robotic manufacturing facility layout design

Economic justification of the industrial robotic automation solution

5.1.3. Objectives for the third case study

The design of a robotic assembly cell for the product illustrated in figure 5.1.3, while going through the stages mentioned below:

- Analysis of the assembly performance of the product shown in figure 5.1.3
- Elaborate an improved version of the product
- Elaborate the final version of the product
- The design concept of the robotic assembly cell
- Economic evaluation of the robotic assembly cell
- Development of the Ladder diagram for controlling the process

Fig. 5.1.3. Initial design of a robotic mounting cell for a sealed metal box for electrical panels (left side) and electrical dose (right side)

For the sealed metal box for the electrical panels take into consideration the following details presented in table 5.1.1 and figure 5.1.4.

Table 5.1.1. Dimensions for the sealed metal box for the electrical panels

Student's name	A [mm]	B [mm]	C [mm]	D [mm]	E [º]	F [mm]	G [mm]	H [mm]	I [mm]	J [mm]
	300	150	400	4	120	130	280	5	45	50
Student 1	600	300	400	4	120	280	580	5	45	50
Student 2	600	250	600	4	120	230	580	5	45	50
Student 3	800	200	800	5	120	780	780	5	45	50
Student 4	800	300	1000	5	120	780	980	5	45	50
Student 5	800	250	1200	5	120	780	1180	5	45	50
Student 6	1000	200	1000	5	120	980	980	5	45	50
Student 7	1000	350	1000	5	120	980	980	5	45	50
Student 8	1200	300	900	5	120	1180	880	5	45	50
Student 9	1200	400	1200	5	120	1180	1180	5	45	50

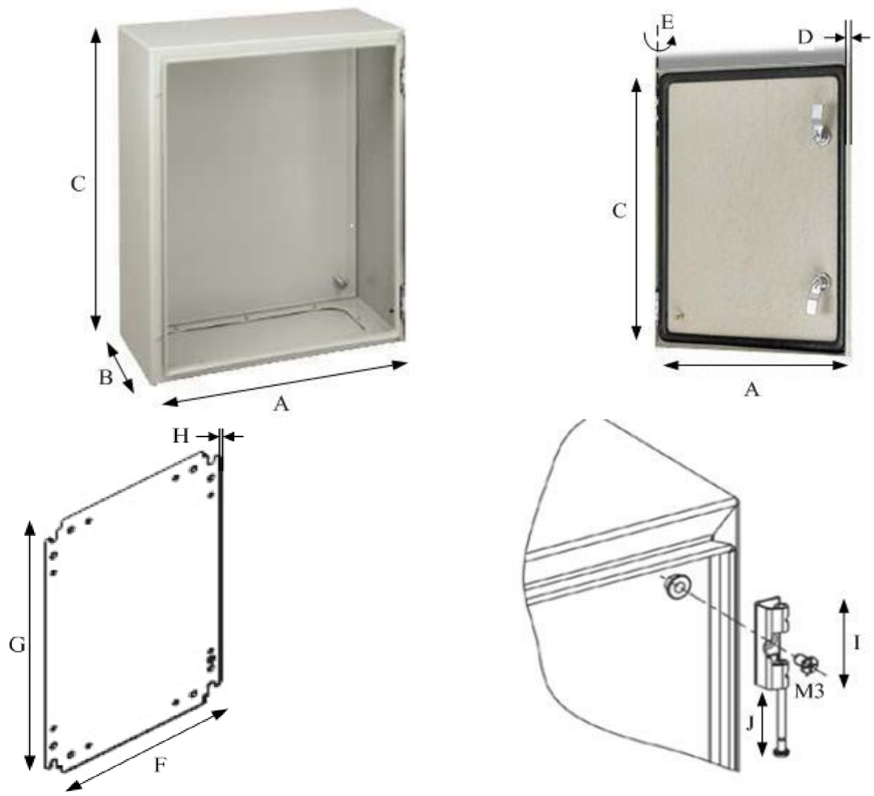


Fig. 5.1.4. Details of the sealed metal box for electrical panels

For the electrical dose take into consideration the following details presented in table 5.1.2 and figure 5.1.5.

Table 5.1.21. Dimensions for the electrical dose

Student's name	A [mm]	B [mm]	C [mm]	D [mm]	E [º]	F [mm]	G [mm]	H [mm]	I [mm]	J [mm]
Student 1	75	75	5	37	20	7.5	25	75	75	5
Student 2	85	130	5	37	20	7.5	25	85	130	5
Student 3	140	140	5	79	20	7.5	45	140	140	5
Student 4	180	180	7.5	91	35	10	45	180	180	7.5
Student 5	200	150	7.5	91	35	10	45	200	150	7.5
Student 6	200	200	7.5	103	35	10	50	200	200	7.5
Student 7	254	254	7.5	125	35	10	50	254	254	7.5
Student 8	300	300	7.5	125	35	10	50	300	300	7.5

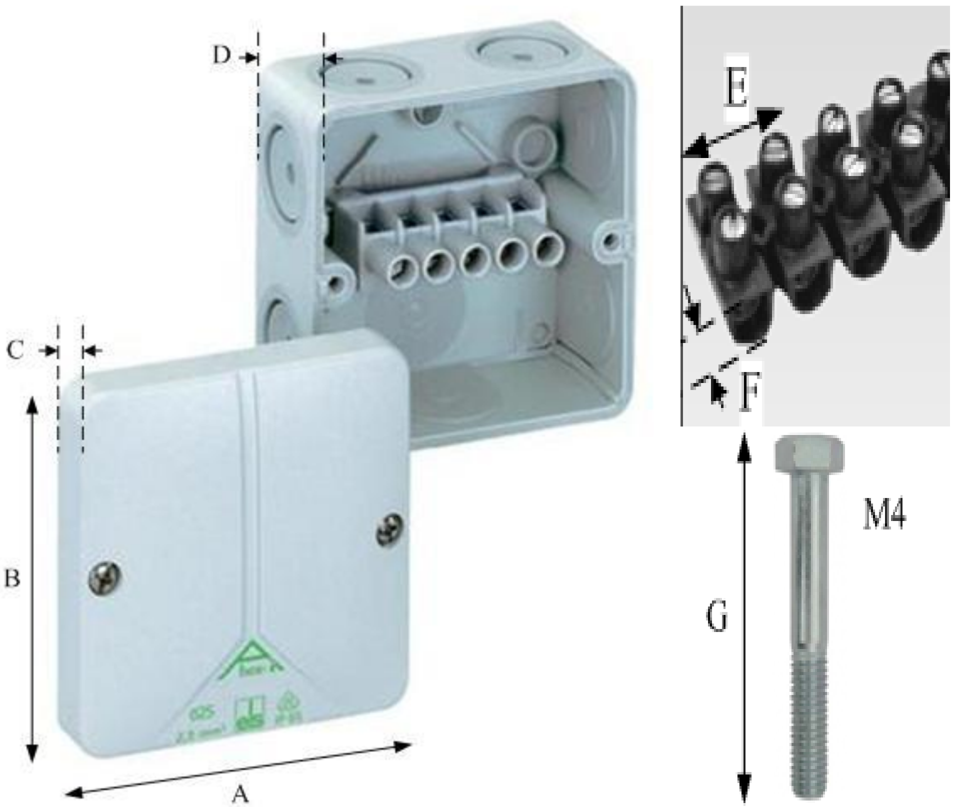


Fig. 5.1.5. Details for the electrical dose

5.2. First case study: assembly and palletization of a Dacia 1300 model car

The examples of the projects outlined below are the exclusive vision, conception, and implemented solutions developed by each student or team of students who have worked on each project.

5.2.1. 1st Project example

Our car is assembled on a support using two M3x30 screws. The initial solution is shown in figure 5.2.1.1.

Therefore, there are no less than 6 parts to assemble, if we include the cover. We also know that the screws are difficult to assemble in a robotized process. If we compute the global (DFAFD – Design for Assembly Function Deployment method) quality level Q_r =76.2%. This low level of quality (Q_r) can be explained only by a big number of parts. Let's reduce it!

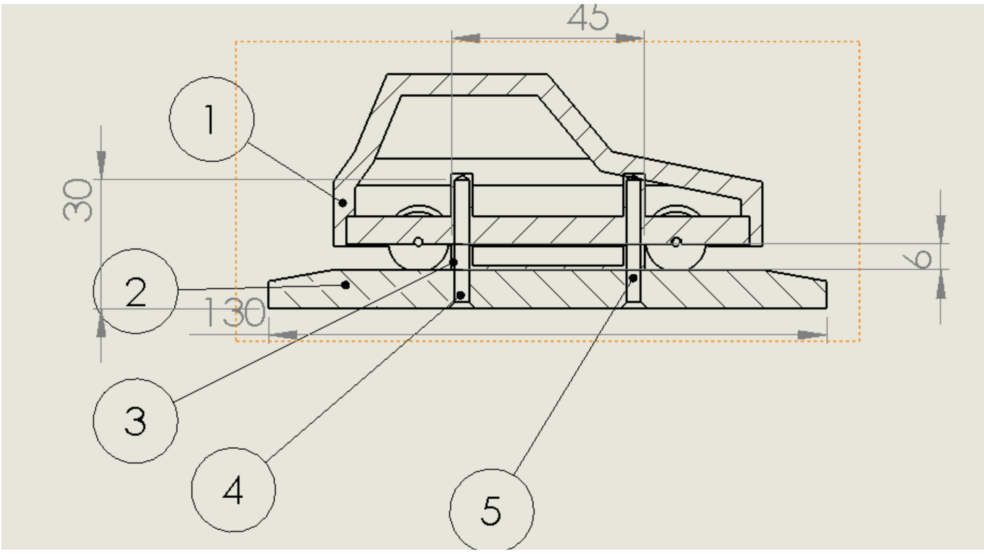


Fig. 5.2.1.1. Initial solution for the assembly of Dacia 1300 model

To reduce the number of the parts, we have chosen a peg hole solution. That suppresses 3 parts. We have obtained now a global quality level of Q_r =80.4%.

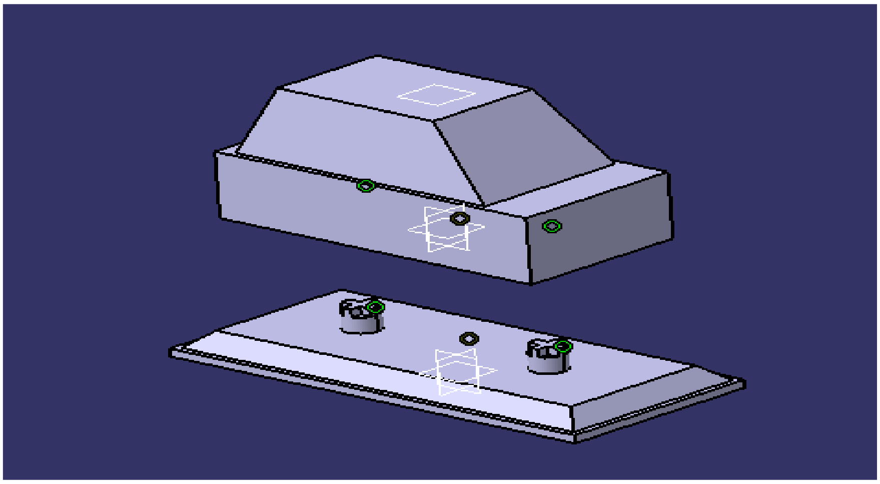


Fig. 5.2.1.2. Virtual prototype of the redesign product

Logic scheme for the process:

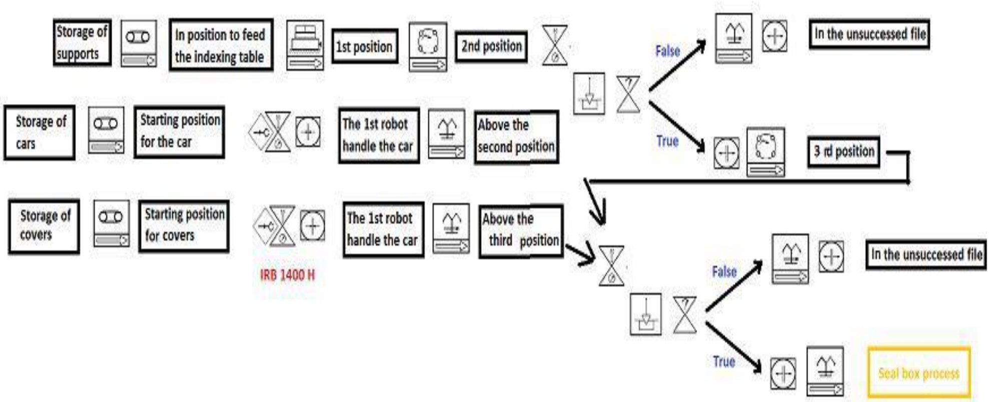


Fig. 5.2.1.3. The assembling processes

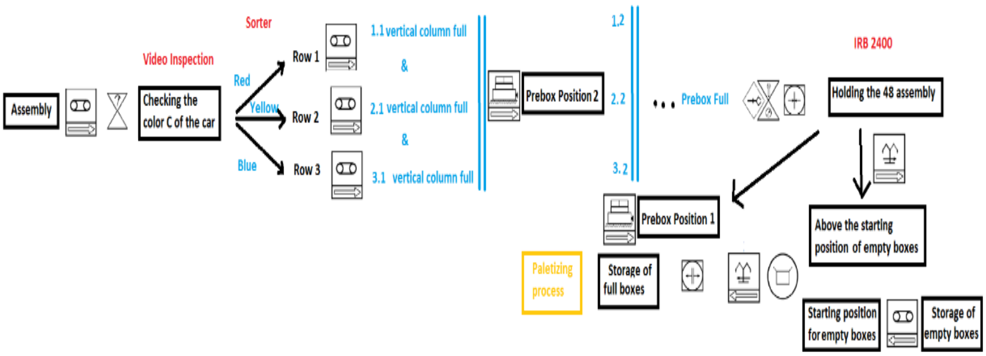


Fig. 5.2.1.4. The process of sorting the cars by color & sealing the boxes

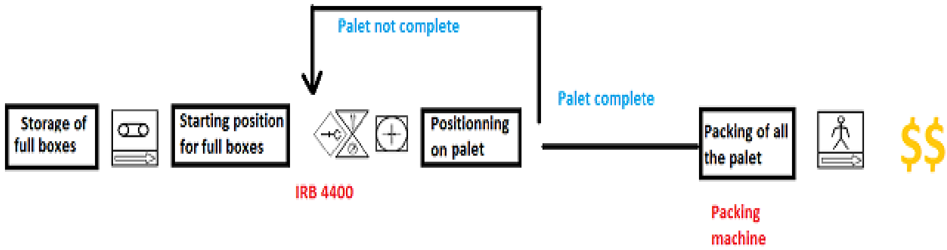


Fig. 5.2.1.5. The palletizing processes

Conception of the robotized line:

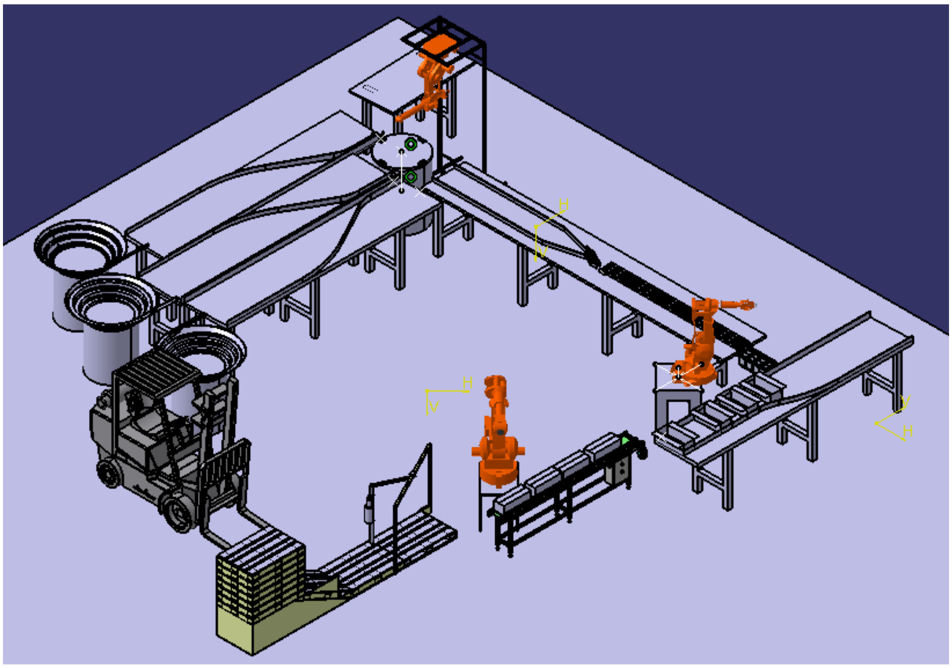


Fig. 5.2.1.6. Main view of the production line

On this overview of the plant we can distinguish all the necessary sub-processes we have mentioned earlier.

All conveyors are equipped with photoelectric sensors 44R AccuSightt (from Allen Bradley) at their extremity, so they can stop automatically if there is nothing on them.

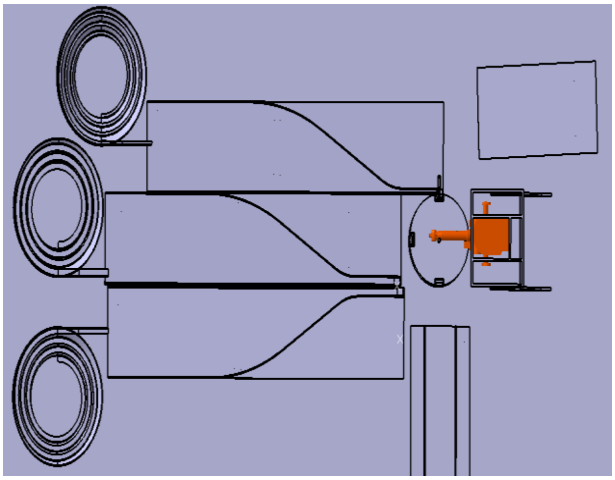


Fig. 5.2.1.7. Top view of the assembly line

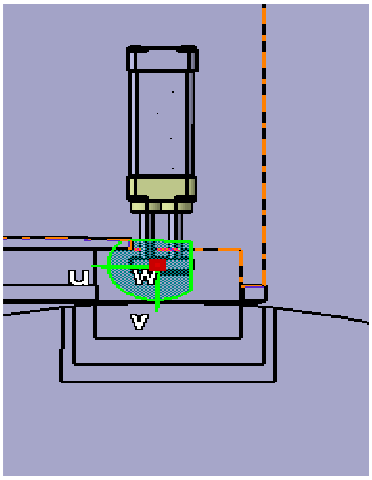


Fig. 5.2.1.8. Air cylinder APN

When focusing on the assembly part, on its equipment, on the left you have 3 different sized vibratory feeders. From top to bottom you have the one for support, car and cover. Then the 3 conveyors are equipped with railing to maintain the orientation of the product. The conveyor for support has its specificity: it is equipped with an air cylinder Festo AEN-16-35-A-P-A-TL. It feeds the indexing table when a car is in the picking place. The robot only has to pick up the car and to directly place the assembly on the 2nd position. Afterwards, the cover is added. The rectitude of the assembly is known due to a Kinect 360 mounted on the robot.

We chose to use the ABB robot IRB 1400H because of its ability to work while in a hanging position. It has a good working range and a maximum payload of 6kg. It is fully adapted to manipulate our component. Its working principle is shown in figure 5.2.1.9. On it we have mounted a Festo vacuum generator ESG-8X20-ON-HA-QS.

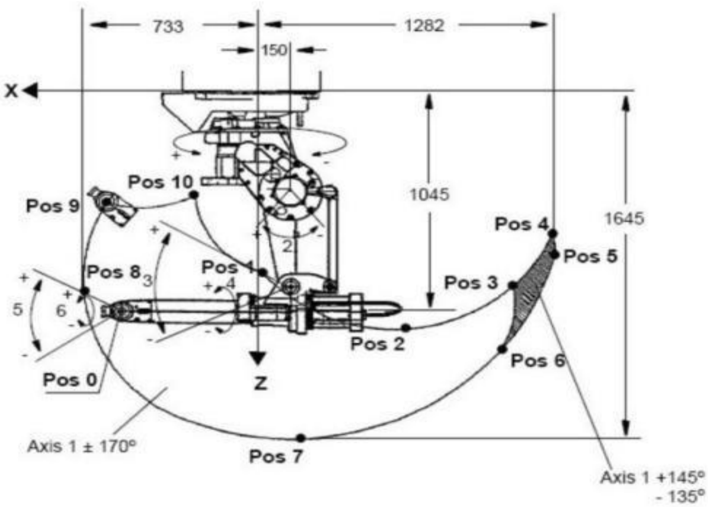


Fig. 5.2.1.9. Working area of IRB 1400H

The sorting and sealing is the most interesting part of our plant. Here we developed an interesting device to sort and fill boxes with the minimum sheet of paper.

After the video inspection performed by a Kinect 360, the sorter places itself in the front of the right row, depending on the signal it receives from the Kinect. Because that part was designed by us, we will focus furthermore on the calculus.

The sorter is an equipment based on parallelogram mechanism. In a parallelogram mechanism, two opposite edges are always parallel. Therefore, situation a, figure 5.2.1.10, is simplified as situation b, figure 5.2.1.11, obtaining:

$$\alpha = \tan^{-1}\left(\frac{3}{1+\frac{9}{77}}\right) \leftrightarrow \alpha = 69.58^\circ$$

To place a blue car in the blue row, we need to input the following:

$$\alpha = 69.58^\circ + 90^\circ = 159.57^\circ$$

To place a yellow car, we would have to input:

$$\alpha = 90^\circ$$

Because of the funnel shape of the sorter, we avoid all blocking risks.

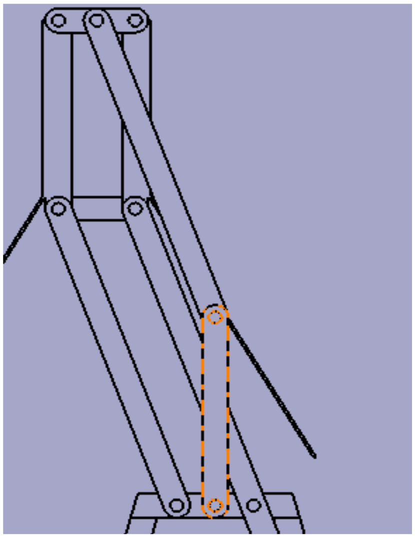


Fig. 5.2.1.10. Situation a

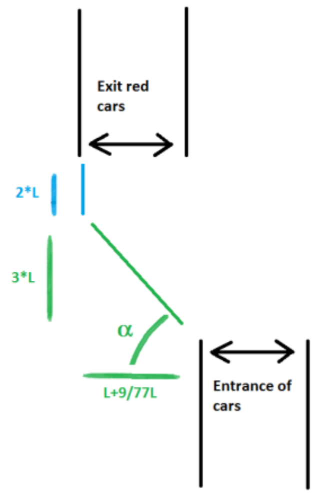


Fig. 5.2.1.11. Situation b

At the end of each row the cars arrive on the column in a "pre-box", that prepares the packing. This "pre-box" is equipped with a spring with a certain elasticity constant so that when an assembly arrives on the spring, it is placed at a certain height. Let's compute this elasticity constant.

From the Fundamental Principal of Statics, we have:

$$k \cdot \Delta h = m_{assembly} \cdot g \, ;$$

Which means that

$$k = \frac{m_{assembly} \cdot g}{\Delta h};$$
$$g = 9.81;$$
$$m_{assembly} = 200\,g$$

Therefore,

$$k = \frac{9.81 \cdot 0.2}{0.050} \; so \; k = 39.24 \; N \cdot m^{-1}$$

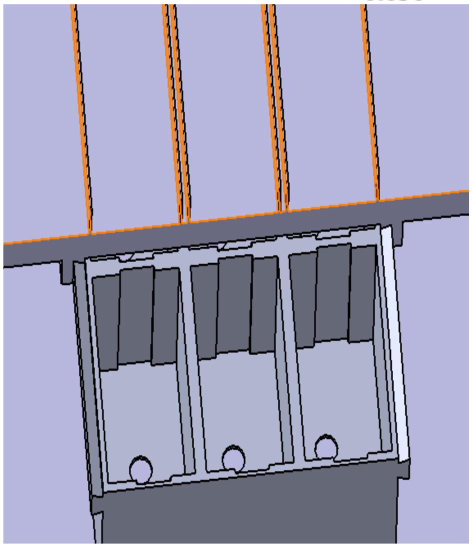


Fig. 5.2.1.12. Pre-box position 1

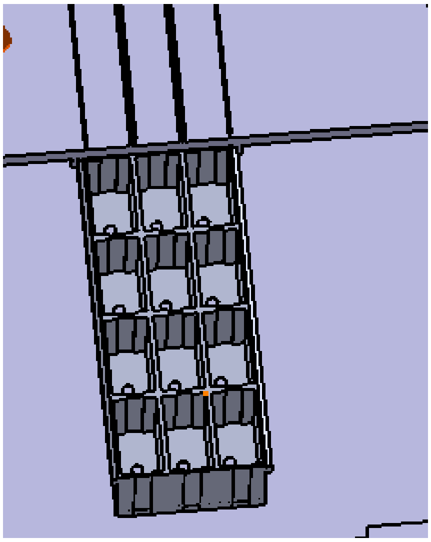


Fig. 5.2.1.13. Pre-box position 4

The pre-box is able, once a row of columns is completed, to move to a second, a third and a fourth position, like it is shown in figures 5.2.1.12 and 5.2.1.13.

We chose a classical ABB robot. This robot will lift a mass of 48*0.2 kg, that means 9.6 kg, to which we must add the weight of the gripper, which is 20 kg.

To lift all the assembly in the same operation we have designed a special gripper. It has basically 12 clamps, 1 for each of the rows. They will descend in the opened "pre-box", and once they reach its bottom, they will close. Then the arm of the robot comes up, and puts the 48 assemblies in a box. Its size is 630*250*200.

The opening and the closing of the clamp are commanded by 4 different air cylinder Festo AEN-16-10-A-P-A-TL. T (fig. 5.2.1.14), capable to deliver a force of 3dAN.

The line shown in figure 5.2.1.15 is a classical solution for palletizing and packing. The boxes will be organized on the pallet in five stages. The global weight of the final pack will be 9.6*5*6~300kg. A fork lift is a must when desiring to transport that load. Our robot IRB 4400 is there only to pick up and place our boxes of 9.6kg, with a good working range and a maximum payload of 60kg. It is equipped with a vacuum gripper Festo ESV-100-SF, which delivers a suction force of 503 N, as shown below, in figure 5.2.1.16.

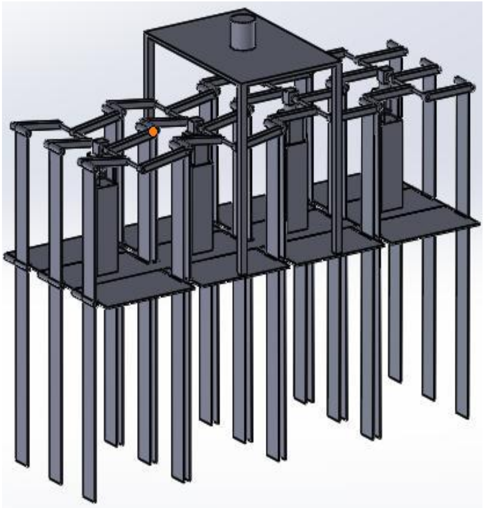


Fig. 5.2.1.14. Loading equipment

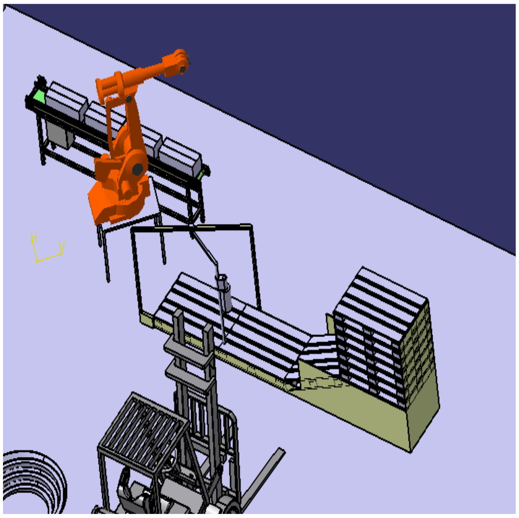


Fig. 5.2.1.15. Packaging line

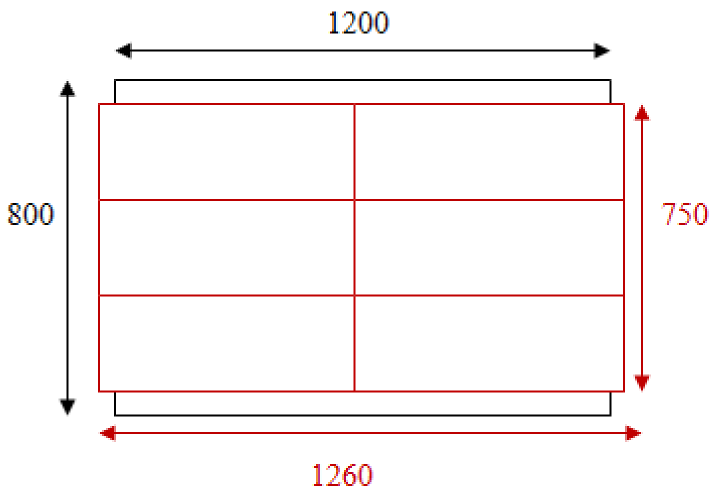


Fig. 5.2.1.16. Organisation on the pallet

Many thanks to our student (Erasmus Student), Henri de Varax, for enabling us to present his solution for this case study!

5.2.2. 2nd Project Example

The process starts with the vibratory feeders, feeding the car model and the car support on conveyor 1. Then, both pass through an inspection system that shows the position they came from the conveyor. At the end of the 2nd conveyor, proximity sensors are placed to "tell" the robot that in that position the object has just arrived, and because the car and the support passed through the inspection video, the robot knows how to grab them.

At the same time, from another conveyor, a top cover is fed on the 2nd conveyor. At the end of the conveyor, we have another proximity sensor for the same purpose as in the previous case.

The assembly process is done on an indexing table. The robot performs the assembly process by placing first the support in the special pocket, then the car, on top on the support in the special gripping system, and then the same robot puts the final top cover finalizing the assembly of one product. All the three components are shown in figure 5.2.2.1. Afterwards, the robot performs the same operation again until the end of the program from the PLC module.

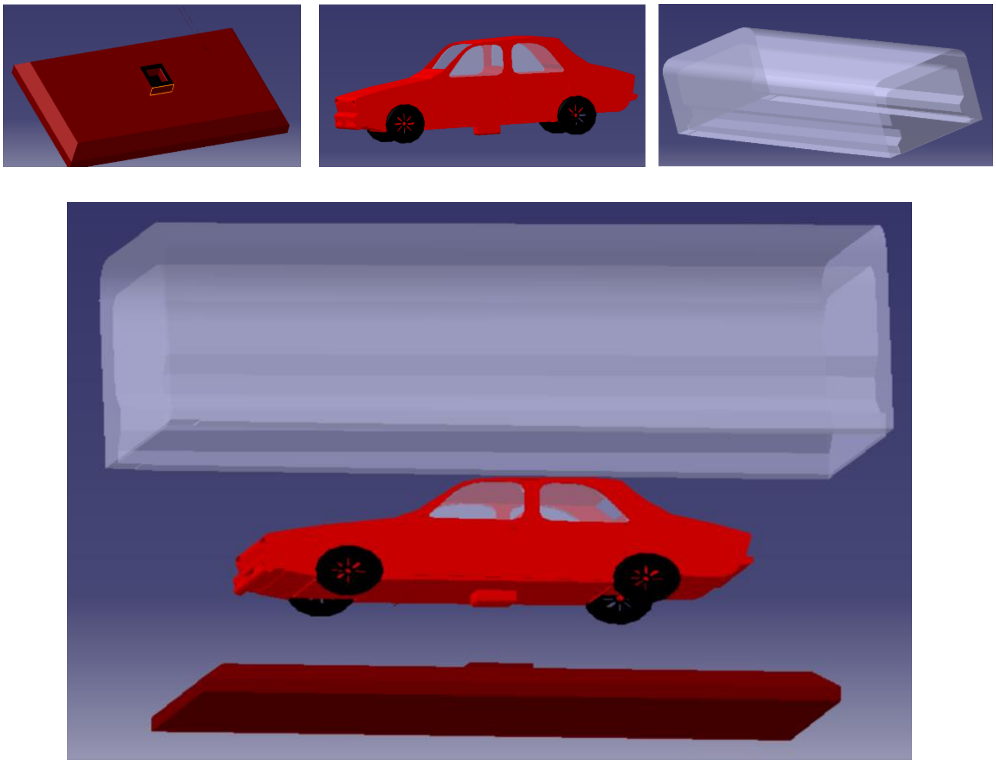


Fig. 5.2.2.1. The 3 sub-assemblies

After the product is assembled, figure 5.2.2.2, the table rotates, until, with the help of a photoelectric sensor that detects its presence, the third robot manipulates the product on the 3rd conveyor. Just after it is placed on the conveyor, it passes under an inspection system, formed by 2 cameras that detect if the product is correctly assembled. The conveyor has a curve that separates the path for the products that are well assembled and the ones that have assembly errors.

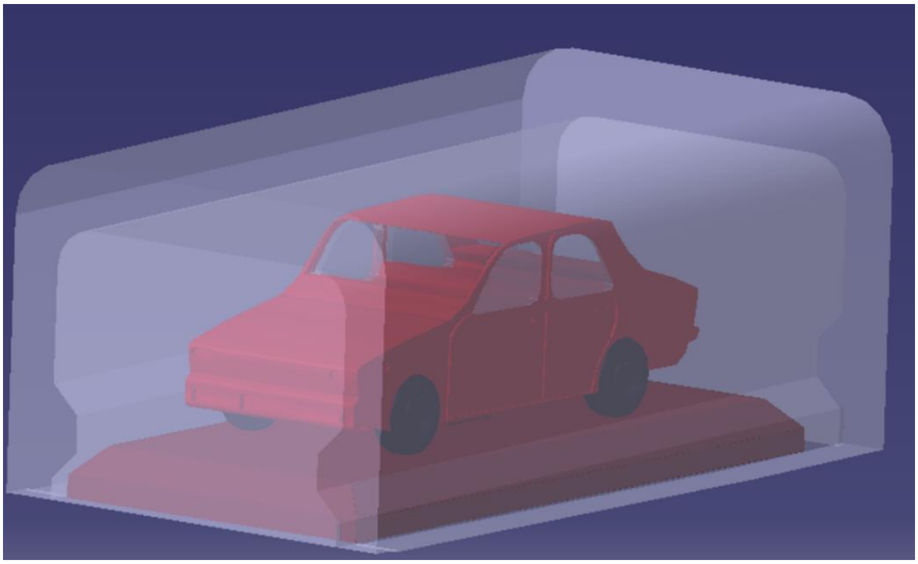


Fig. 5.2.2.2. Design of the final assembly

At the middle of the conveyor, before the curve, we have a photoelectric sensor, and when the wrong assembled product is detected, after passing by the sensor, a trap opens and with the help of rollers under the conveyor, it is redirected in a special box. When the box is full, it is automatically evacuated, descending at the bottom, where it's pushed outside by 2 pneumatic pistons.

The products that passes through the inspection system follow the normal direction of the conveyor. At the end of the conveyor another inspection system is placed for detecting the color of the car, the top cover being transparent. Here we have an accumulation conveyor, that is linked to the previous one. The product passes through the inspection system that has a camera that detects the color. The conveyor splits in 3 directions, each color on its own conveyor. The direction is made by 2 direction parts; if the color is red, the traps slides to the left and the product is redirected on the first conveyor. For the yellow color the traps remain in position, and for the blue color the traps slide right.

When, at the end of the conveyor arrive four of each color, the robot grabs them with a vacuum end effector with 12 vacuum cups. If at the end there arrive more products of the same color, they are redirected to perform a rotation until 4 of each color arrives.

A box making machine feeds the conveyor with boxes for the assembled cars. The cars are placed in 3 lines and 4 rows and 4 levels. When the box is full, it's sealed and transported with the conveyor to another robot that puts the boxes on a pallet. When the pallet is full of boxes, a forklift truck places the pallets on the folding machine, then they are deposited for transport.

The DFAFD method shows us that the assemble with the two screws entails some difficulty in the automatization assembly process. Therefore, based on the results, we have considered another method for the assembly process.

The method consists in the assembly with Lego concept. On the bottom of the car we have an extrude part that inserts in the hole from the support (pedestal).

The functioning is based on the tightening mechanism principle which makes the car and the support connect together, with friction, so that the car would stick to the pedestal.

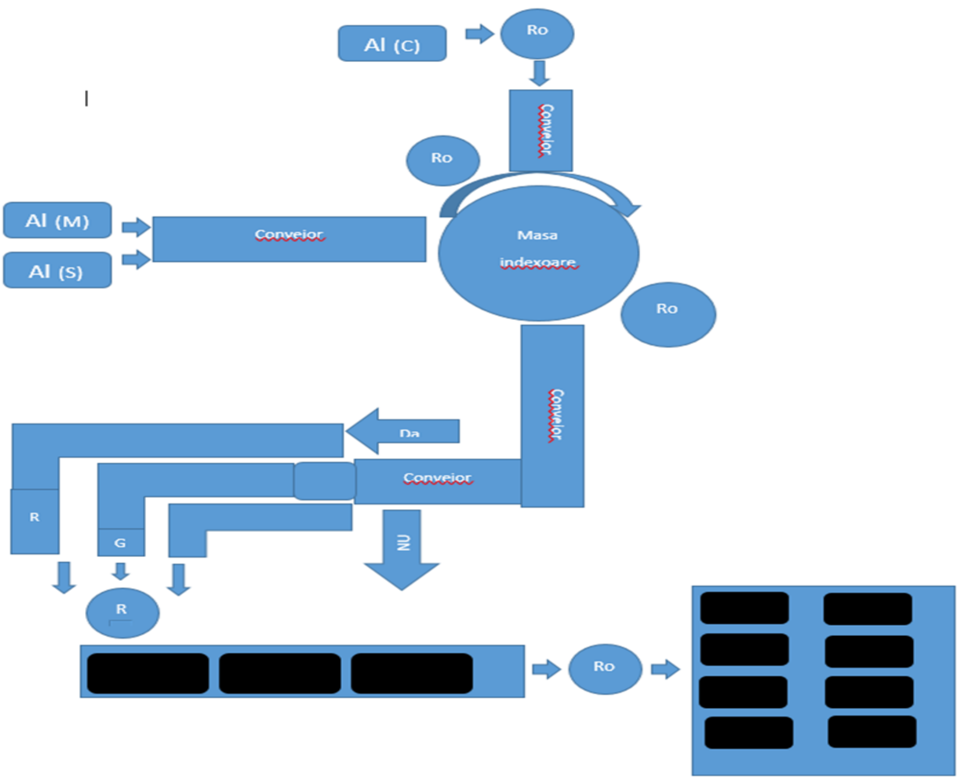


Fig.5.2.2.3. The robotic cell conception

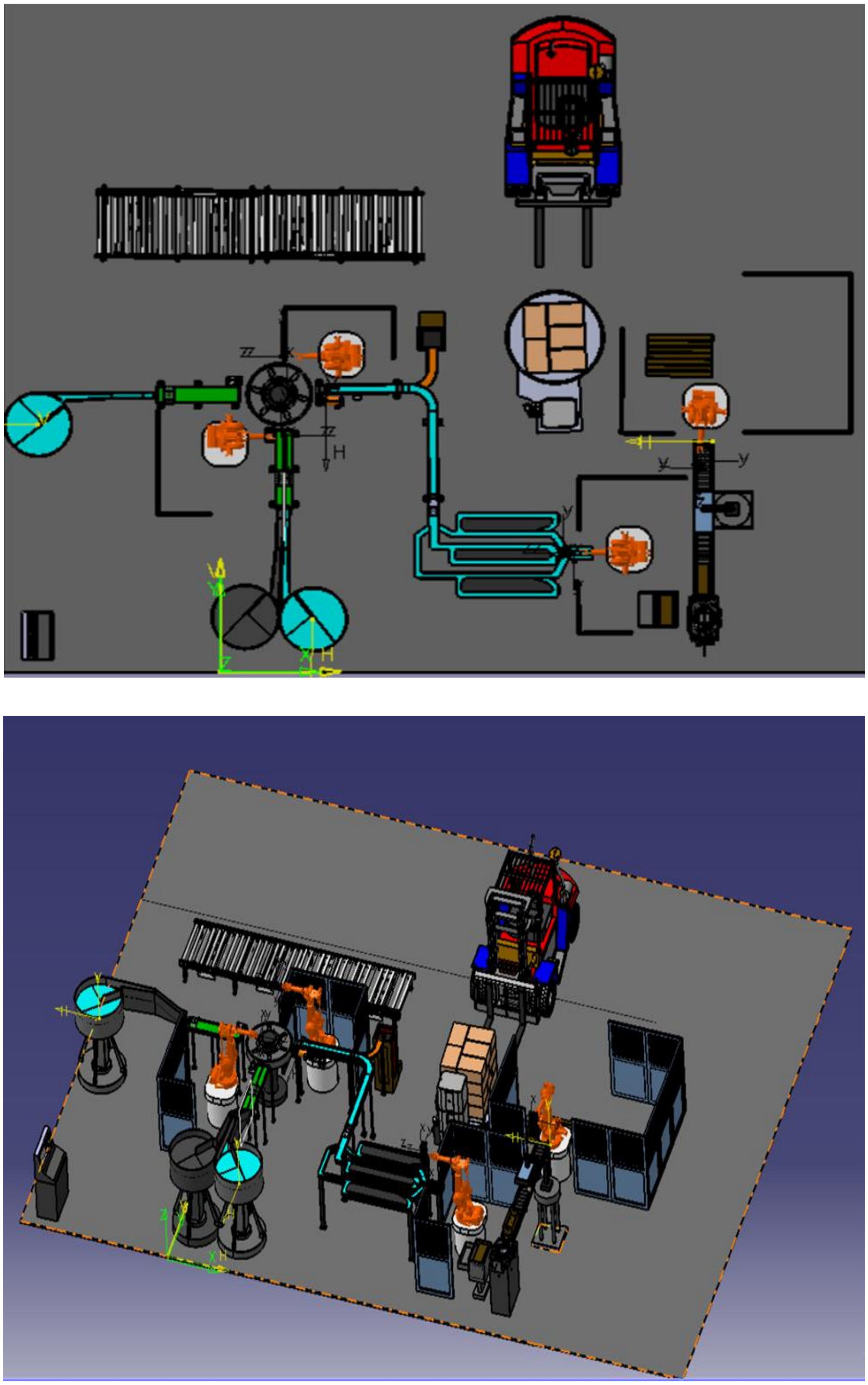


Fig. 5.2.2.4. The robotic line model

Figure 5.2.2.3 presents the conception in the design phase of the robotic cell, while figure 5.2.2.4 presents the robotic line model.

Economic evaluation of the robotic cell:

- 3 vibratory feeders: 3x 1000 $
- 5 proximity sensors: 5x 44.5 $
- 2 photoelectric sensors: 2x 39 $
- 4 inspection systems: 4x1200$
- 1 indexing table: 200 $
- 1 PLC: 5000 $
- 4 robots: 4x 30000 $
- 5 conveyors: 5x 1000 $
- 1 folding machine: 2000 $
- 1 pallet truck: 2500 $
- 1 box making machine: 4000 $
- palletizing gripper: 650 $
- assembly gripper 100 $

Total value of the robotic line production is 147550.2 $.

Many thanks to our student, Daniel Cozmi, for enabling us to present his solution for this case study!

5.2.3. 3rd Project Example

The analysis of the assembly's performance of the initial product will be carried out using the Design for Assembly Function Deployment method.

The initial product consists of:

- Car model;
- Pedestal;
- Intermediate element;
- M3x30 Screw x2.

Based on the DFAFD analysis, it can be observed that the initial product does not have good automated assembly performance, due to the intermediate element and to the two M3x30 screws.

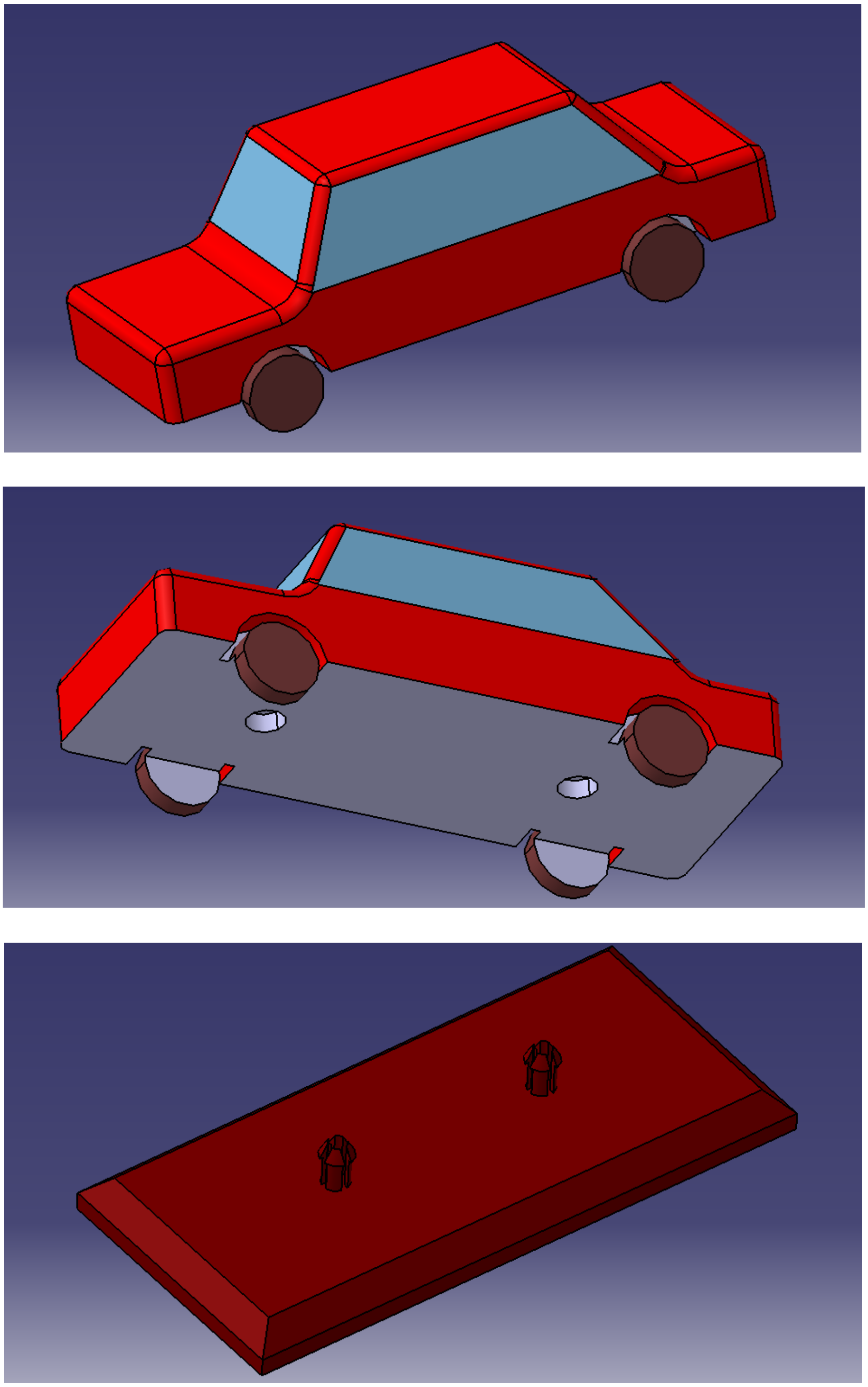


Fig. 5.2.3.1. Redesigned car model and redesigned pedestal

Therefore, a redesign of the product proves necessary in the sense of eliminating the intermediate element and the screws. The final version of the product is presented in the following chapter.

In the final version of the product, both the screws and the intermediate element have been eliminated in order to increase the automated assembly performances.

The chosen assembly method is using two cylindrical plastic clamps embedded in the pedestal (base support) which fit into two holes pierced in the bottom of the car model. The disassembly procedure is carried out using a pair of tweezers.

Pictures of the redesigned products are presented in Figure 5.2.3.1.

The analysis of the assembly performance of the redesigned product will be carried out using the Design for Assembly Function Deployment method.

The results of the DFAFD analysis for the redesigned product are shown in table 5.2.3.1.

Table 5.2.3.1. Results from DFAFD method

Sum(TI)	Target
2077,00	1757,00
99,90	
1939,00	1757,00
98,13	

sum M	sum T
4016,00	3514
procent Qr	
	87,5

It can be observed that after redesigning the product, the automated assembly performance has increased by 19.5%, making it more suitable for assembling within a robotic cell.

The assembly process begins with 2 vibratory feeders, one for the car model and one for the pedestal. The feeders are equipped with 2 proximity sensors, one to detect the presence of an object at the feeder output gate and one at the middle of the tray to signal the fact that the feeder is half empty and needs to be refilled.

The car model and the pedestal are then transported to the assembly area with 2 conveyors equipped with 2 proximity sensors each, at both ends of the conveyor.

The components are then taken by the robot and placed on the indexing table and assembled from the top. An inspection system consisting of 2 video cameras is mounted on the indexing table to verify both the correct assembly of the products and their integrity. If the inspection returns a positive result, the assembly is then placed by the robot on the automated packaging machine.

The products are individually packed in a plastic housing with a cardboard bottom. The correct gluing of the plastic housing to the cardboard bottom is checked by a weight sensor within the machine. If the check is ok, the packed product is ejected onto a recirculating conveyor.

A video color detection system is mounted on the recirculating conveyor to detect the color of the model. The differently colored models are dispensed separately onto a gravitational accumulating conveyor. Should this conveyor be full, the product will be recirculated until an empty space is created.

At the end of the accumulating conveyor, the 3 ordered models are pushed together and then taken by the robot and placed in the box. The process repeats until the box is filled.

The boxes are automatically formed by the machine and sealed after filling. A sheet of thin cardboard will be placed between the 4 layers of products by the same robot.

After sealing the box, the machine pushes it to the ejection area, where the box is taken by the palletizing robot and placed onto the pallet. The process is repeated until the pallet is filled.

The full pallet advances to the foiling machine, where it is surrounded by plastic foil in order to secure the boxes altogether. After the foiling process is completed, the pallet is transported to the final output area, where it will be picked up by a forklift. The roller conveyors used to transport the pallets are all equipped with 2 proximity sensors, one at each end, to ensure a correct positioning of the pallet on the conveyor.

The palletizing process is also equipped with an automatic pallet feeder, which can handle an entire pallet stack, dispensing them individually to the palletizing area, by lifting the stack and allowing only the bottom pallet to proceed on the conveyor.

The entire process is controlled by a Mitsubishi Q series PLC.

The conception of the robotic assembly line is presented in the diagram below. The process roadmap depicted by the red cells and the sensors and devices used for each step are depicted by the orange cells.

Pictures of the assembly line components and of the entire layout are presented in figures 5.2.3.2, 5.2.3.3, 5.2.3.4, 5.2.3.5, 5.2.3.6, 5.2.3.7, 5.2.3.8 and 5.2.3.9.

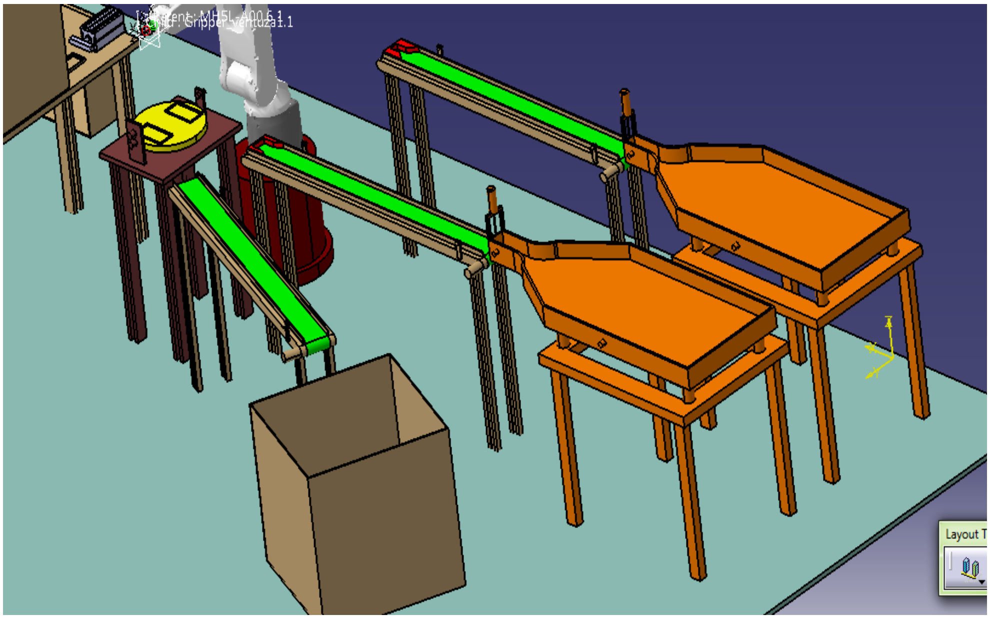


Fig. 5.2.3.2. Vibratory feeders and conveyors

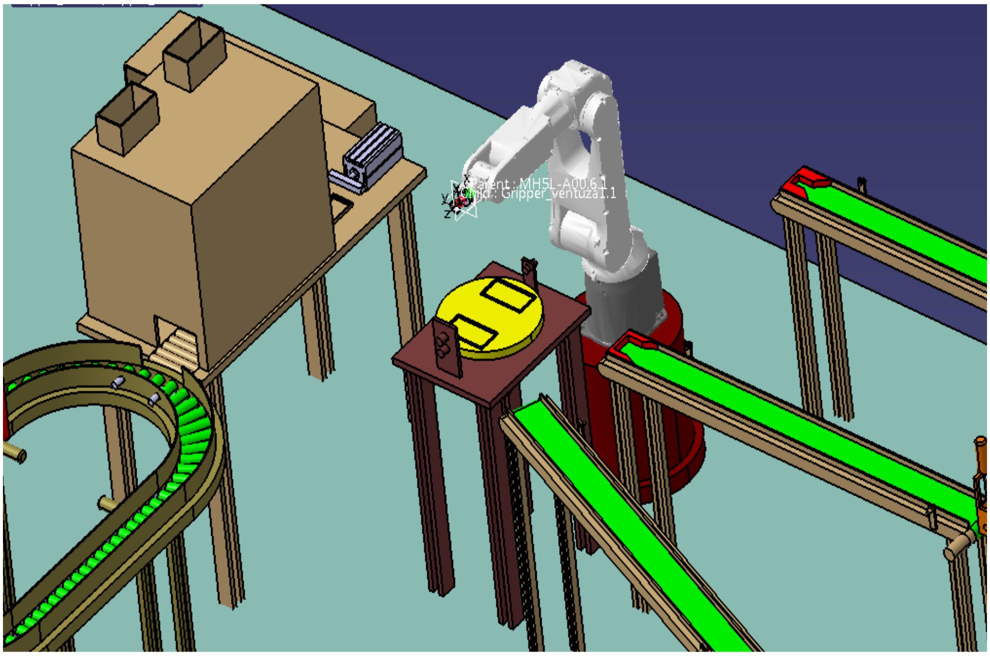


Fig. 5.2.3.3. Indexing table and assembly robot

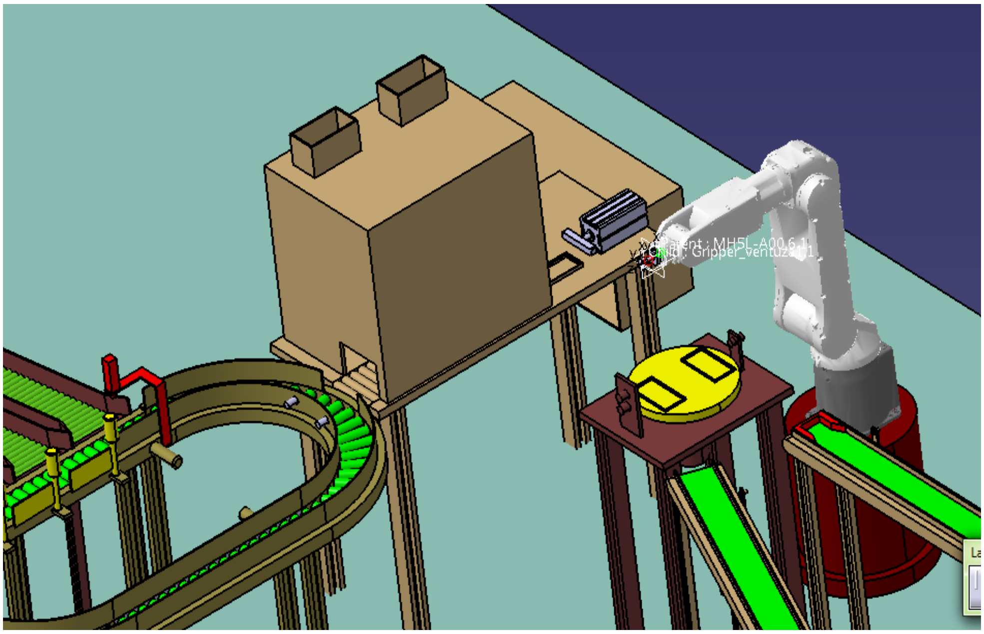


Fig. 5.2.3.4. Individual packaging machine

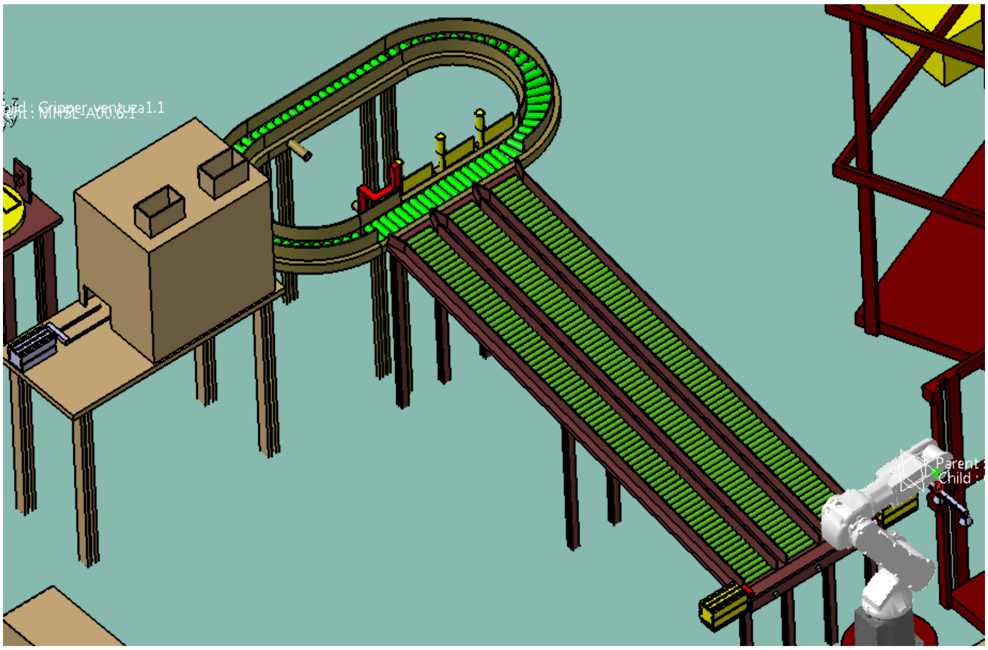


Fig. 5.2.3.5. Recirculating conveyor and accumulator

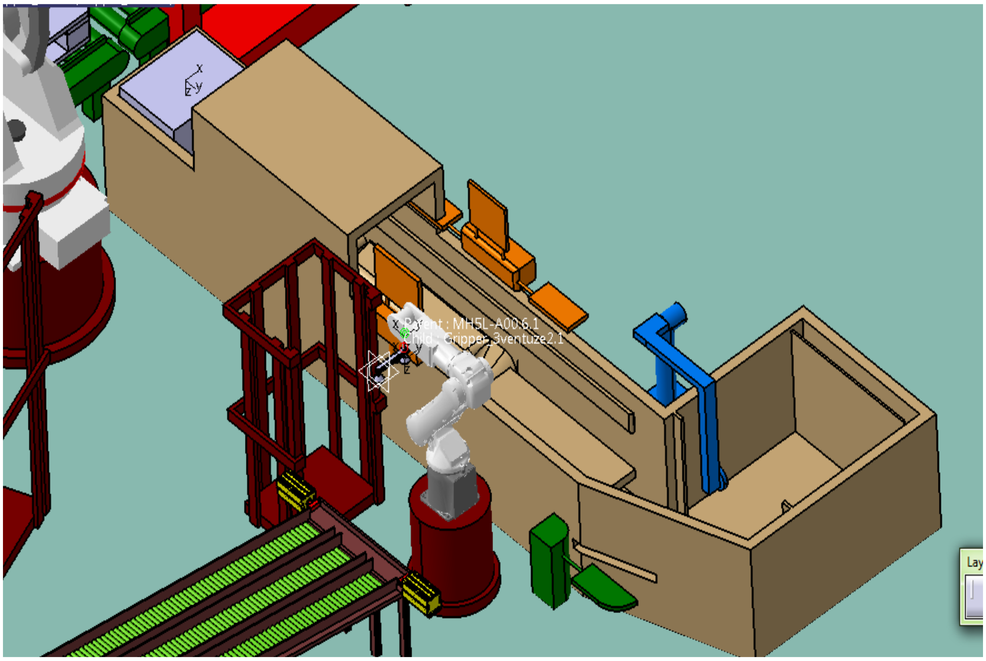


Fig. 5.2.3.6. Box forming machine and box filling robot

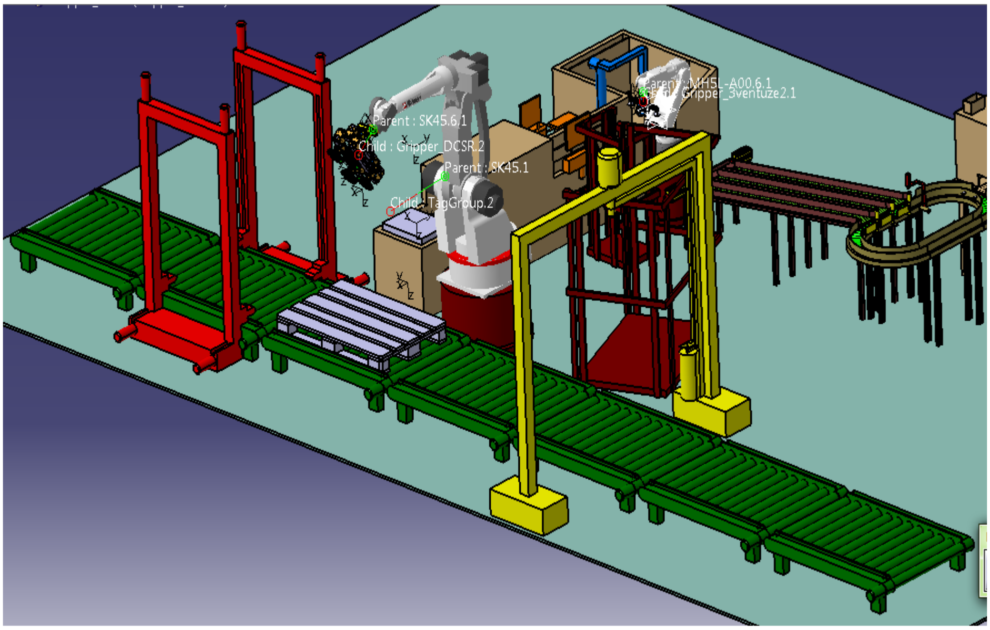


Fig. 5.2.3.7. Palletizing system and palletizing robot

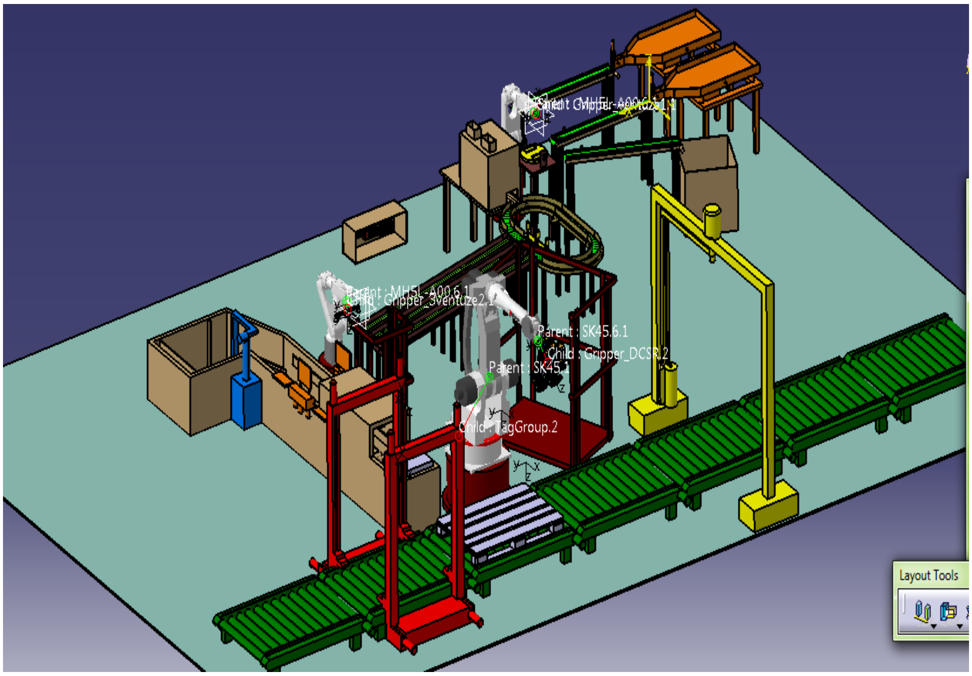


Fig. 5.2.3.8. Overview of the assembly line

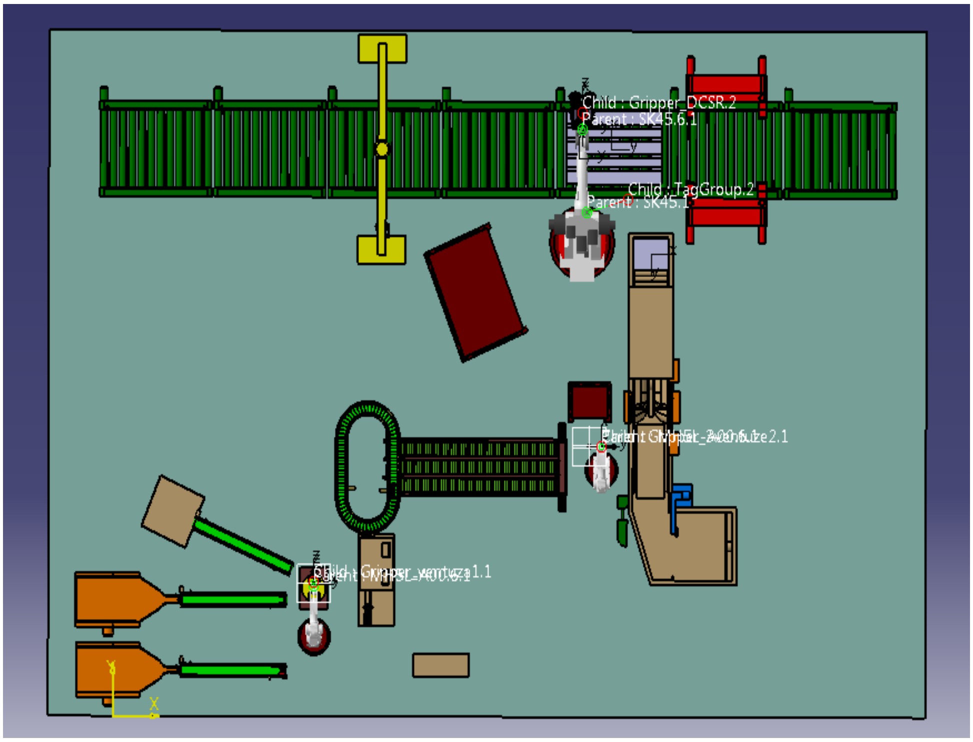


Fig. 5.2.3.9. Top view of the assembly line

The robots used within the cell are the following:

1. Yaskawa Motoman MH0005L – payload 5 kg – 2 pcs.

2. Yaskawa Motoman SK45 – payload 45 kg – 1 pc.

The total estimated cost of the robots is 100000 Euros.

The total estimated cost of the auxiliary equipment is 50000 Euros.

This results in an initial cost of the cell of 150000 euros.

Given the output rate of the system of 150 units/hour and considering a working time of two eight hour shifts a day, 5 days a week, it results in a production rate of 2400 units/day. This results in a weekly production of 12000 units/ week.

Considering a year has 260 working days, the total annual production will be 624.000 units/year. Considering the selling price of 2 euros/unit, it results the total yearly income of the system is 1.248.000 Euros. This means the system will turn to profit after only 2 months after implementing.

Many thanks to our student, Sergiu Dobos, for enabling us to present his solution for this case study!

5.2.4. 4th Project Example

The initial assembly method between the car model and its pedestal settlement consists of using two small screws. This assembly method is very hard to automate, so we had to find another solution in order to achieve an automated assembly and, then, in order to palletize the products.

The solution we adopted is the following: we wanted to perform the assembly process using a Lego type mounting process, with a rough surface cross section profile, as in figure 5.2.4.1.

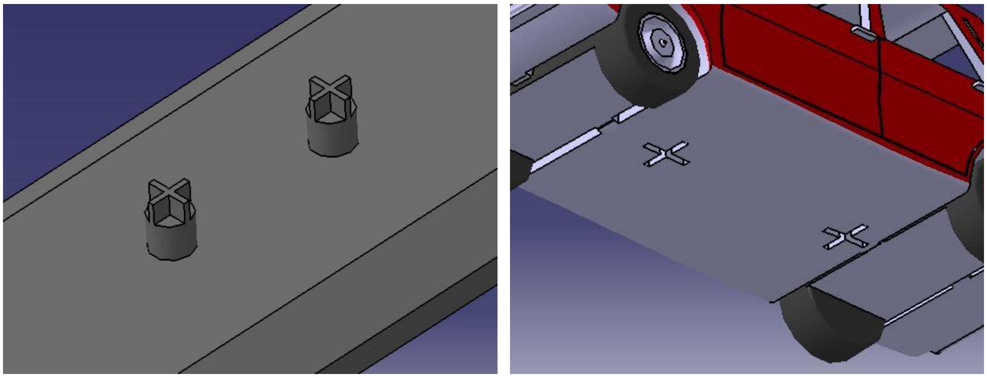


Fig. 5.2.4.1. The assembly process using a Lego type mounting process

We chose to adopt this assembly method because, the assembly being made through rough surfaces pressing, the final product will be stable enough in order to not easily disassemble while using. Moreover, the mounting process between these two components can be automated.

For the performance analysis of the final product we will use the so called DFAFD method.

The final solution of our product can be seen in figure 5.2.4.2.

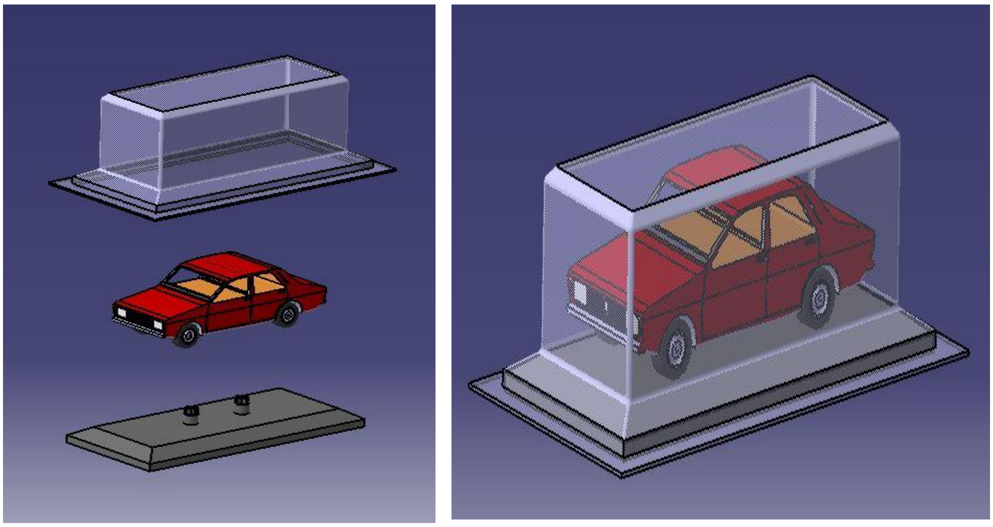
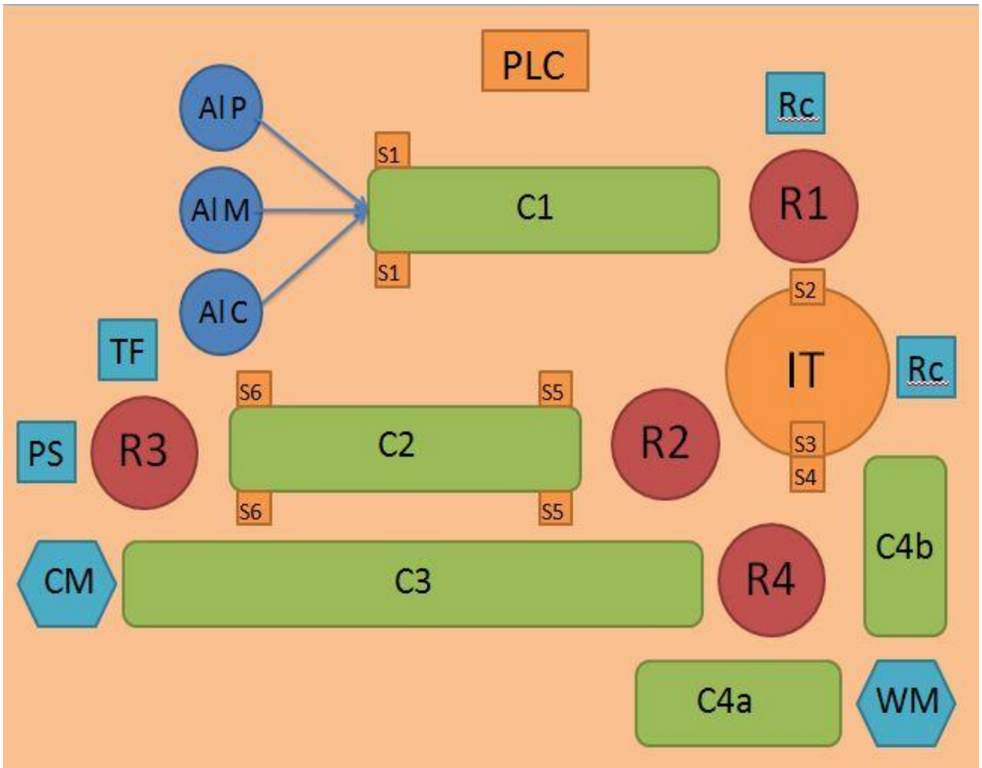


Fig. 5.2.4.2. Final solution of the product

The assembly line of our process can be observed in figure 5.2.4.3. Each part of the process can be seen in figures 5.2.4.4, 5.2.4.5, 5.2.4.6, 5.2.4.7, 5.2.4.8, 5.2.4.9, 5.2.4.10, 5.2.4.11, 5.2.4.12 and 5.2.4.13.



Al P – pedestal feeder;
Al M – car feeder;
Al C – case feeder;
C1 – partitioned conveyor;
C2 – accumulation conveyor;
C3 – box conveyor;
C4a, C4b – pallet conveyor;
IT – indexing table;
R1, R2, R3, R4 – industrial robots;
CM – cardboard box forming machine;
WM – wrapping machine;
TF – cardboard box top feeder;
PS – paper sheet feeder;
Rc – parts recycle;
PLC – programmable logic controller;

S1 – video inspection sensors;
S2, S3 – proximity sensors;
S4 – video inspection sensor;
S5 – color detection sensor;
S6 – photoelectric sensors;

Fig. 5.2.4.3. The assembly line of the process

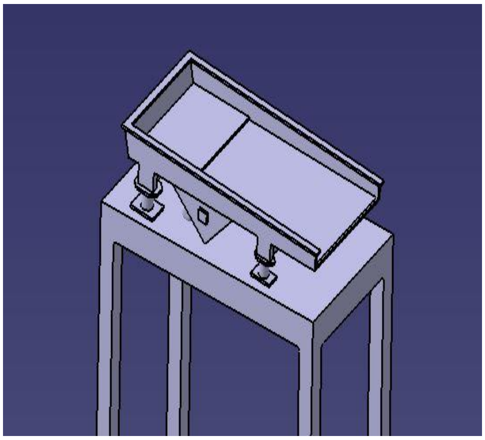


Fig. 5.2.4.4. Parts feeder

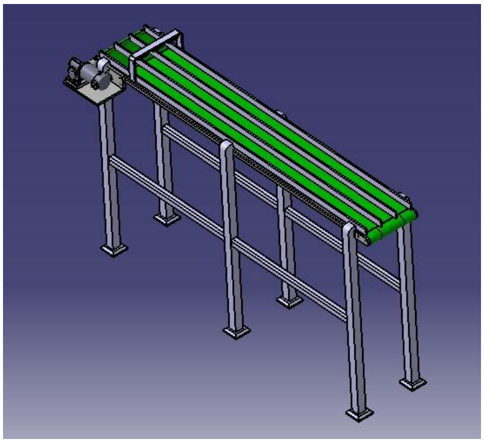


Fig. 5.2.4.5. Partitioned conveyor

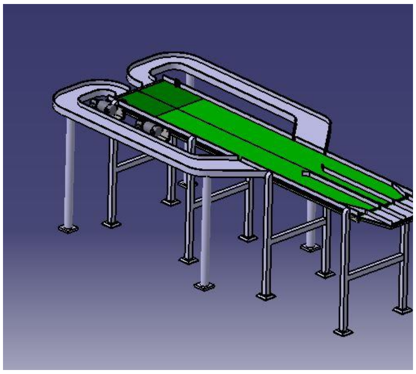


Fig. 5.2.4.6. Box conveyor

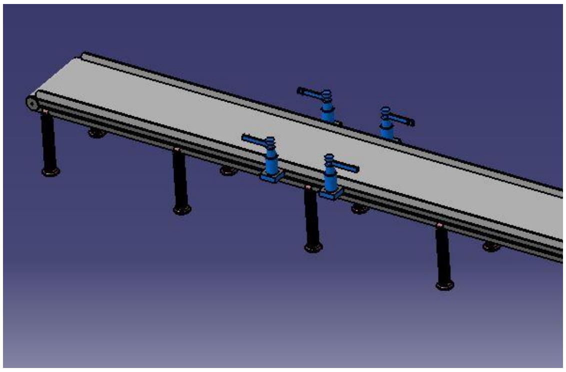
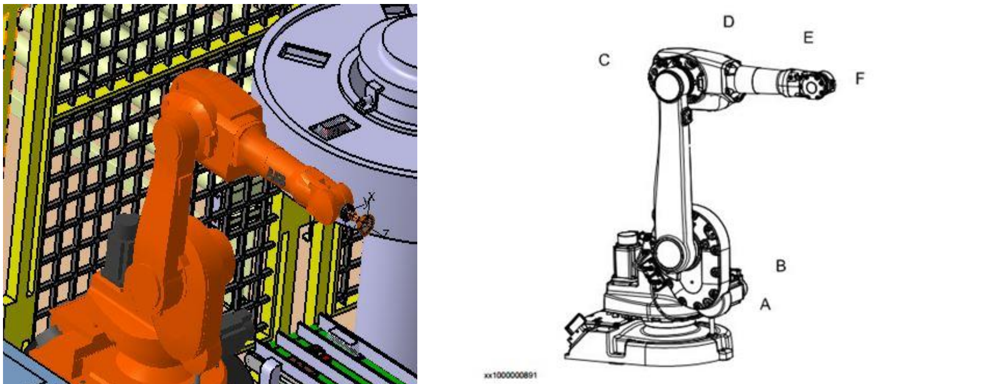


Fig. 5.2.4.7. Pallet conveyor



Pos	Description	Pos	Description
A	Axis 1	B	Axis 2
C	Axis 3	D	Axis 4
E	Axis 5	F	Axis 6

Fig. 5.2.4.8. Industrial robots (IRB model)

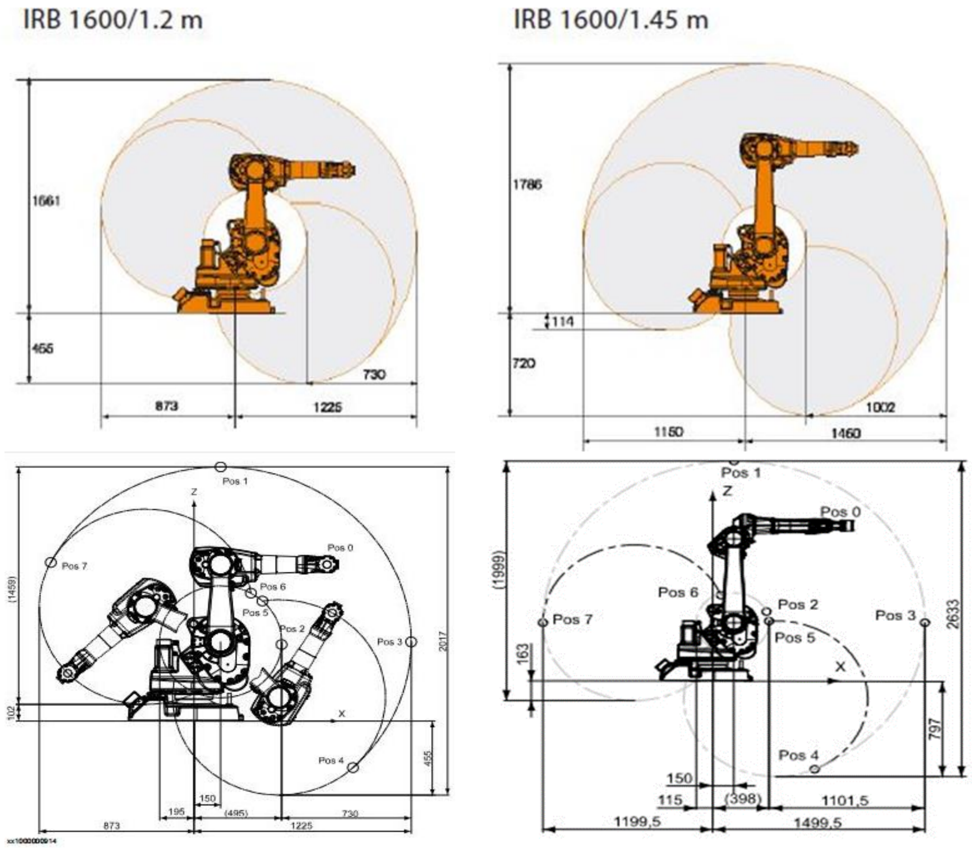


Fig. 5.2.4.9. Working range

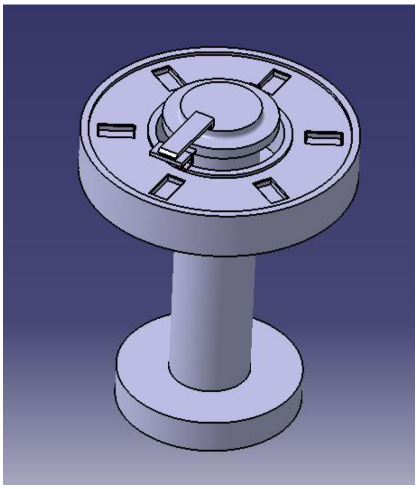


Fig. 5.2.4.10. Indexing table

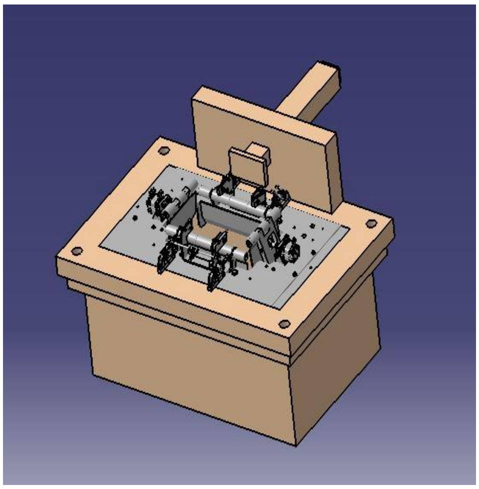


Fig. 5.2.4.11. Cardboard box forming machine

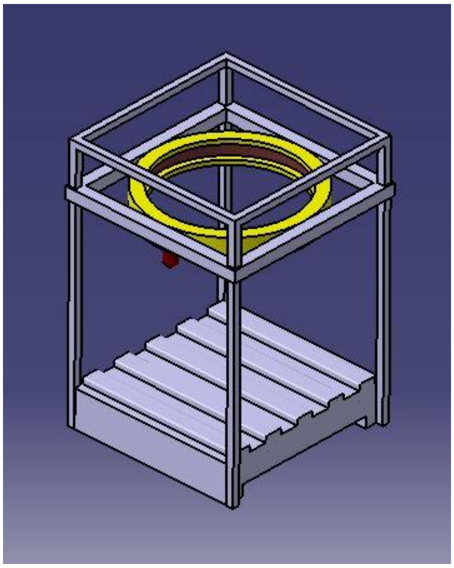


Fig. 5.2.4.12. Wrapping machine

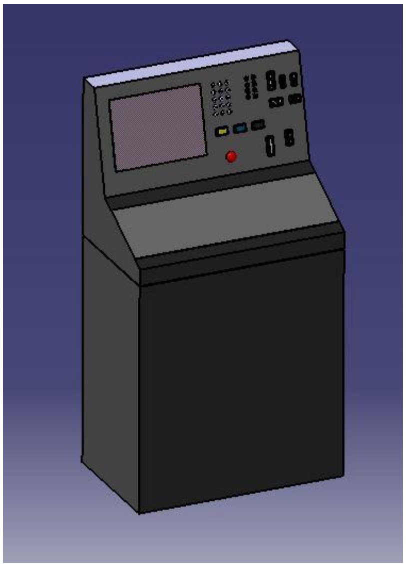


Fig. 5.2.4.13. PLC

For the automation of the process we used the following sensors:

1) Video inspection sensors

IMPERX manufactures high performance cameras for industrial, military, medical and municipal applications. Combining extensive, easy-use features with the best CCD and CMOS sensors, IMPERX cameras are available in resolutions from VGA to 29 MP. Designed to perform to the highest standards in harsh environments, the extended operating temperature is -40˚C to +85˚C with a MTBF > 660,000 hours @ 40˚C. IMPERX camera outputs: GigE Vision®, PoE, Camera Link®, CoaXPress and HD-SDI.

IMPERX leads the frame grabber market and was the first to introduce Camera Link®, HD-SDI and full analog video streaming to laptop computers. IMPERX laptop and desktop frame grabbers feature "Self-Learn" software, and advancement that eliminated the need for camera configuration files.

2) Proximity sensors

A proximity sensor is a sensor able to detect the presence of nearby objects without any physical contact.

A proximity sensor often emits an electromagnetic field or a beam of electromagnetic radiation (infrared, for instance), and looks for changes in the field or return signal. Details can be seen in figure 5.2.4.15.

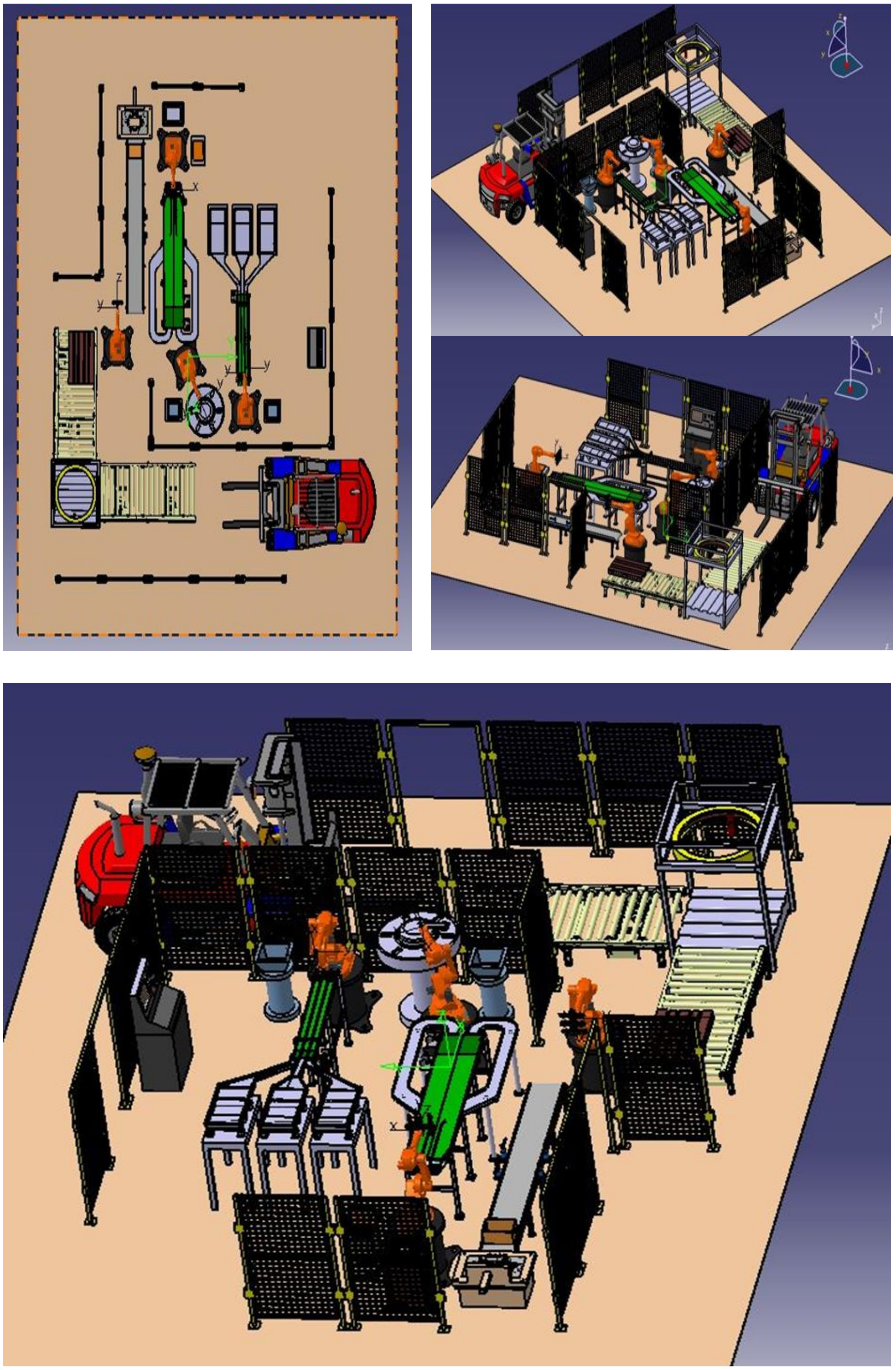


Fig. 5.2.4.14. Final design of the assembly line

The object being detected is often referred to as the proximity sensor's target. Different proximity sensor targets demand different sensors. For example, a capacitive or photoelectric sensor might be suitable for a plastic target; an inductive proximity sensor always requires a metal target.

The maximum distance that this sensor can detect is defined as "nominal range". Some sensors have adjustments of the nominal range or means to report a graduated detection distance.

Proximity sensors can have a high reliability and long functional life because of the absence of mechanical parts and lack of physical contact between sensor and the sensed object.

Proximity sensors are commonly used on smartphones to detect (and skip) accidental touchscreen taps when held to the ear during a call. They are also used in machine vibration monitoring to measure the variation in distance between a shaft and its support bearing. This is common in large steam turbines, compressors, and motors that use sleeve-type bearings.

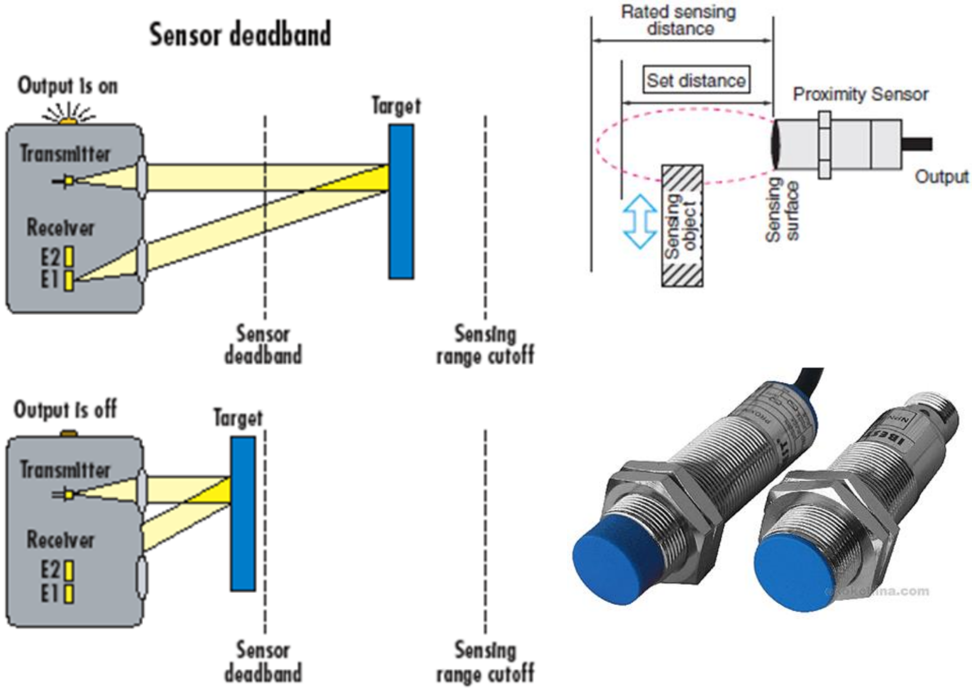


Fig. 5.2.4.15. Proximity sensors

3) Color recognition sensors

Available in two versions for application flexibility: QC50 models for most applications and QCX50 models for more challenging applications such as differentiating dark blue from black. Accurately analyzes and compares color to color or varying intensities of one color. Features easy-to-set push-button programming options for one, two or three colors. Delivers fast sensing with a response time of 335 microsecond for the QC50 and selectable 1 or 5 milliseconds for the QCX50. Features compact, self-contained design. Includes three programming parameters: channel, sensing mode and tolerance level. Available in models with three NPN or three PNP outputs, one for each color channel.

4) Photoelectric sensors

A photoelectric sensor, or photo eye, is an equipment used to discover the distance, absence, or presence of an object by using a light transmitter, often infrared, and a photoelectric receiver. They are largely used in industrial manufacturing. There are three different useful types: opposed (through beam), retro-reflective, and proximity-sensing (diffused).

The economic evaluation of the assembly robotic line can be observed in table 5.2.4.1.

Table 5.2.4.1. Economic evaluation of the assembly robotic line

No	Component	Price ($)	No. of elements
1.	Industrial robot IRB 1600-12-5.3	30.000	4
2.	Partitioned conveyor	3000	1
3.	Accumulation conveyor	4000	1
4.	Box conveyor	2500	1
5.	Pallet conveyor	3000	2
6.	Vibratory feeder	7500	3
7.	Indexing table	1500	1
8.	Cardboard box forming machine	6900	1
9.	Wrapping machine	3100	1
10.	PLC	10000	1
11.	Sensors	1000	5
12.	Auxiliary costs	5000	-
TOTAL		**185.500**	

Many thanks to our student, Natanael Catuna, for enabling us to present his solution for this case study!

5.2.5. 5th Project Example

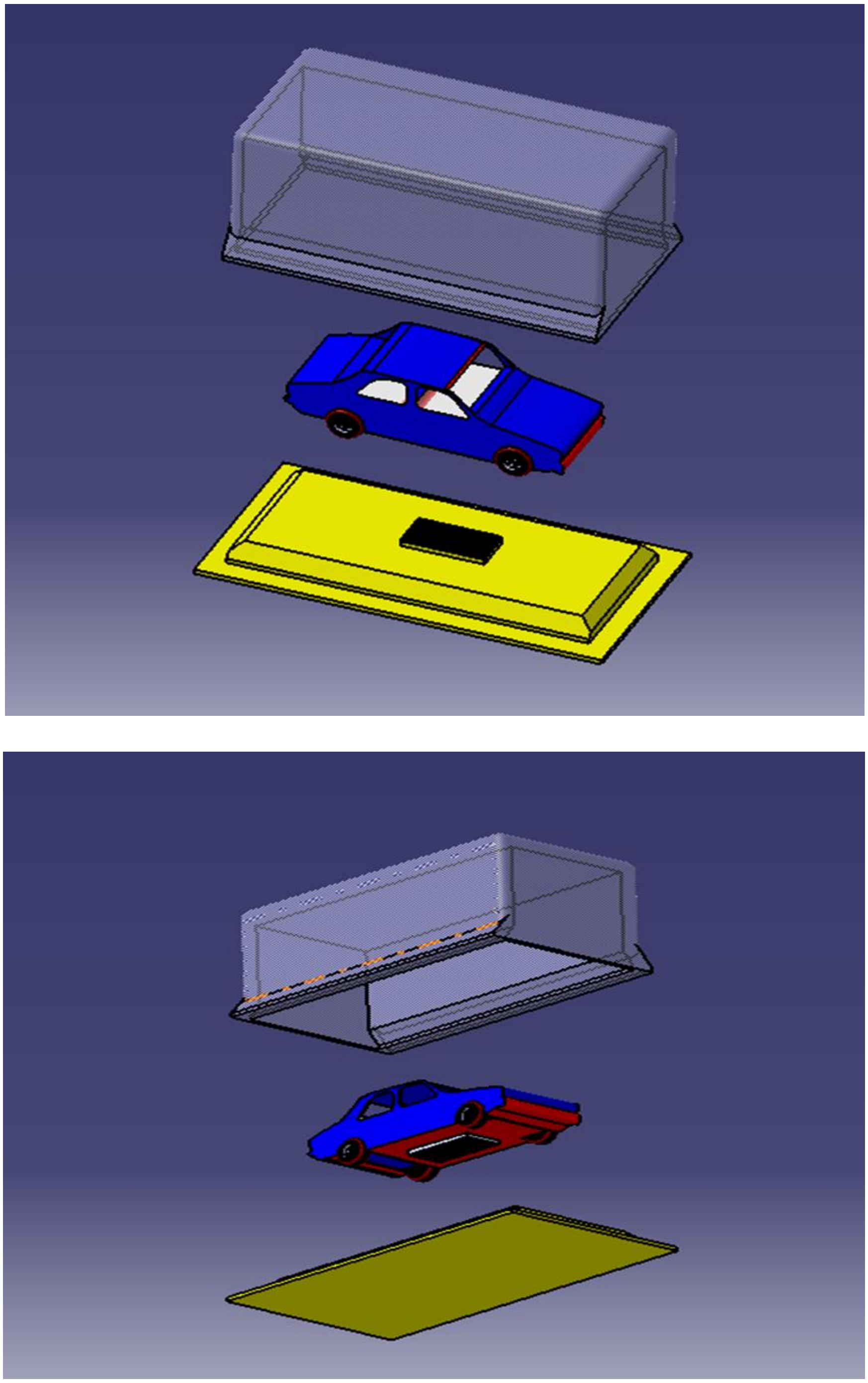
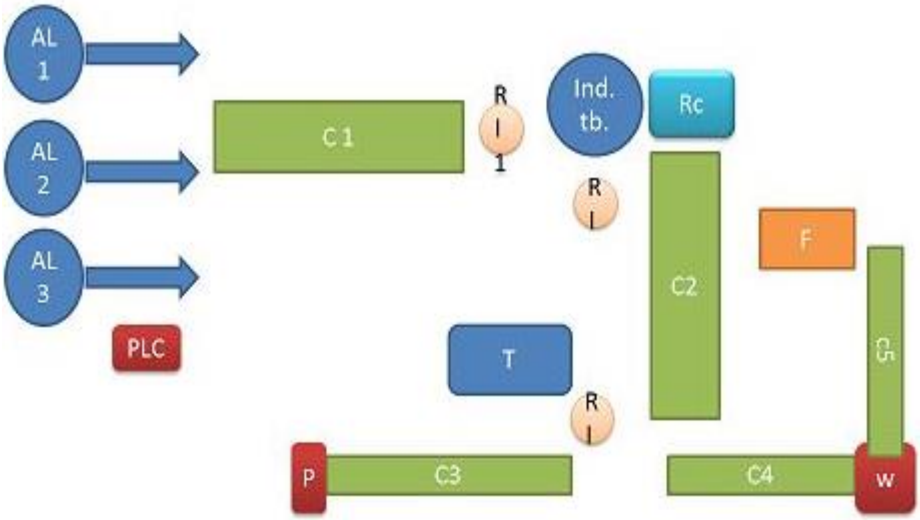


Fig. 5.2.5.1. The displayed product



AL1 – Belt conveyor feeder for car model
AL2 - Belt conveyor feeder for pedestal
AL3 - Belt conveyor feeder for cover
C1 – Belt conveyor with three dividers for each component part
RI1 – Industrial robot which makes the assembly
RI2 – Industrial robot with role in handling of the assemble
C2 – Accumulation conveyor which order based on colors the assemblies thanks to the video inspection system
RI3 – Industrial robot with 12 vacuum gripper
P - Box forming machine
C3 – Roller conveyor which transfer the boxes to the place where will be filled with the toy cars
C4 – Roller palette conveyor
W – Wrapping machine
C5 - Roller palette conveyor
F – Forklift machine
T – Table for the sheets of paper
Rc – recycling container
PLC

Fig. 5.2.5.2. Components of the assembly line

The process starts by operating the belt feeder for each component of the toy car and transferring of the elements on the conveyor. The parts are set on the indexing table by a robot, where the assembly performed by the robot takes place. The assembled product is transported by the second robot on the inspection section, which consists of a conveyor and a video inspection camera. With the help of the photoelectric sensors, the product's shape and size is detected. After this phase, the products will be manipulated by a robot, fitted in boxes, then transferred to the palletizing process. The proximity sensor sends the signal to the PLC to stop the conveyor, and, at the same time alerts the robot to start the palletizing process.

Packaging of the product will be made in boxes, in which 12 products (3x4) will be placed on 4 layers. In total, 48 products in each box. The order of each of the products is displayed in figure 5.2.5.1. The order identification of each product will be made with the help of the video inspection system. The palletizing process will be performed on euro-palettes of standard dimensions 1200X800 (mm).

After applying the DFAFD we have noticed that the assemble of the two screws gives some difficulties in the automation of the assembly process. Based on the results we considered another method which consist of assembling the parts with two precise magnets, one placed on the pedestal and one on the car.

The assembly line’s components are shown in figure 5.2.5.2. The 3D view of the assembly line can be seen in figures 5.2.5.3, 5.2.5.4 and 5.2.5.5.

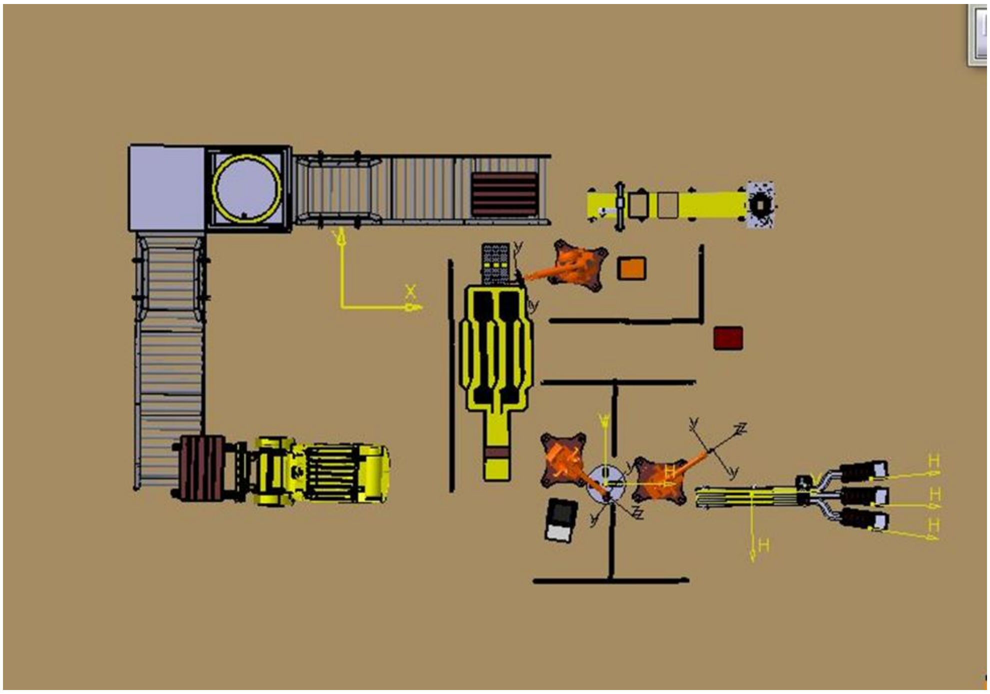


Fig. 5.2.5.3. The 3d model of the assembly line - top view

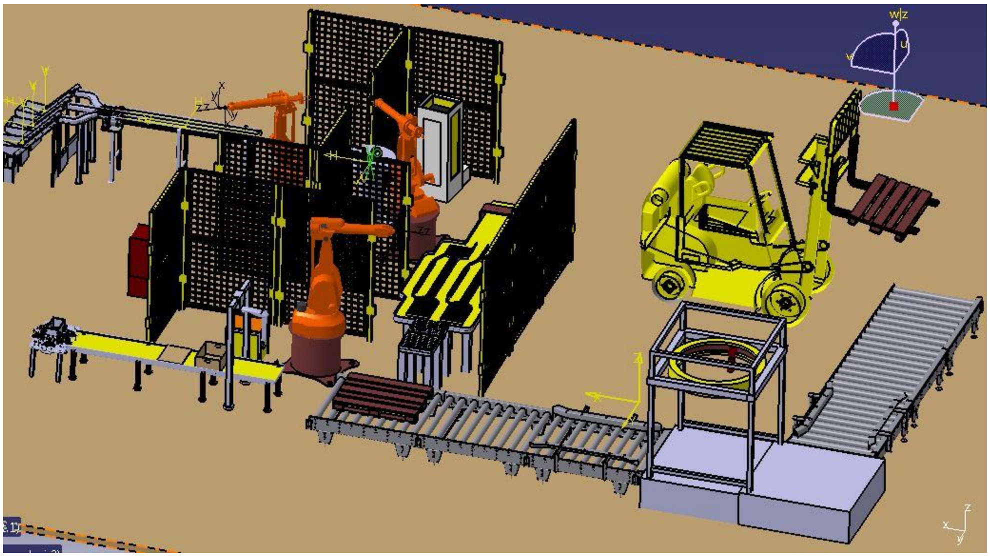
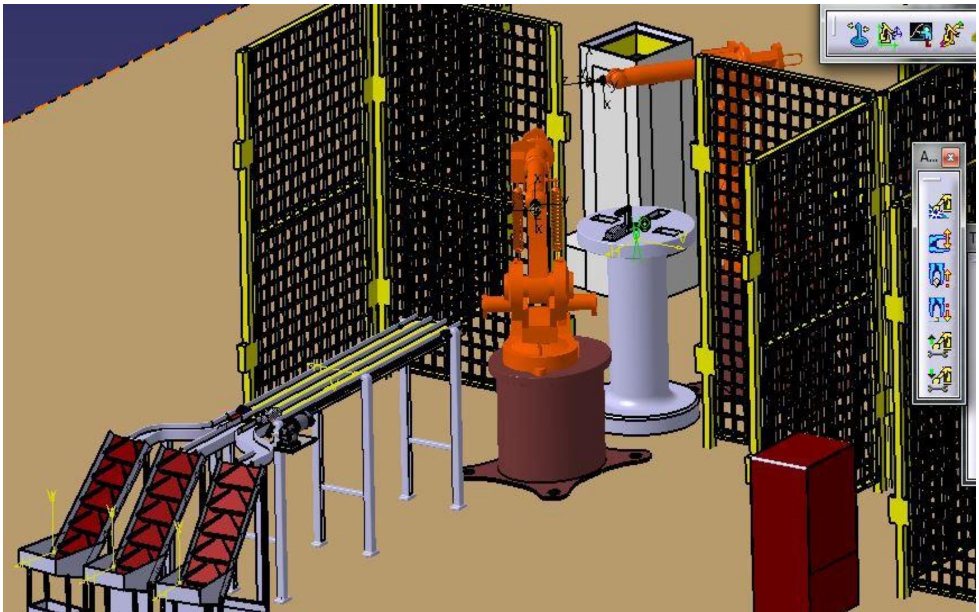


Fig. 5.2.5.4. Assembly and palletizing line - isometric view



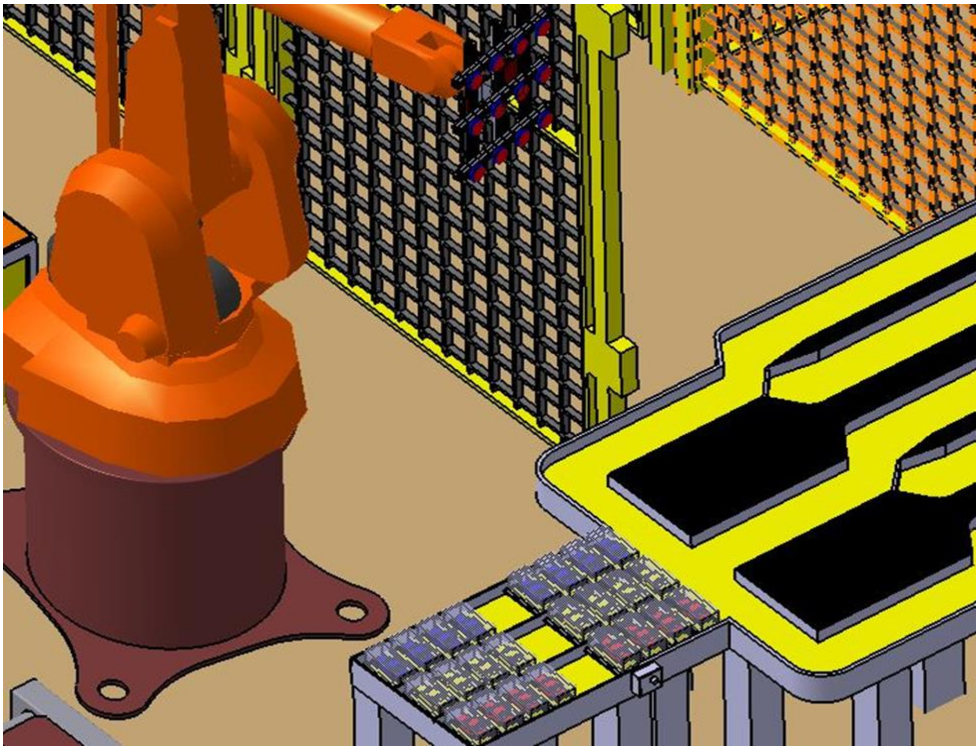


Fig. 5.2.5.5. Assembly cell

In the process we will use the following sensors:

- 2 Inductive proximity sensors
- 2 Photoelectric sensors: Detect Object - plastic, PVC, magnetic, metal, etc.
- 2 Video camera inspection

Economic evaluation of the robotic cell:

- 3 x INDUSTRIAL ROBOTS – 2 x IRB 1410 - 20.000 euros each
  – 1 x IRB 2400 - 25.500 euros each
- 2 x palette conveyors - 1569-175 pitch - 4.000 euros each.
- 1 x roller conveyor (for the boxes) - 800 euros
- 1 x accumulation conveyor - 5.600 euros
- 1 x conveyor - 800 euros
- 3 x belt feeder- 5.000 euros each
- 1 x wrapping machine - 4.000 euros
- 1 x indexing table - 1.300 euros
- 1 x packaging machine for cardboard boxes - 12000 euros
- 1 x forklift vehicle – 10000 euros
- 2 x photoelectric sensors - 12 euros each
- 2 x proximity sensors - 20 euros each

- 2 x inspection video system - 50 euros
- 2 x simple vacuum grippers - 40 euros each
- 1 x 12 vacuum gripper structure - 472 euros
- 1 x PLC - 9000 euros

TOTAL cost of the system: 236868 EUROS

Many thanks to our student, Florin Valentin Pausan, for enabling us to present his solution for this case study!

5.2.6. 6th Project Example

Fig. 5.2.5.1. Scaled replica of the DACIA 1300 model car

The product of the factory is a toy car, a scaled replica of the DACIA 1300 car, as seen in figure 5.2.5.1.

Initially, the car was assembled manually to the pedestal, using 2 screws placed underneath the car and the pedestal. The process had very low efficiency and needed repetitive work done by the human operators.

Using a DFAFD analysis, we got high scores, which meant that the chosen process is suitable for robotization, not only practically, but also theoretically, on paper.

The robotized process consists of two flexible cells, one for assembly and one for palletizing. Each cell will have one articulated robot and a couple of pneumatic manipulators for handling the products. The process would have a consistent higher productivity and a better economic report. The robotized system aims for a low reboot rate and fast debugging, in case it is needed.

The robotized system is divided in 3 sub-systems:

- Assembly – as seen in figure 5.2.5.2
- Packaging – as seen in figure 5.2.5.3
- Palletizing – as seen in figure 5.2.5.4

The assembly process should follow the logic of the product assembly. The product consists of the following parts:

- Bottom
- Pedestal
- Car model
- Case

The bottoms are contained in an industrial stack holder. They are placed on the rotary table using a 2-degrees of freedom pneumatic manipulator, having as an end-effector a small suction cup. The rotary table has 4 dwellings, each of them having a vacuum underneath. The rotary table indexes with the first 90 degrees movement, and takes the bottoms in front of the gluing robot. The gluing robot is a 3-degree Cartesian robot which accurately applies glue on the bottoms' margins. The rotary table indexes another 90-degree movement, taking the bottoms in front of the ABB IRB 120 articulated robot. The serial manipulator has to pick and place the pedestal, car and case, in this order, from the conveyors surrounding it.

The pedestals are introduced on the conveyor from a vibrating feeder. The cars are introduced from a pneumatic rotary feeder at the end of the conveyor. They come randomly in red, yellow or blue color. The cases are fed, as the bottoms, from a stack holder, nearby the robot.

After the industrial robot picks and places the pedestal, it will put the car over it. The 2 parts will snap together due to the complementary LEGO assembly. After this assembly, the robot will wait for the signal given by the 2-optical sensors, which are placed near the margins of rotary table. Both have to confirm the presence of the car, in order for the robot to do the final assembly, which consists of putting the case over the car, matching the glued margins of the bottom, applying pressure, in order for the case and bottom to hermetically snap together.

If the signal from the sensors in not given in 3 seconds, the robot will check with its optical sensor, whether the product exists or not. If it does exist, but it was not well placed, the robot will place it on the conveyor which will take the product to the reboot container. If the product does not exist at all, then the process restarts from the point where the bottoms arrive in front of the robot.

Next, the rotary table indexes another 90-degree rotation, taking the product in front of the conveyor, which will take it to the following operation. In order for the product to exit the index table, a linear motor will push it out. The motor is set parallel with the conveyor.

$$positions := 4$$

$$speed := \frac{4}{min}$$

$$A := 0\ deg$$

$$B := \frac{360\ °}{positions} = 90\ deg$$

$$C := 270\ deg$$

$$D := 360\ deg$$

$$index\_time := \frac{B}{360\ °} \cdot \frac{1}{speed} = 3.75\ s$$

$$dwell\_time := \frac{D}{360\ °} \cdot \frac{1}{speed} = 15\ s$$

$$cycle\_time := index\_time + dwell\_time = 18.75\ s$$

$$production\_rate := \frac{1}{cycle\_time} = 192\ \frac{1}{hr}$$

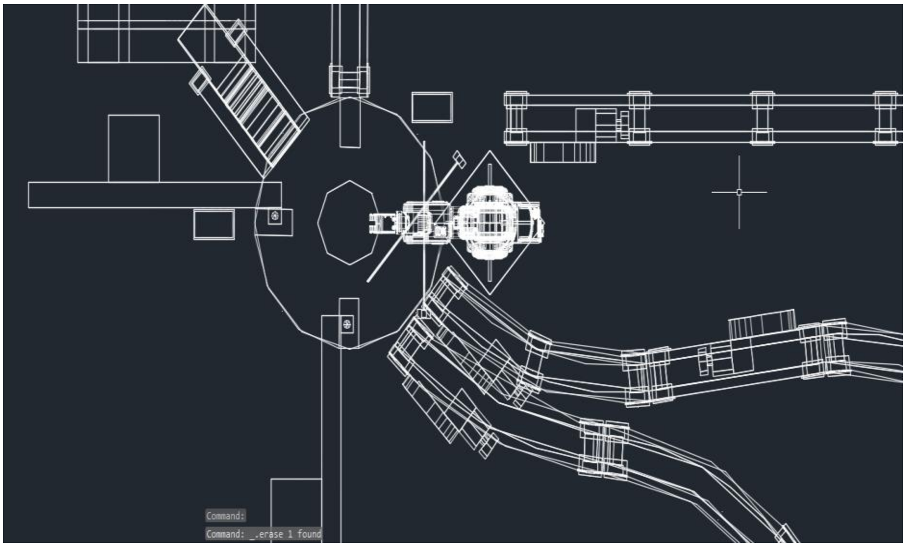


Fig. 5.2.5.2. The assembly of the product

Packaging process

Before being put into boxes, the products have to be checked for quality and sorted by color. In order for this to happen, another 2 optical sensors will check the product. If the car is not correctly placed on the pedestal, the whole product will be pushed onto the conveyor taking it to the second reboot container.

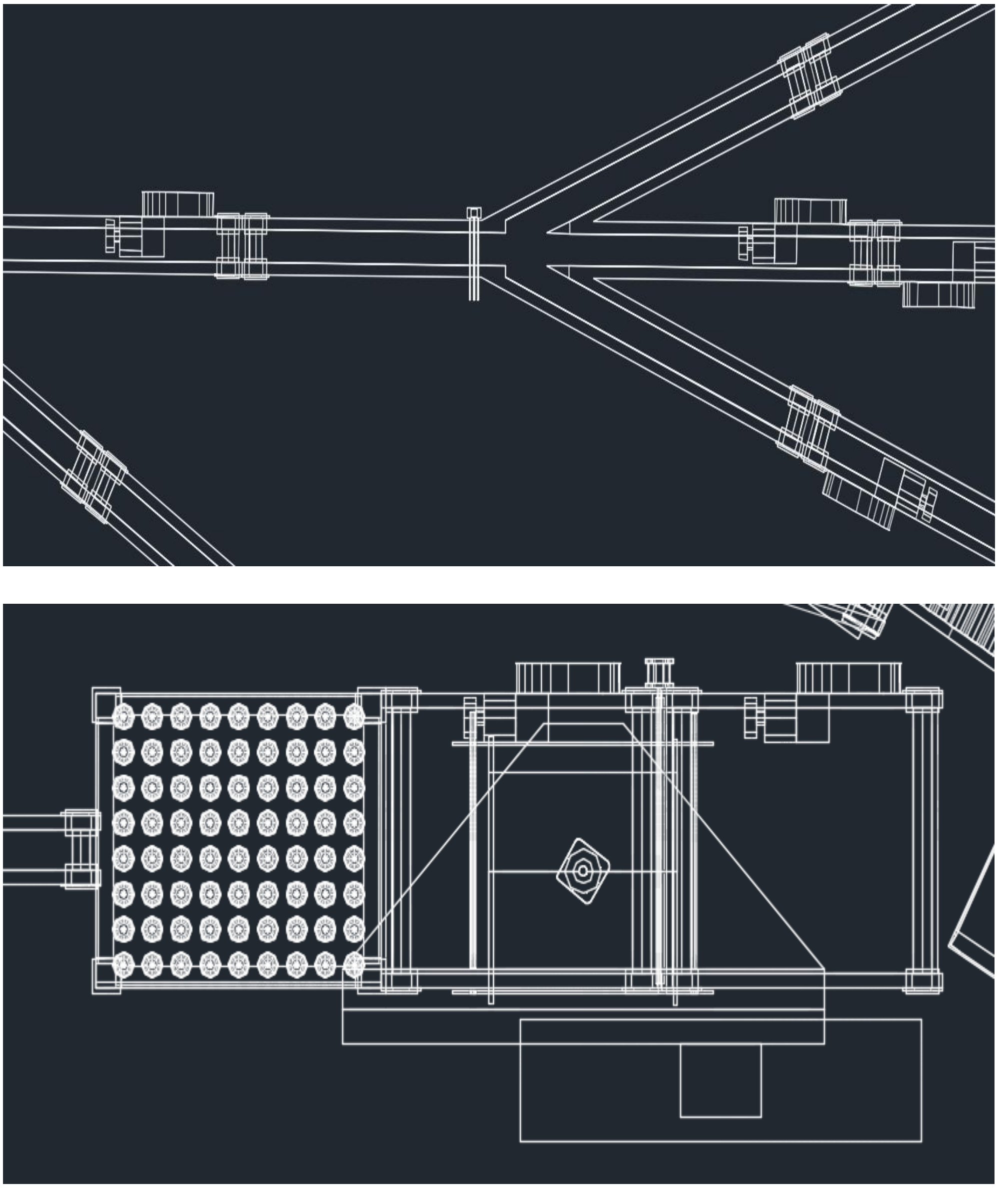


Fig. 5.2.5.3. The packaging of the product

If the product passed the second quality check, then the main conveyor takes it through the color inspection zone. The inspection is done by an industrial RGB color sensor. The sensor will inform the PLC of the color of the products. The PLC will command the 2 linear motors which are set in front of the conveyor trifurcation. If the color of the product is red, the motor set on the left will push the product on the right branch, and vice versa if the product is blue. If the product is yellow, it will continue onto the main branch. Near the unification point of the 3 branches of the main conveyor, barriers are installed, in order for the cumulating and the ordering of the products. One product will be released in time by each barrier, so that they enter as ordered on the main conveyor, the first red, the second yellow and the third blue.

The products are then arranged on a much broader conveyor by a ball transfer conveyor. It will make queues with products of the same color. Nearby, a bigger barrier is placed, in order to cumulate the exact number of products needed. After 3 queues of 4 pieces each will be filled, the barrier will let them pass onto the next conveyor. This conveyor will stop immediately after the 12 products enter the line.

A pneumatic manipulator having 2-degrees of freedom will put a metal case over the products. The case modifies its dimensions by adjusting its width. This is done by a moving barrier, commanded by 2 stepper motors. The aim is to wrap together the 12 pieces, leaving no space between them.

Then the pneumatic manipulator raises the metal case, leaving space for the second articulated robot, ABB IRB 4600, a robot specialized in palletizing.

Before palletizing, it will grab the 12 products with its gripper having 12 suction cups, and place them inside the box that arrived from the automatic case erector. After each series of 12 pieces, the robot will grab a sheet of paper from a stack and place it over them. After 4 series of 12 products, the conveyor on which the box is sitting, will start and take it to the automatic case sealer while, also, bringing another empty box in front of the robot.

Palletizing process

The last step is the palletizing. The robot will grab the newly sealed box from the conveyor and place it on the pallet nearby. The pallet cumulating the boxes is placed on a pallet conveyor. The pallet conveyor transports the pallets from the pallet feeder, in front of the robot, waits for the pallet to be stacked and takes it to the AGV waiting for the pallet.

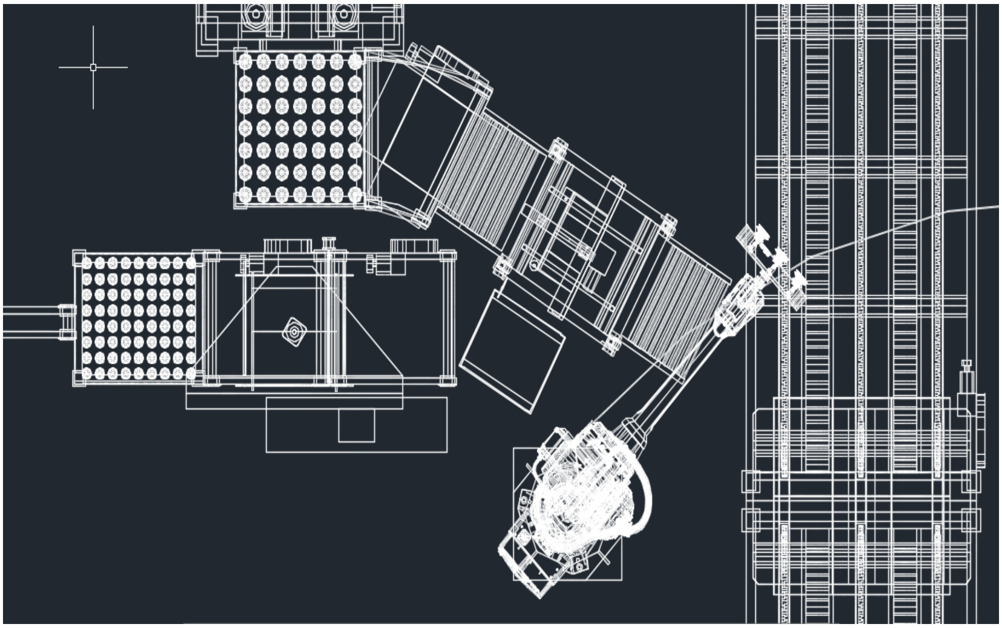


Fig. 5.2.5.4. The palletizing of the products

The robot will place rows, each consisting of 2 boxes and cover them with a large sheet of paper that comes from the paper supply unit. After completing 4 stocks, the pallet will be ready to be taken outside the factory, with the AGV. A forklift operated by a human operator will be waiting for the AGV in front of the lorry. It will take the pallet from the AGV and take it in the back of the lorry.

Economic evaluation of the robotized cell:

Equipment	Price (Euro)
Robots	105000
Pneumatic manipulators	40000
Conveyors	20000
Case erector	20000
Case sealer	15000
Feeders	40000
AGV	25000
Forklift	5000
Others	10000
Total	**280000**

The logic diagram of the process can be observed in figure 5.2.5.5.

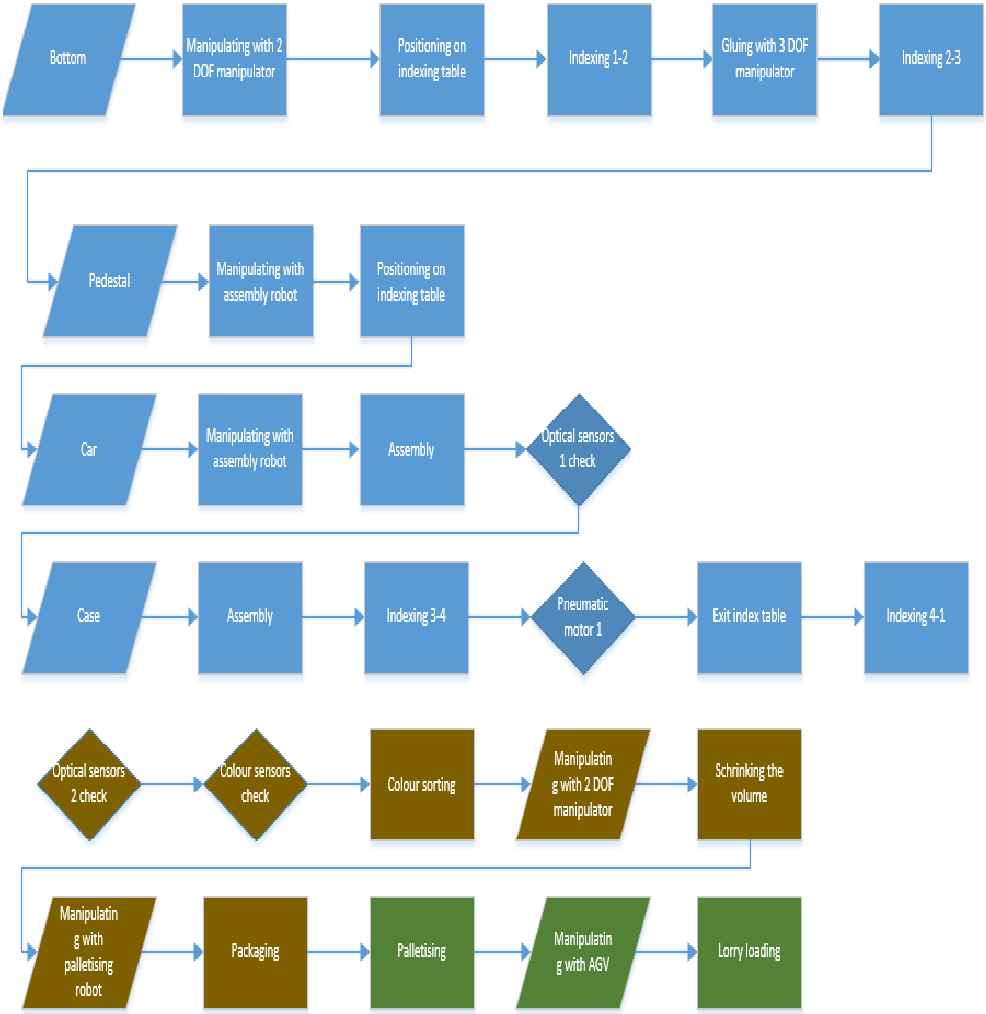


Fig. 5.2.5.5. Logic diagram of the process

A robotized assembly and palletizing line may be expensive, but, if we take into consideration a long-term strategy for a company, it is highly feasible because it strengthens the quality and speed of the process and decreases human costs and potential injuries.

Many thanks to our student, Cosmin Delea, for enabling us to present his solution for this case study!

5.3. Second case study: assembly and palletization of electric switches

The examples of the projects outlined below are the exclusive vision, conception, and implemented solutions developed by each student or team of students who have worked on each project.

5.3.1. 1st Project Example

At the beginning of the project, the extension is assembled manually. Taking into consideration the idea of reducing assembly time and production costs, we chose to redesign the original product and to automate/robotize the assembly and palletizing line.

Assembling is an important process in production because it is an important component of the total cost of production.

In order to analyze and redesign the product and the assembly process, we will use the DFAFD (Design for Assembly Function Deployment) method. This method helps to get a better view of the design process and the product.

The initial product (Fig. 1.3) has the following components:

A. Top cover;
B. Blades;
C. Switch Mode;
D. Lower cover;
E. Fastening screws.

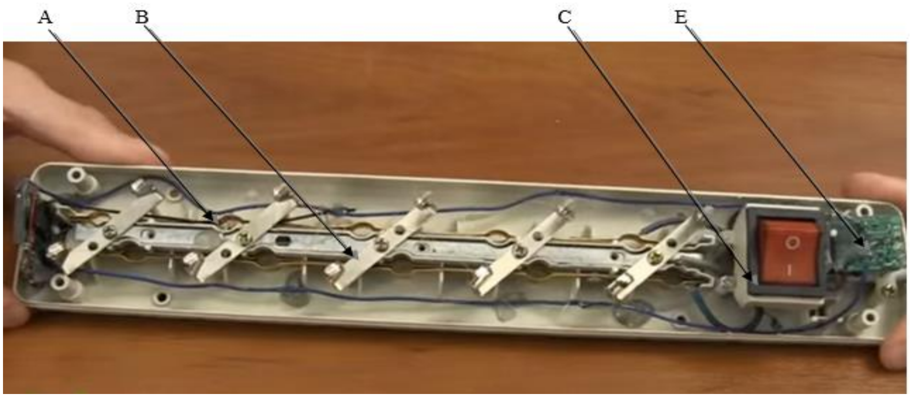


Fig. 5.3.1.1 Initial product

The diagram of interdependence of component parts is presented in figure 5.3.1.2, while the draft of the assembly process is presented in figure 5.3.1.3.

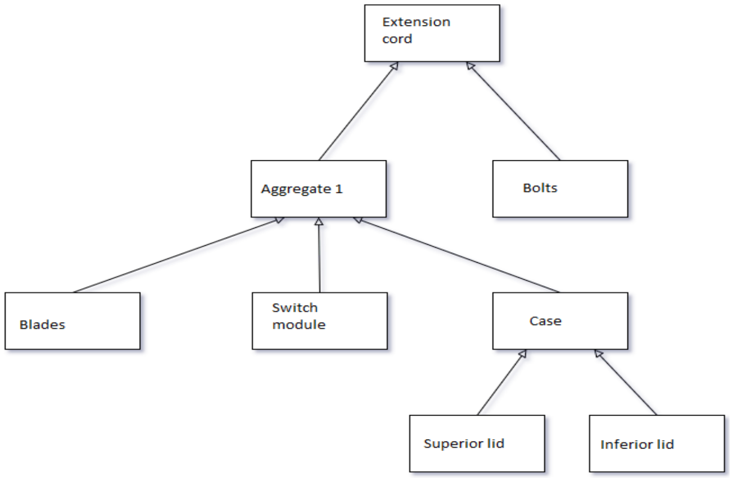


Fig. 5.3.1.2. Diagram of interdependence of the component parts

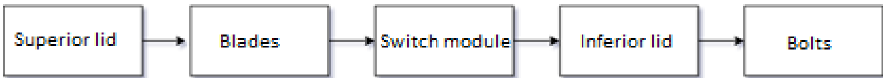


Fig. 5.3.1.3. The draft of the assembly process

To analyze the initial product and the assembly process, we will use the DFAFD method. The results of this method are presented in table 5.3.1.1.

Table 5.3.1.1. DFAFD results for the initial product

Sum(Ti)	Target
2219.00	1223.00
2219.00	1223.00
2291.00	1049.00
2291.00	1049.00
2117.00	835.00
2138.00	697.00

Sum M	Sum T
13275.00	6076.00

Procent Qr
45.77024482

Weaknesses and intervention priorities are presented in table 5.3.1.2.

Table 5.3.1.2. Weaknesses and intervention priorities

Weaknesses	**Intervention priorities**
Bolts	They will be removed
Carcass	It will be redesigned

The bolts' clamping of the case is a weakness of the product because they are extremely difficult to mount with a robot. When redesigning the carcass, it should be taken into account that the grip must be rigid in order not to endanger the user's life, but also to be easily dismantled if a malfunction occurs.

As a result of these observations, the extension will need to be redesigned so that its assembling can be done on an automated line.

As a result of redesigning the extension, the bolts have been removed so that the robot has no difficulty in assembling the carcass. Figure 5.3.1.4 shows how the two top and bottom lids are clamped by four clamps.

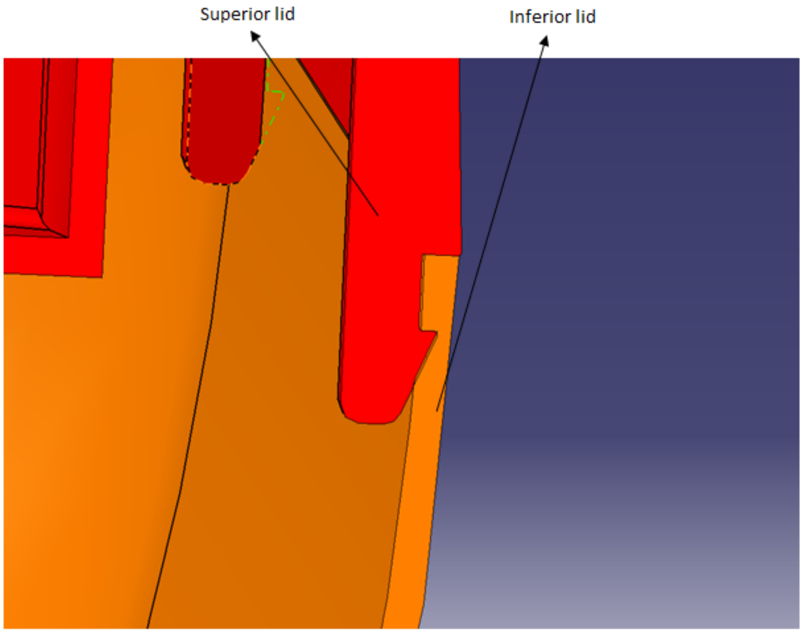


Fig. 5.3.1.3. Clamping of the top and bottom lids

The diagram of interdependence of component parts of the final product is shown in figure 5.3.1.4 and the draft of the assembly process of the final product is shown in figure 5.3.1.5.

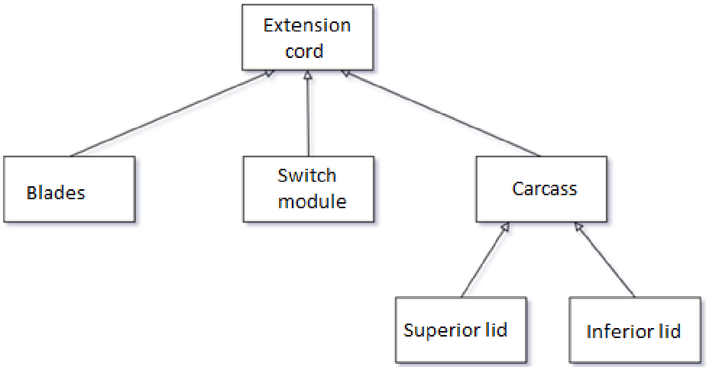


Fig. 5.3.1.4. The diagram of interdependence of component parts of the final product

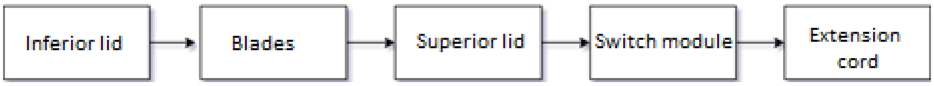


Fig. 5.3.1.5. The draft of the assembly process of the final product

For a better understanding of the assembly process, the pieces of the finished product are shown in figures 5.3.1.6, 5.3.1.7, 5.3.1.8 and 5.3.1.9 below.

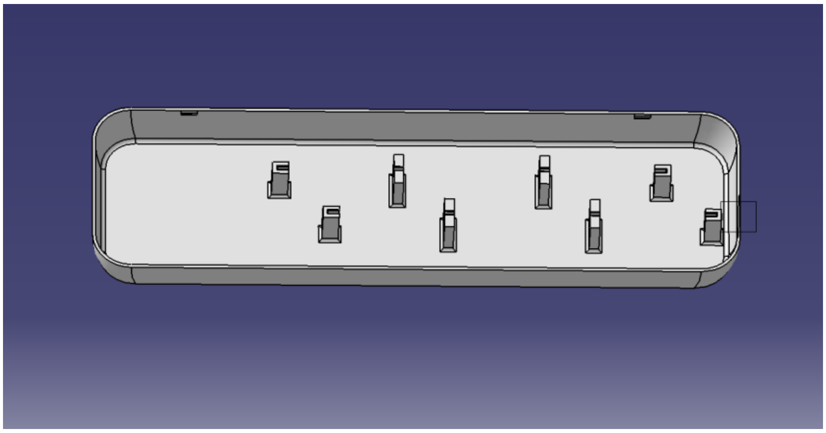


Fig. 5.3.1.6. Inferior lid

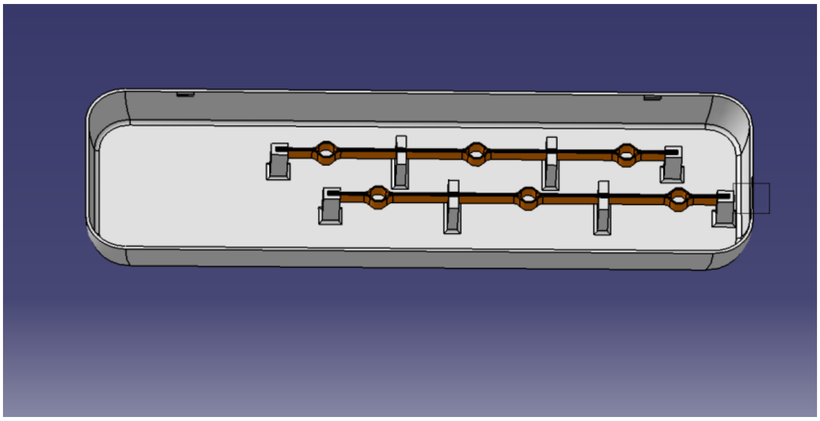


Fig. 5.3.1.7. Blades

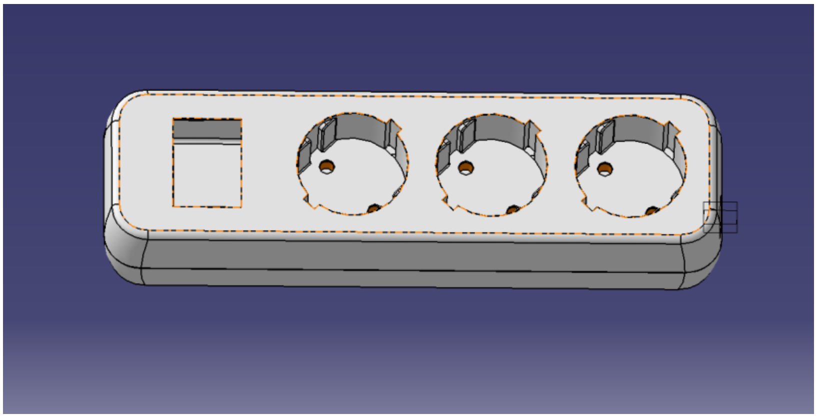


Fig. 5.3.1.8. Superior lid

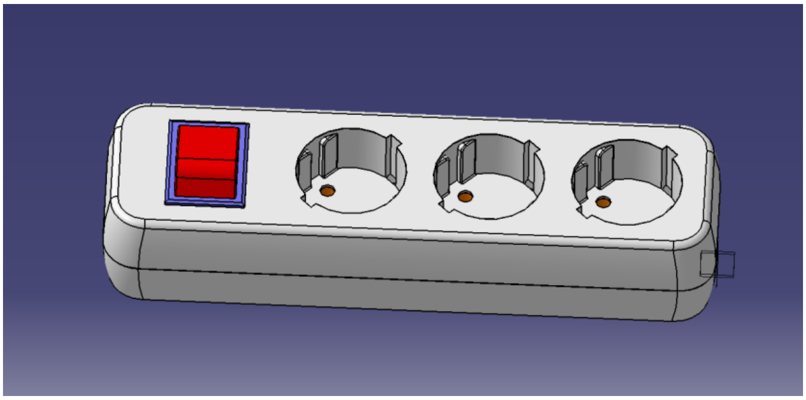


Fig. 5.3.1.9. Switch module

After redesigning the product, we will apply the DFAFD method to see if the actual product is better than the previous one. The result of this method is presented in table 5.3.1.3.

Table 5.3.1.3. Results of the DFAFD method

Sum M	Sum T
11637.00	5871.00

Procent Qr
50.4511472

If we compare the results of the two tables, we will see an improvement.

The robotic cell shown in figure 5.3.1.10 is designed for assembling and palletizing the electrical extensions and has the following components:

A. 3 IRB 1600 robots
B. 1 IRB 4400 robot
C. 2 helical feeders
D. 2 vertical feeders
E. 2 accumulating conveyors
F. 1 index table
G. 4 tape conveyors
H. 4 roller conveyors
I. 1 packing machine
J. 1 carton box format
K. 1 sealing machine boxes
L. 1 pallet feeder
M. 1 folding machine
N. 1 forklift
O. 2 cardboard holders

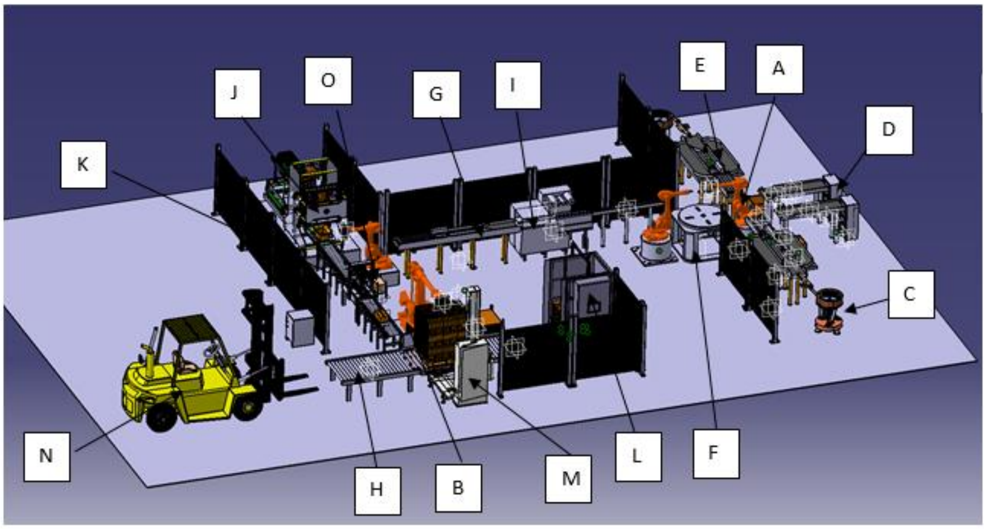


Fig. 5.3.1.10. Assembling and palletizing cell

For a better understanding of the technological processes within the cell, we will divide it into three important subdivisions:

1. Supply and assembly area;
2. Packaging area;
3. Palletizing area;

These will be explained in more detail below.

Supply and assembly area:

In this area, both the power supply and the assembly of the product take place. In figure 5.3.1.11 one can see area 1 with its components.

A. 2 IRB 1600 robots
C. 2 helical feeders
D. 2 vertical feeders
E. 2 storage conveyors
F. 1 index table

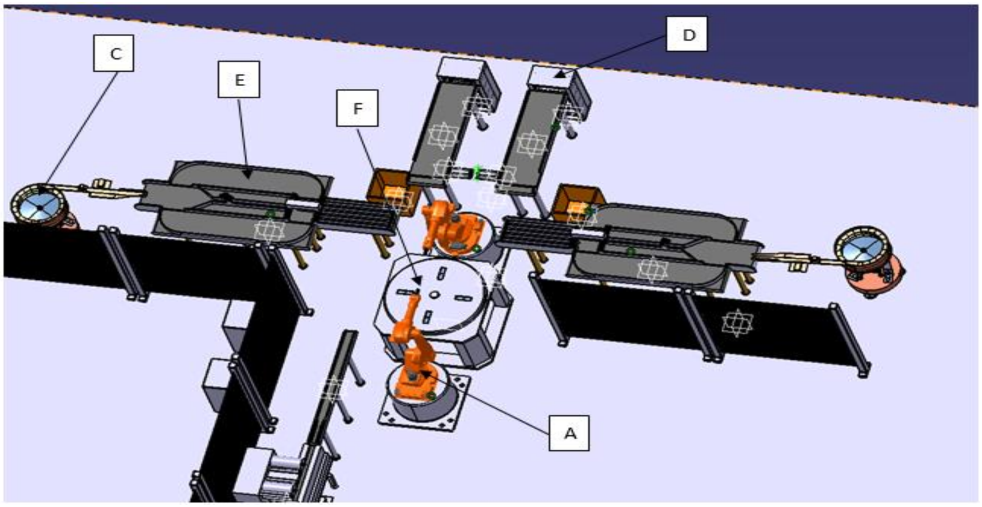


Fig. 5.3.1.11. Supply and assembly area

Packaging area:

Packaging of the finished product takes place in this area. After assembly, the product is transported on a conveyor to the packaging machine. The bag-wrapping machine uses a roll of foil, forming the bags. After packing, they reach a storage conveyor where they are sorted by color. An IRB 1600 robot picks up the extensions and puts them into boxes. The robot gripper is capable of grabbing 8 pieces.

After all the 32 extenders have been put in the box, it goes further to the box-lock machine. The displacement of the boxes is made on roller conveyors.

The packaging area contains the below elements, presented in figure 5.3.1.12.

A. 1 IRB 1600 robot
G. 2 tape conveyors
H. 2 roller conveyors
I. 1 packaging machine
J. 1 carton box format
K. 1 sealing machine boxes
O. 1 cardboard carrier

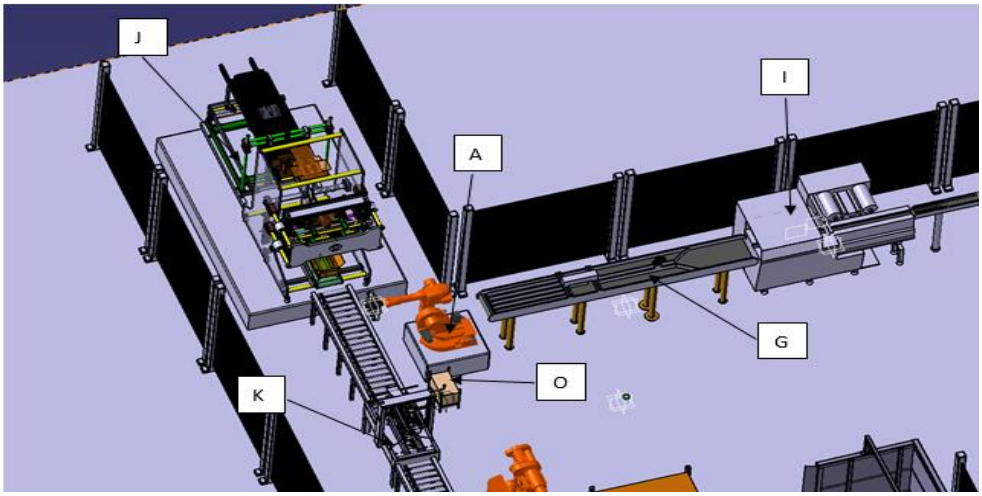


Fig. 5.3.1.12. Packaging area

Palletizing process

In this area (Fig. 5.3.1.13) there is the final stage, the palletization. The sealed boxes will be transported on a roller conveyor to the IRB 4400 robot area. It will take them and place them on a pallet. At the end of the stack, the pallet will be inflated and then picked up by a human operator and taken to the storage area.

B. 1 robot IRB 4400
L. 1 pallets' loader
M. 1 wrapping machine
N. 1 fork lift
O. 1 cardboard sheets support

The purpose of this project was to improve a product. To reach the goal I used the methods learned during this semester at school. After analysing the original product by the DFAFD method, we redesigned the product so that its packaging can be made on an automated line. Automating the production process has the advantage of increasing productivity by reducing production time.

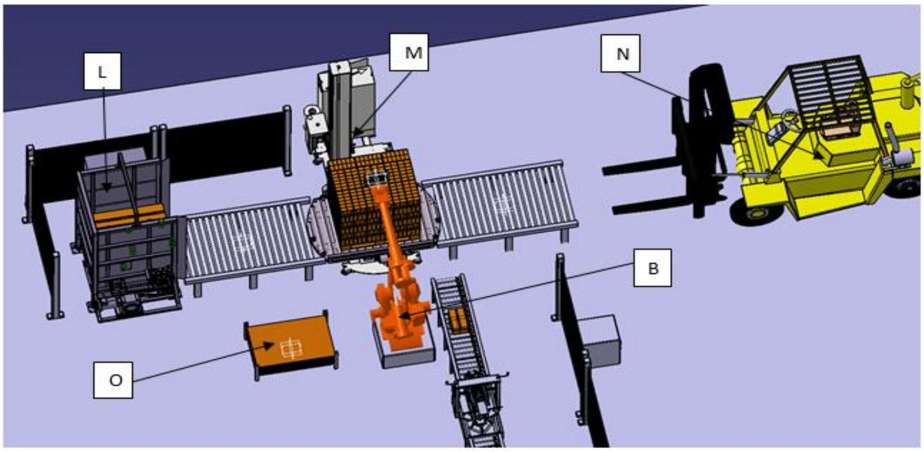


Fig. 5.3.1.13. Palletization area

We can say that due to the results of the DFAFD method, we were able to improve both the technology and the finance part. This leads to higher productivity and higher revenues.

Many thanks to our students, Calistru Cosmin and Gheorghe Slevoaca, for enabling us to present their solution for this case study!

5.3.2. 2nd Project Example

The initial product is assembled manually, presenting the extension before redesigning the product and applying the automation/robotization solutions to the process.

Structure of the product and interrelations of the parts:

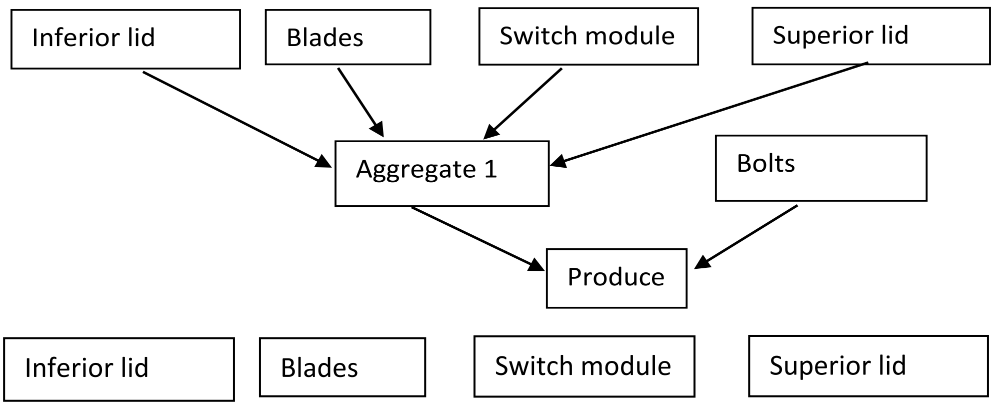


Fig. 5.3.2.1. Draft of the product's structure

Following the analysis of the above diagram in figure 5.3.2.1, it has been observed that designing a robotic cell of the initial product will be quite difficult to accomplish, due to the top cap attachment system on the lower lid. This would be done by gripping with bolts that can be screwed by hand or using rather complex devices.

To highlight the weaknesses of the inherent product from the perspective of the robotic process, we have used the DFAFD method. Following the DFAFD analysis, a 43.90% ease of installation was obtained, to show how difficult it would be to assemble this extension with a robotic cell.

It can be noticed that there are problems with all parts of the original product, especially the 3x15 bolts, which would make it difficult to screw on correctly.

So it has come to the conclusion that the extension has to be redesigned so that robotic assemblies can be adapted.

After redesigning the extension, the 3x15 holsters were dropped and I chose a fastening and locking mechanism as a fastening for the upper cover on the lower one. The top cover is provided on one side and the other with a clamp, which, by a simple push and a translation movement, enters the left and right lower case, thus making a simple and precise assembly. In order to disassemble the extension, it is necessary to apply the opposite force, each cap being drawn in different directions guided by the guides of the clamping system. In figure 5.3.2.2 below are presented the redesigned versions of the lower and upper cover.

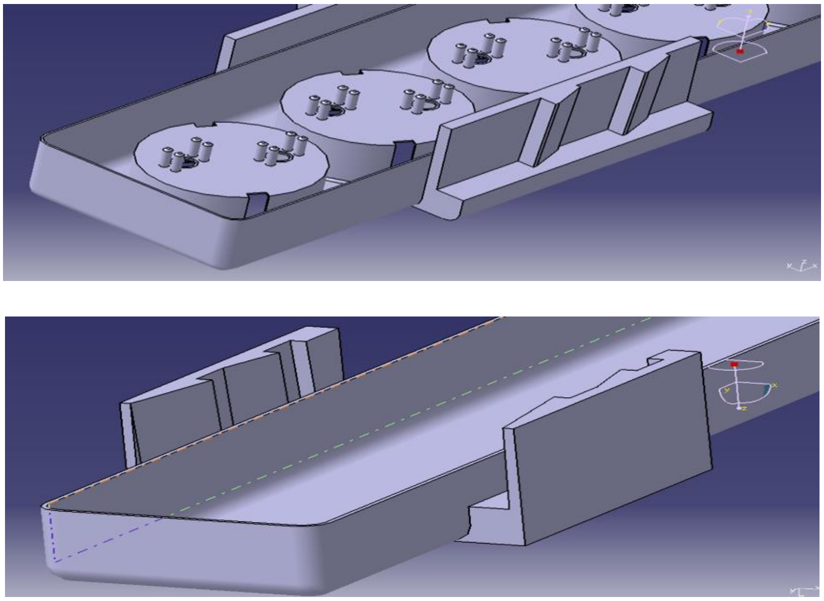


Fig. 5.3.2.2. Superior and inferior lid after redesign (top to bottom)

Figure 5.3.2.3 shows how to assemble the lower cap assembly, the blades, the switch module and the top cover.

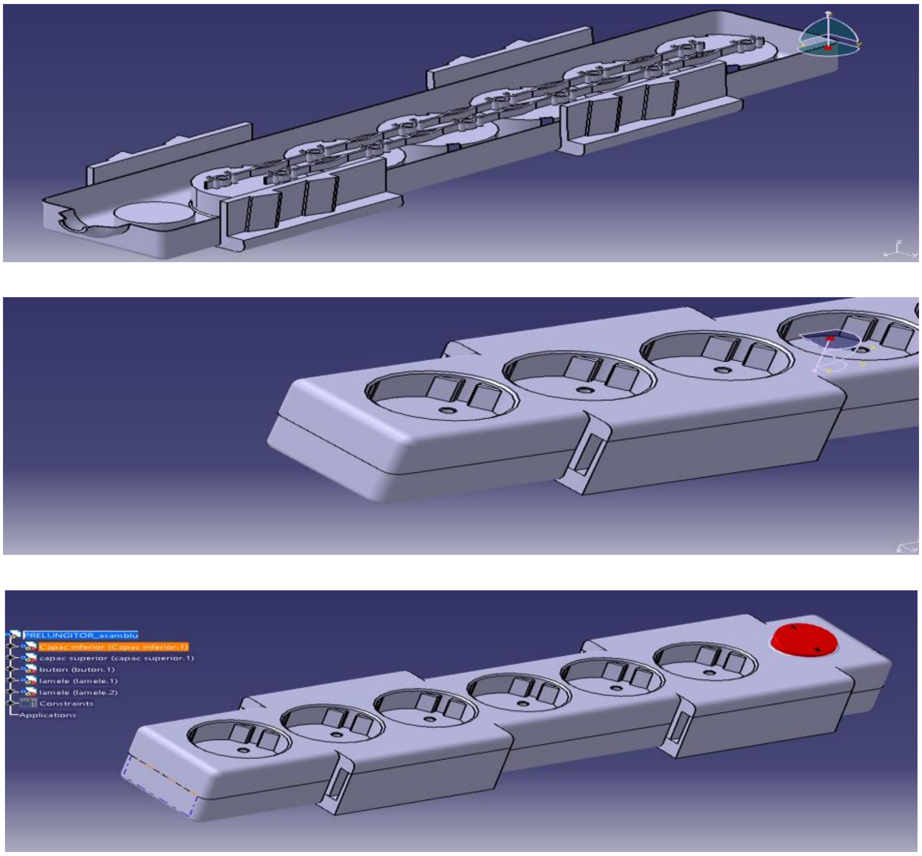


Fig. 5.3.2.3. Assembly of the lower cap assembly, the blades, the switch module and the top cover; final product (top to bottom)

From a structural point of view, the robotic assembly cell (Fig. 5.3.2.4) is divided into three important areas:

- Power supply and assembly areas for component parts;
- Colouring and colouring area;
- Packaging and palletising area;

Supply and assembly area of component parts:

The main components of this area are (Fig. 5.3.2.5):

- Kit feeders;
- Conveyors with tape;
- Index table;
- Video-inspection camera
- ABB IRB 2400L Robots

- Gripper with fingers;
- Robot controllers;
- Conveyor with storage;
- Sensors.

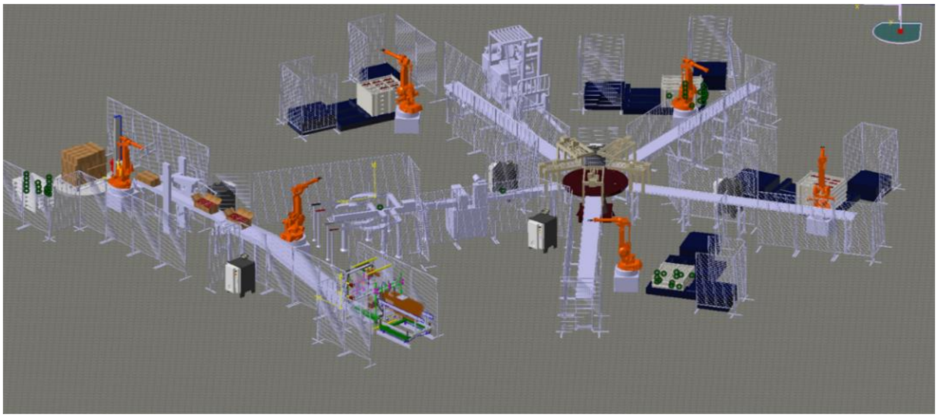


Fig. 5.3.2.4. The robotic assembly cell

In order to feed the parts, we will use forklifts that will place the kits with pieces in the area intended for them and then they will be fixed with the help of two pistons. Next, the ABB 2400L will take over and put them on the conveyor where they will be transported to the assembly area.

Four Cartesian robots will be used in the assembly area. Each of them will handle a component part of the extension and the assembly table will be assembled. After the assembly was completed the 5^{th} cartesian robot will move the extension on a conveyor. Then the next stage will be the in foliation.

The components of the supply and assembly area include the following:

- Forklift
- ABB 2400L
- Conveyors with tape
- Feeders
- Video-inspection camera
- Cartesian robots
- Proximity sensors

The wrapping area and color sorting:

The electrical extender after being picked up the 5^{th} cartesian robot on the index table and placed on the conveyor will be guided along the conveyor belt to the area where it will be inflated. After this, it will move through a video inspection area. In this area, the video inspection will recognize the color of the extension and let the command of the guides close in the accumulating area specific to each color. The process's machines are presented in figure 5.3.2.6.

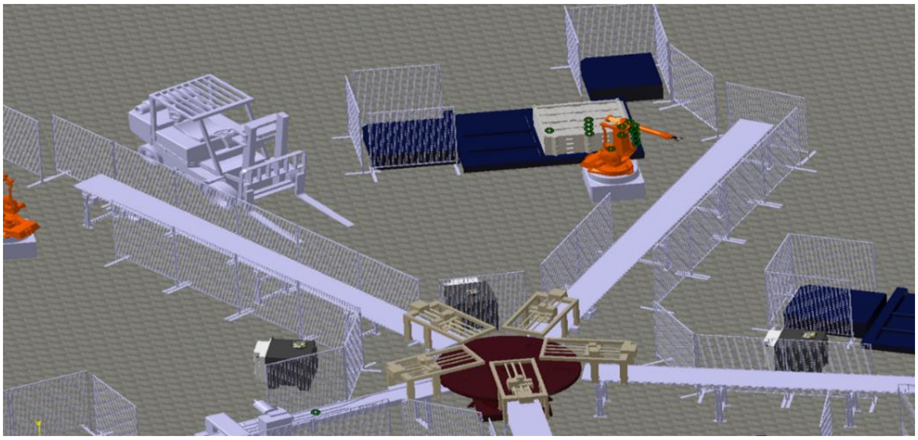


Fig. 5.3.2.5. Supply and assembly area of component parts

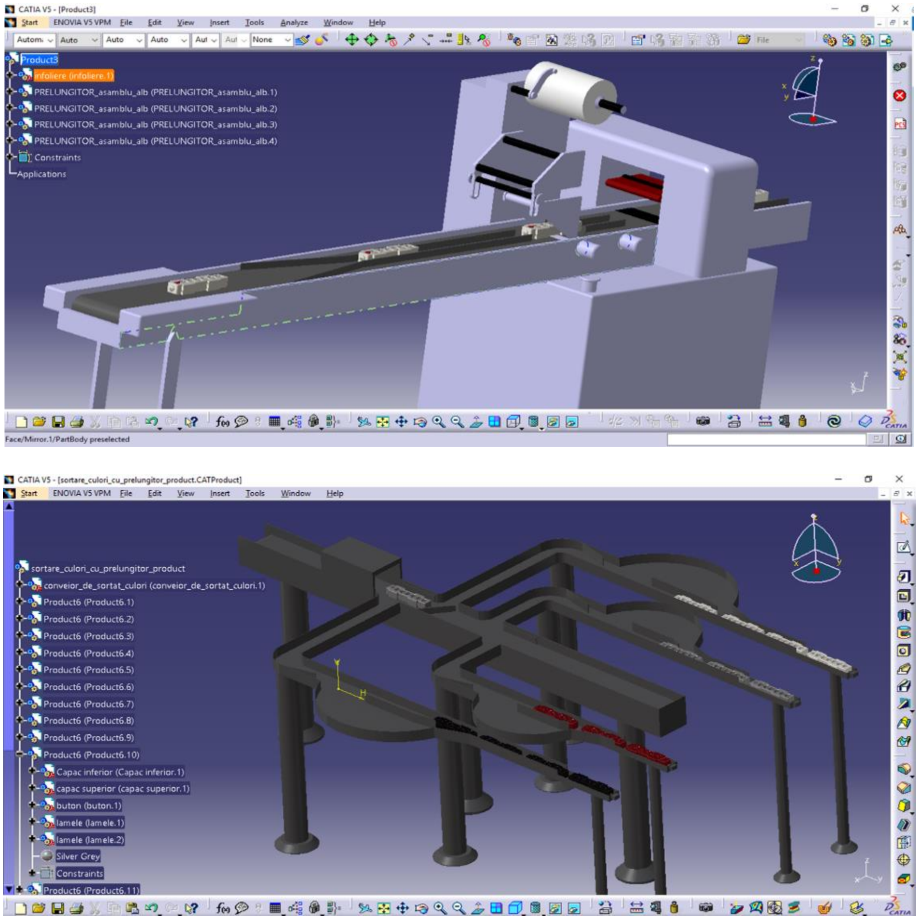


Fig. 5.3.2.6. The wrapping machine and the colour sorting equipment (top to bottom)

Packaging and palletizing area

For packing and palletizing we used two ABB 2400L robots, a boxing machine, a box closure and sealing machine, a palletizing machine and a forklift.

After making the box it reaches the stop position at the end of the conveyor. There are the extensions in the box. Then the box will be transported from the conveyor that has been placed on the other conveyor where the box will be sealed.

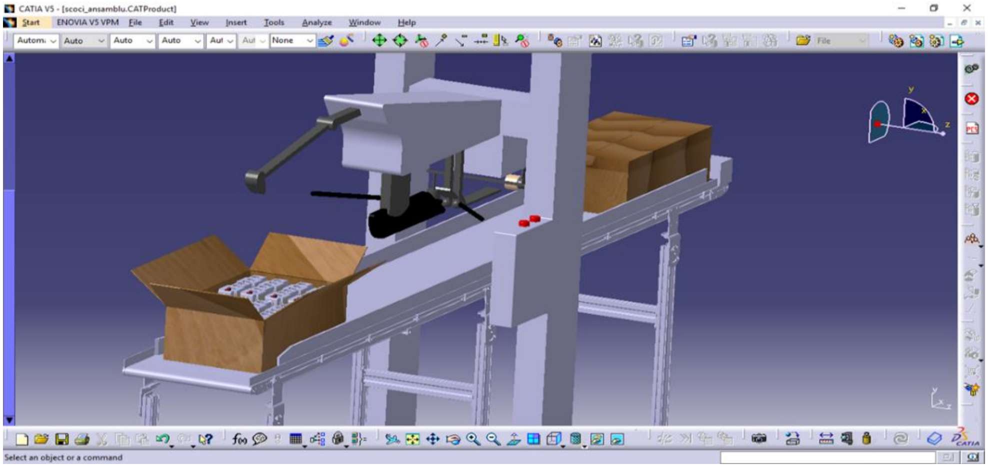


Fig. 5.3.2.7. Closing and sealing the box

After the box has been sealed (Fig. 5.3.2.7), the second ABB 2400L robot will pick up with an 8-pipe gripper and place it on a pallet. The pallet (Fig. 5.3.2.7) will be loaded up to a height of 2 meters (about 8 rows of boxes). Therefore, after completing the palletizing on the infiltration machine, the palette will be inflated. After completing the roll-off operation, the pallet will be taken off the machine with a forklift.

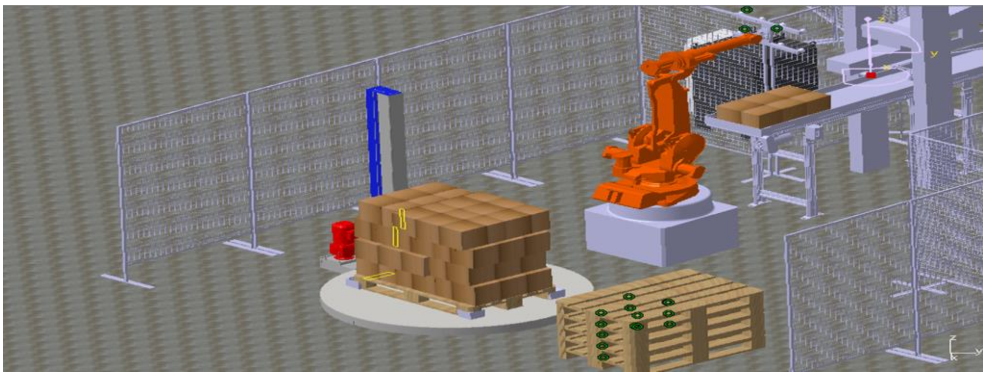


Fig. 5.3.2.8. Palletizing area

Many thanks to our students, David Porosnicu and Denis Svab, for enabling us to present their solution for this case study!

5.3.3. 3rd Project Example

The electric extension in its standard form is assembled manually, as in figure 5.3.3.1.

Fig. 5.3.3.1. The assembled product - the initial version

Following the DAFD method, we can see that there are difficulties in assembling the product within an automatic production system. We have therefore concluded that the screws are very difficult to mount with a robot and so the extension must be redesigned.

A degree of "ease of assembling" of 41.99% has been achieved, indicating that the assembly will be very difficult to assemble with a robotic cell.

Screws also have a heavier handling process during automated assemblies.

Figure 5.3.3.2 shows the 3D model of the product. When elaborating the final version of the product, we have to:

- Discontinue the screws and replace them with another constructive version in which the extension can be mounted.
- The pins in which the bolts have been screwed have elongated and beveled at the ends, for centering purposes.
- On the side of the extension cord comes a caucus band. The method is designed in such a way that the frictional force between the rubber and the plastic cover of the extension does not allow disassembly of the extension.

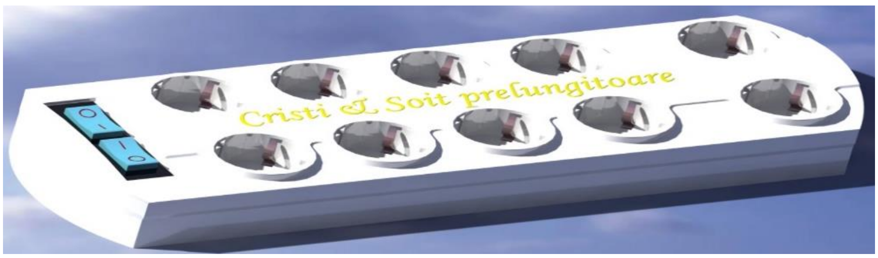


Fig. 5.3.3.2. The 3D model of the product

Component representation of the electric extension is shown in figures 5.3.3.3 and 5.3.3.4.

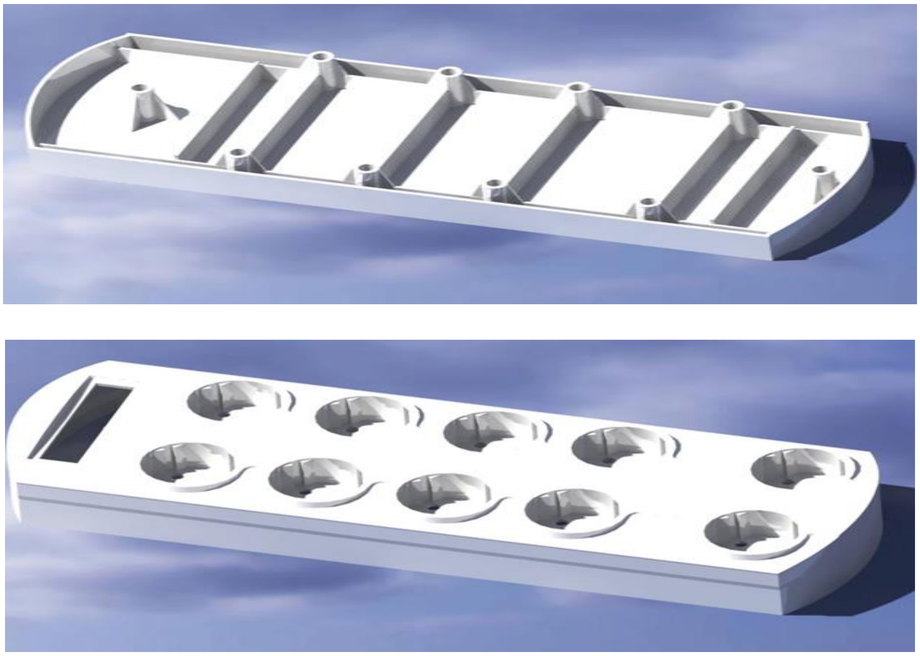


Fig. 5.3.3.3. Bottom lid and top lid (top to bottom)

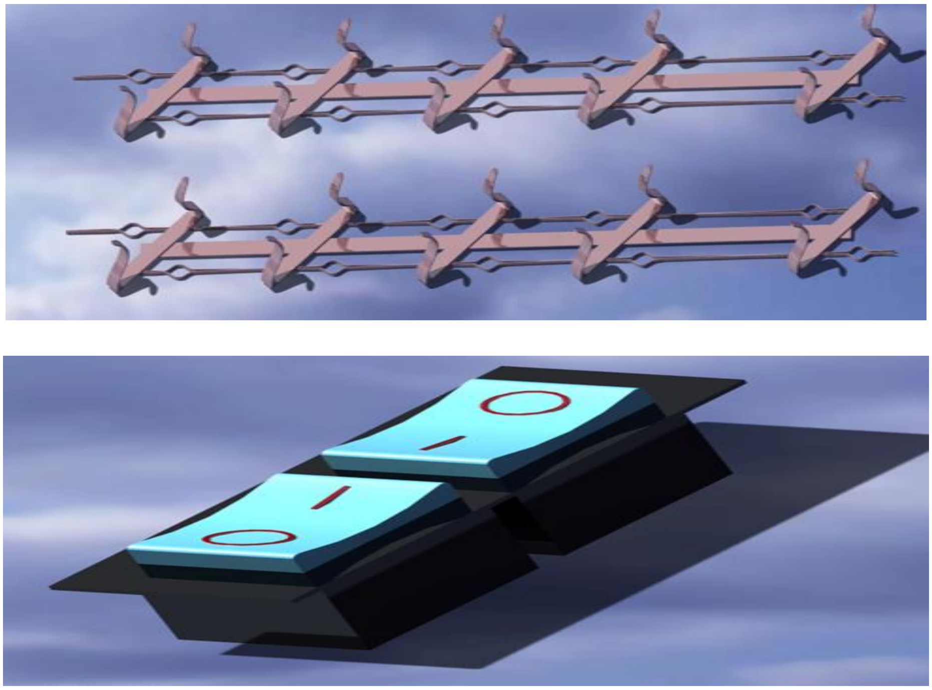


Fig. 5.3.3.4. Grounding+ lamellae and on/off mode (top to bottom)

The screws, as an assembly, have been removed, and the remaining components to be assembled are: the top cap, the bottom cap, the grounding, the lamellae, the on/off module.

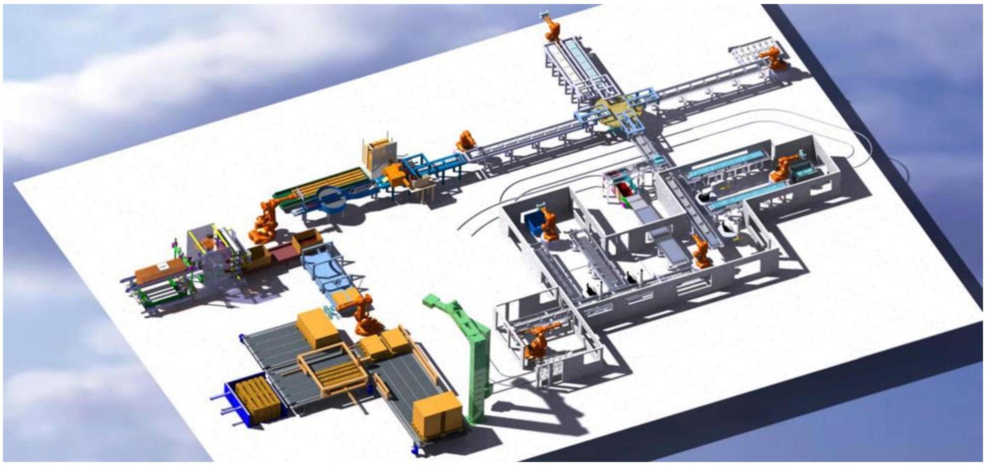


Fig. 5.3.3.5. The robotic cell overview

The robotic cell consists of (Fig. 5.3.3.5):

I. Supply (Fig. 5.3.3.6)

1. Supply top caps
2. Grounding power supply
3. Feed the blades
4. Feed down lids
5. Power on / on mode

II. Assemblies (Fig. 5.3.3.7)

1. Bottom cover with grounding
2. Bottom cap + blades
3. Bottom cap + top cap
4. Bottom cover + lamellas + grounding + on / o mode

III. Infoline (Fig. 5.3.3.8)

IV. Bagging in boxes (Fig. 5.3.3.9)

V. Palletizing

Fig. 5.3.3.6. Feeding area

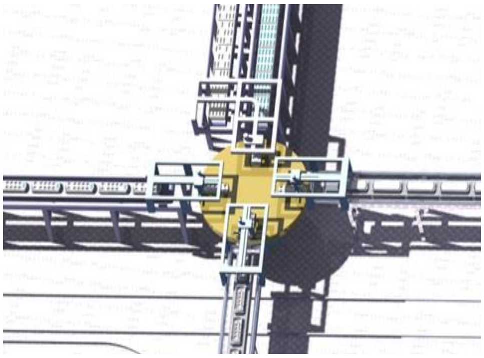


Fig. 5.3.3.7. Assembly area

Fig. 5.3.3.8. Sorting and inspection area

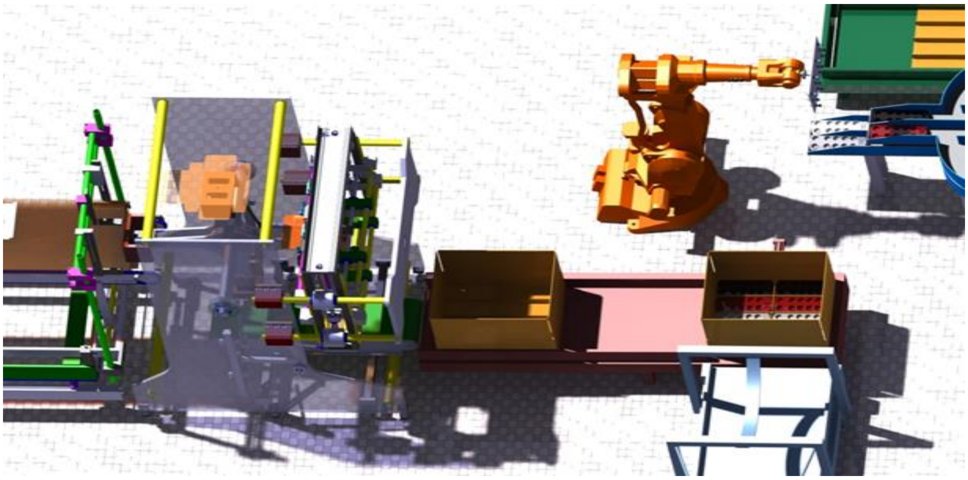


Fig. 5.3.3.9. Packaging area

Supplying the top caps (Fig. 5.3.3.10) is done with robots tracking optical bands, the robot carries the entire kit with the top caps.

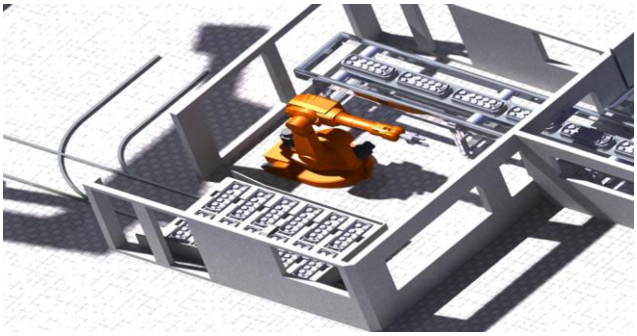


Fig. 5.3.3.10. Feeding the top caps

Supplying the grounding is also done with robots. A robot takes the kits and places them on the band, from where they will be further assembled, as electrical extensions, by the robot.

Supplying the lamellas (Fig. 5.3.3.11) is the same as supplying the grounding.

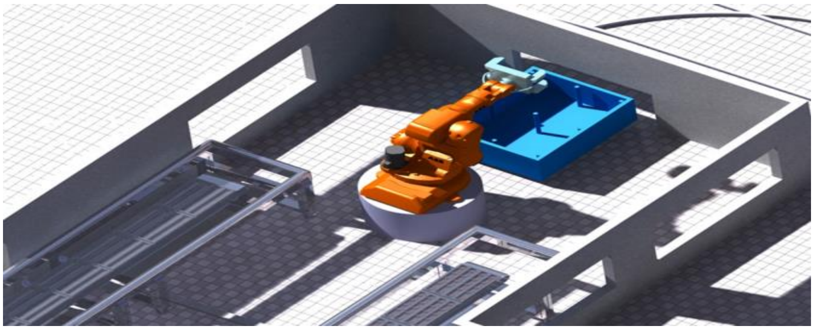


Fig. 5.3.3.11. Feeding the lamellas

Feeding the bottom caps and the on/off modules (Fig. 5.3.3.12) is done with the help of robots that place the kits for each feed in the predefined position, confirmed by the proximity sensors.

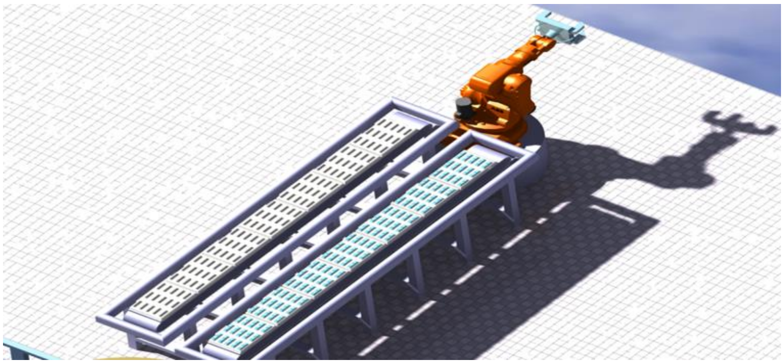


Fig. 5.3.3.12. Feeding the bottom caps and the on/off modules

Grounding assembling (Fig. 5.3.3.13): The grounding comes in kits on the strip, from where they are picked up by robots that grippers specially designed for this application, and, afterwards the extension is assembled.

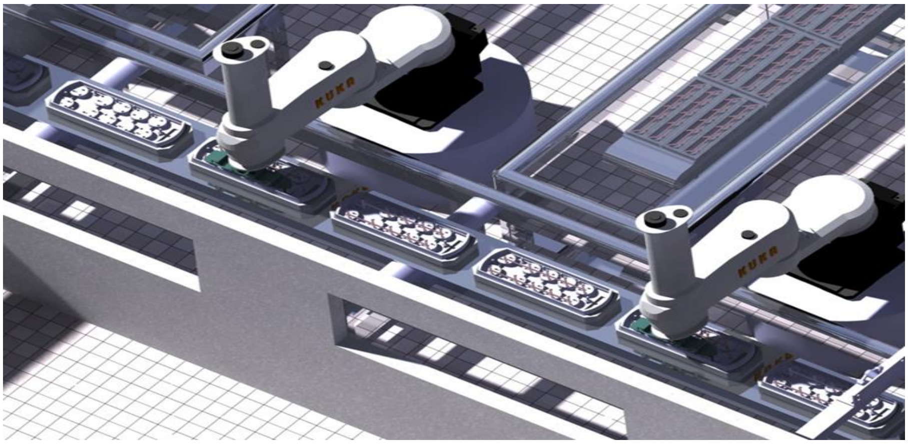


Fig. 5.3.3.13. Grounding assembling area

Assembling the on/off module & bottom caps (Fig. 5.3.3.14): Assembling these components is done using an index table and manipulators.

The infoliating (Fig. 5.3.3.15) is carried out by means of a specially designed machine for this application. The conveyor carrying the assembled end-to-end extension pieces is composed of two strips having a channel in the middle. A stopper allows the passage of only one extension to pass it, being pushed by a piston that exits the fold channel through the foliage drawn by the infiltration machine, which is then melted by a vertical-movement piston which is then conveyed to an accumulation conveyor.

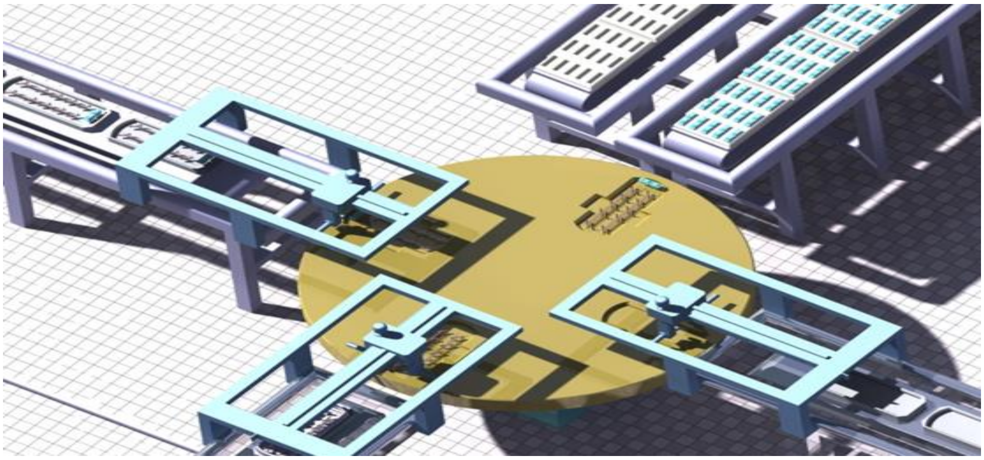


Fig. 5.3.3.14. Assembling the on/off module & bottom caps area

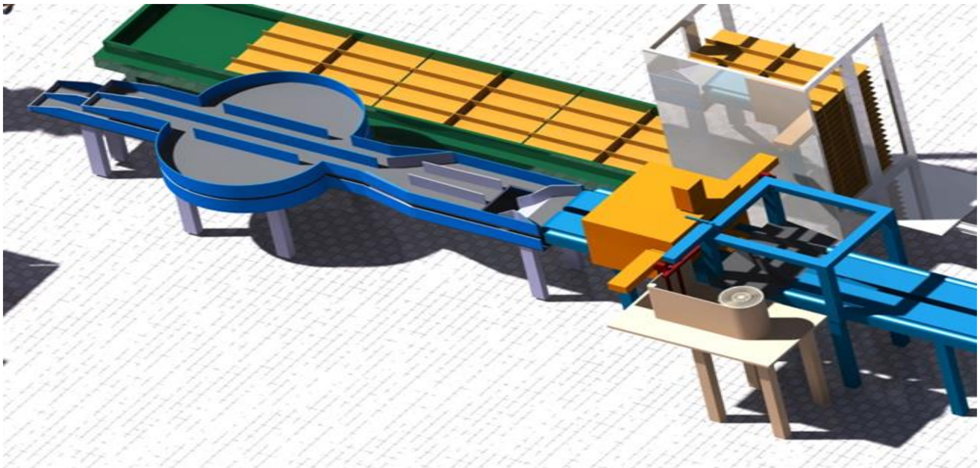


Fig.5.3.3.15. Wrapping area

Bagging of the electrical extension cords (Fig. 5.3.3.16) is done by an ABB IRB_1600 robot with a suction gripper that holds up to four extensions at a time and puts them in the boxes. Inside an 8-layer is a cardboard board with the same robot and gripper.

The pallets (Fig. 5.3.3.17) are powered by a feeder below the floor level, the pallets are pushed by pneumatic pistons on the conveyor. The pallets are positioned in the exact position by some pistons, from which a robot puts the boxes with the electrical extensions on the pallets.

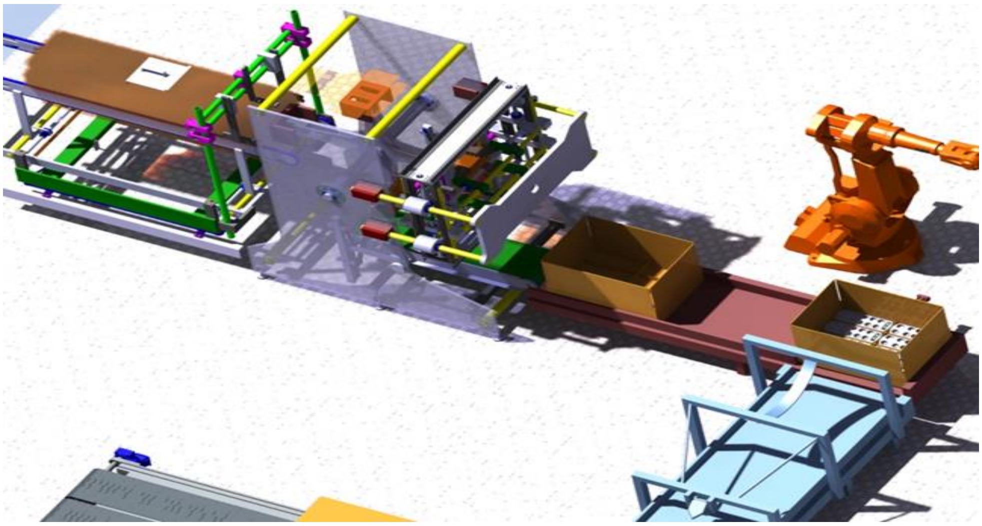


Fig. 5.3.3.16. Packaging of electrical extension cords area

The robots used were SCARA & serial robots from ABB. SCARA robots were used because of their precision, and serial robots were used to cover the necessary work space.

In table 5.3.3.1, we have specified the investment we made to buy each robot.

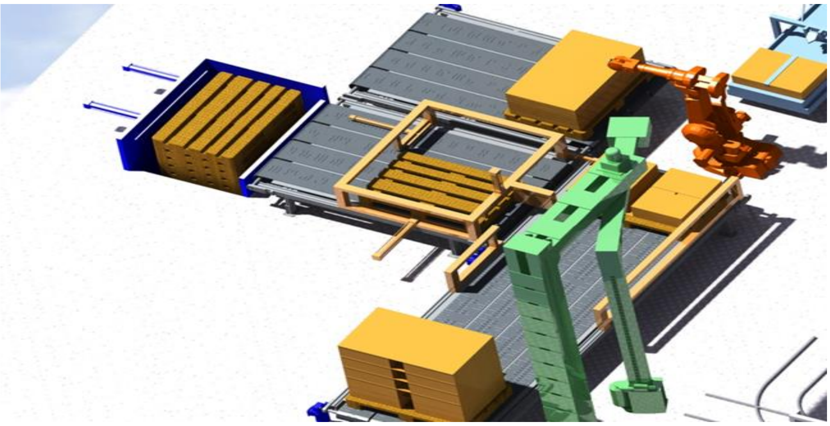


Fig. 5.3.3.17. Palletization area

Table 5.3.3.1. Monetary investments

Equipment	Price (GBP)
ABB IRB 1600	21500 GBP
KR10 SCARA R600	7500 GBP
KR10 SCARA R600	7500 GBP
KR10 SCARA R600	7500 GBP
KR10 SCARA R600	7500 GBP
ABB IRB 140	11000 GBP
ABB IRB 140	11000 GBP
ABB IRB 140	11000 GBP
ABB IRB 140	11000 GBP
ABB IRB 140	11000 GBP
ABB IRB 140	11000 GBP
ABB IRB 2400	15000 GBP
3 Axis Gantry Type Cartesian Robot for picking and placing	3000-8000 GBP
3 Axis Gantry Type Cartesian Robot for picking and placing	3000-8000 GBP
3 Axis Gantry Type Cartesian Robot for picking and placing	3000-8000 GBP

Equipment	Price (GBP)
3 Axis Gantry Type Cartesian Robot for picking and placing	3000-8000 GBP
ABB IRB 2400	15000 GBP
TOTAL COST OF ROBOTS	**162000 GBP**
Other necessary equipment	150000 GBP

From the previous table we concluded that if we sell an electric extension at a price of 2 pounds, and we produce 30 boxes per day, we could recover the investment in about a year and a half.

Many thanks to our students, Razvan Soit and Cristian Roca, for enabling us to present their solution for this case study!

5.3.4. 4th Project Example

The initial product is assembled manually, in figure 5.3.4.1 the electrical extension is presented, before redesigning the product and applying the automation/ robotization solutions to the process. Also, in figure 5.3.4.1 one can see the assembled product.

Fig. 5.3.4.1. Initial product and assembled product (top to bottom)

Structure of the product:

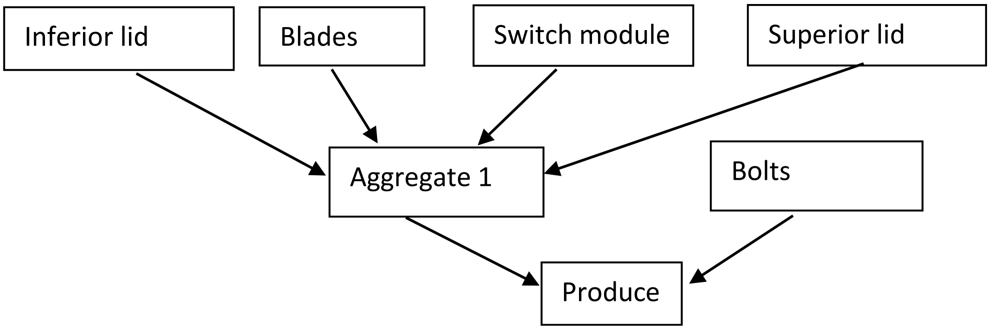


Fig. 5.3.4.2. Draft of the product’s structure

Following the analysis of the above diagrams, it has been found that the design of a robotic cell of the initial product will be quite difficult to perform due to the top cap attachment system on the lower cap. This would be done by gripping with screws that can be screwed by hand or using rather complex devices.

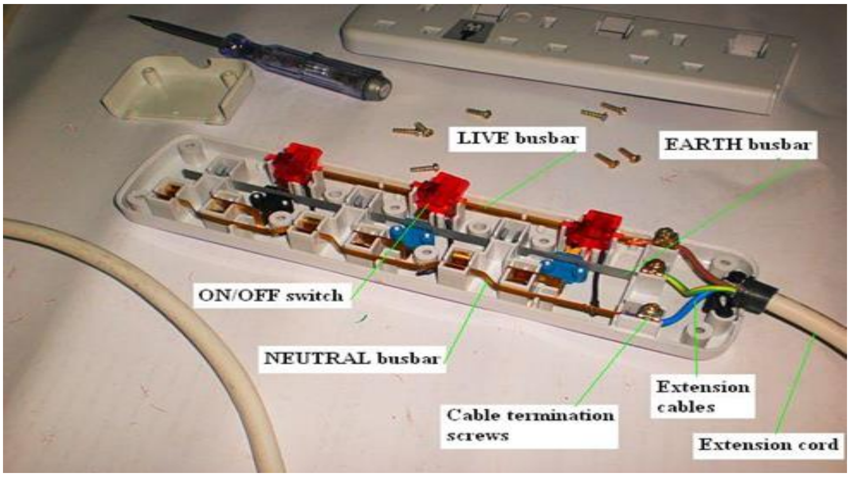


Fig. 5.3.4.3. Components electrical extension

To highlight the weaknesses of the inherent product from the perspective of the robotic process, we have used the DFAFD method. Following the DFAFD analysis, a 57.32% ease of mounting was obtained to show how difficult it would be to assemble this extension with a robotic cell.

It can be noticed that there are problems with all the parts of the original product, especially the 6 bolts, which would make it difficult to screw on correctly.

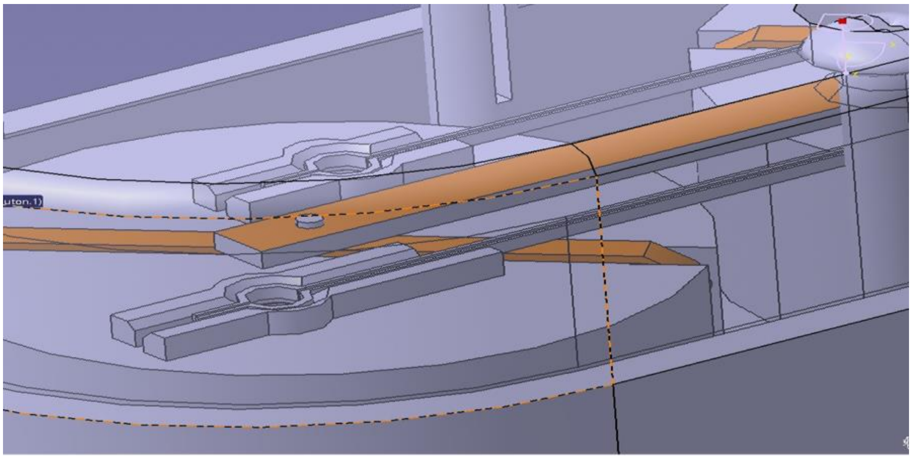


Fig. 5.3.4.4. Superior lid after redesign

So, we have come to the conclusion that the extension has to be redesigned so that robotic assemblies can be adapted.

Following the redesign of the extension, I ceased using the 6 bolts and I chose the upper cover on the lower one with a clamping mechanism with flexible clamps. The top cover is provided on one side and on the other with a clamp which, by a simple push, embeds the left and right lower case, thus ensuring a simple and precise assembly. In figure 5.3.4.4 below is presented the redesigned version of the lower and upper cover.

Figures 5.3.4.5, 5.3.4.6 and 5.3.4.7 show how to assemble the lower cap assembly, the blades, the switch module and the top cover.

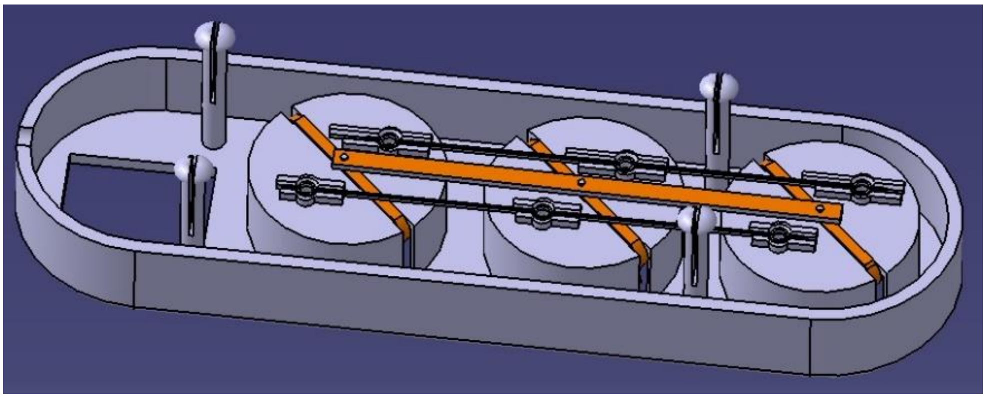


Fig. 5.3.4.5. The first move consists in fixing the blades on the lower cover

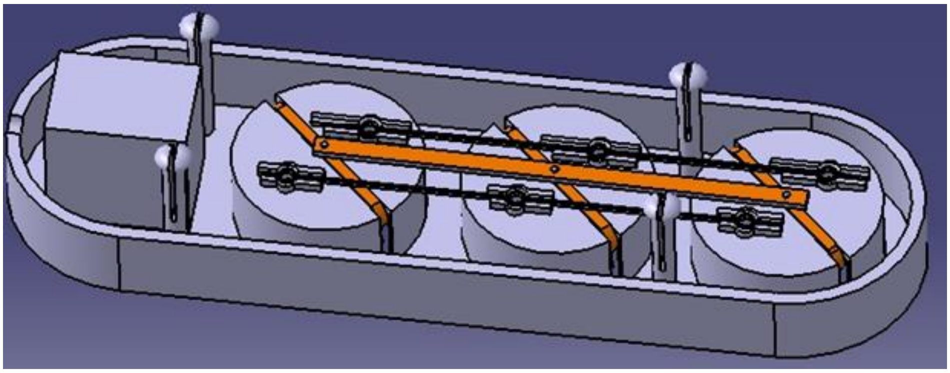


Fig. 5.3.4.6. The second move consists of assembling the switch module on the lower cover

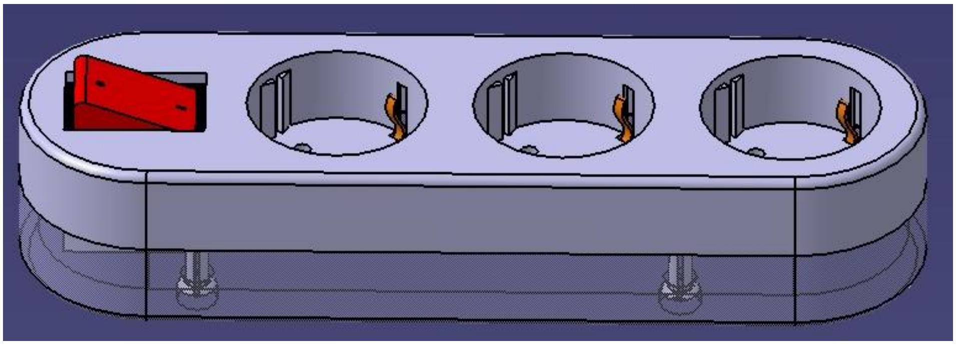


Fig. 5.3.4.7. The third move consists in attaching the top cover to the already formed assembly

In figure 5.3.4.7 is presented the final product after redesign, then it will be packed in plastic bags, put in boxes, palletized etc.

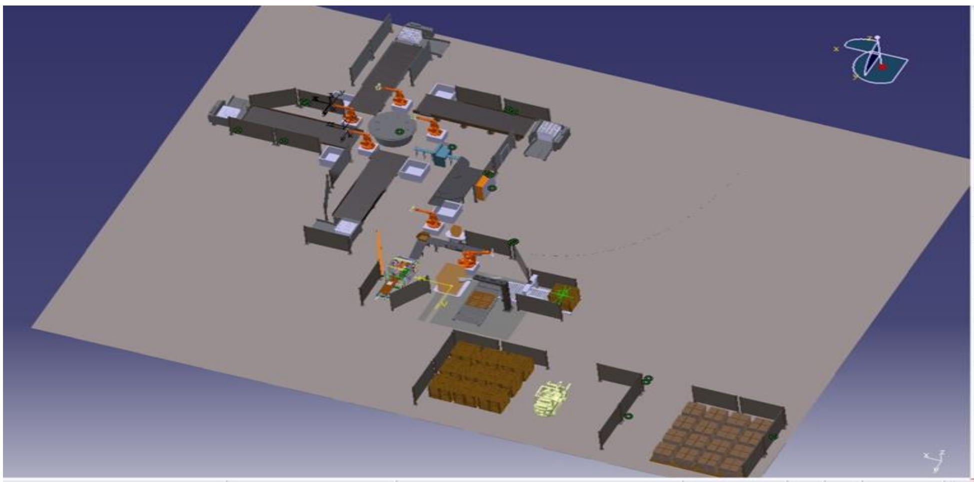


Figure 5.3.4.8. Overview of the robotic cell

From a structural point of view, the robotic assembly cell (Fig. 5.3.4.8) is divided into three important areas:

- Component parts supply and assembly area;
- Packaging and sorting area of the final product;
- Palletizing area

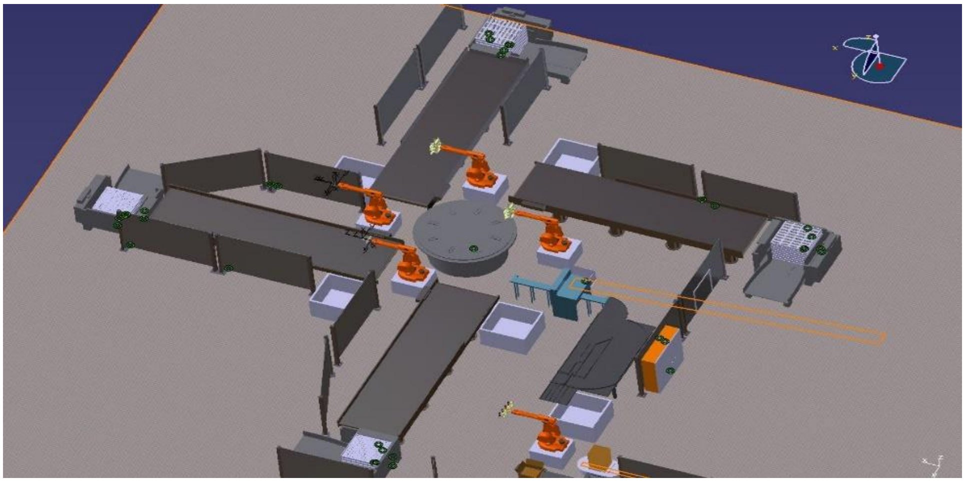


Fig. 5.3.4.9. Area of supply and assembly of component parts

Supply and assembly area of component parts (Fig. 5.3.4.9)

The main components of this area are:

1) Vibrational helical feeders;
2) Conveyor belts;
3) Robocars;
4) Vertical feeders with kits;
5) Index table;
6) Video Inspection Camera;
7) ABB IRB 2400 Robots
8) Gripper with fingers;
9) Controller robots;
10) Accumulator conveyor;
11) Sensors.

To assemble the product, we used four vertical kits for feeders (Fig. 5.3.4.10), because the parts are simple and more efficient to work than kits.

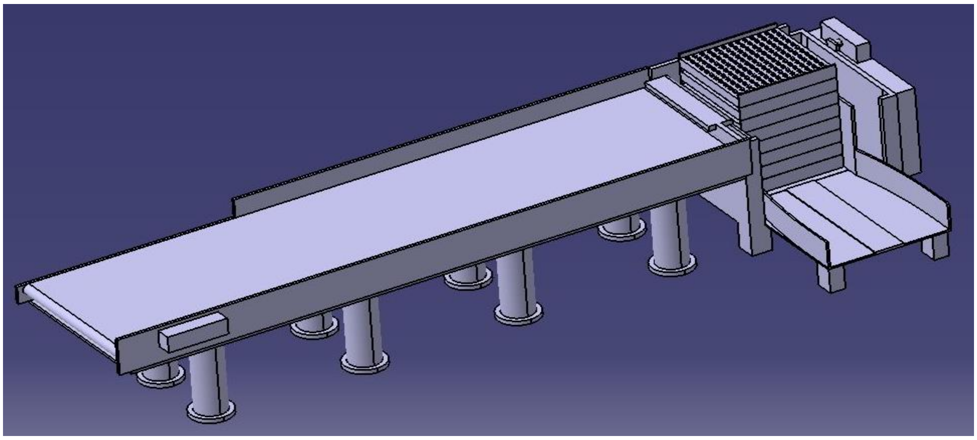


Fig. 5.3.4.10. Vertical feeder

For each piece we used a feeder and a conveyor (Fig. 5.3.4.11) to increase productivity.

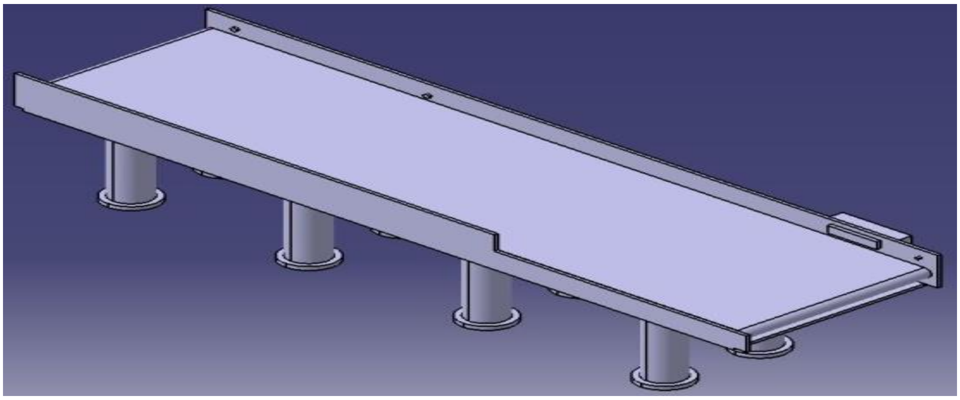


Fig. 5.3.4.11. Belt conveyor

The belt conveyors used to transport the component parts to the indexing table are provided with capacitive proximity sensors placed at the beginning of the conveyor to detect the position of the kits on the belt and transmit the signal to the drive conveyor motor, and, the other sensor is tactile, at the end of the conveyor, to stop the belt.

Six robocars (Fig. 5.3.4.12) were used on electro-magnetic rails, four of which were used to transport empty kits after they were removed from the conveyor belt of the feeder. The other two are used for scrapping.

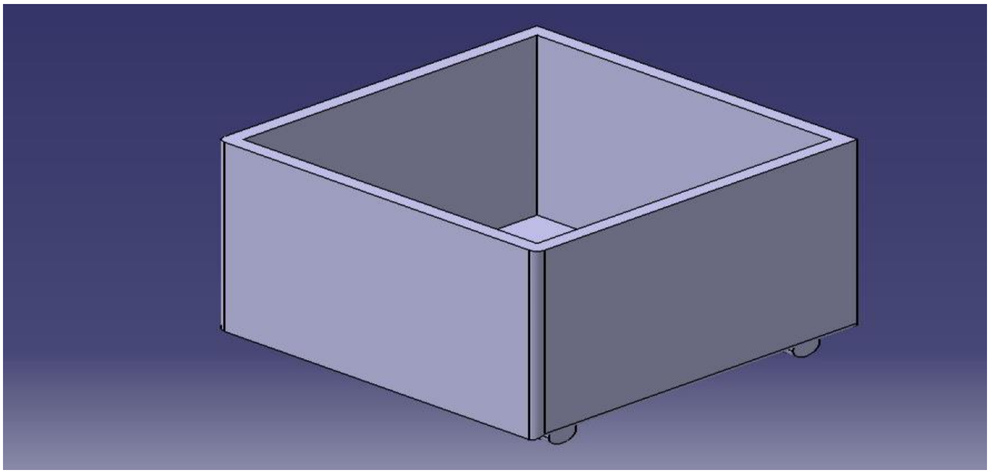


Fig. 5.3.4.12. Robocars

The index table (Fig. 5.3.4.13.) is a very important component for the assembly area of the product. It is provided with 9 indexing positions, with an angle of 40 degrees between them. Each position has a capacitive proximity sensor for position detection at the bottom and a photoelectric sensor to determine the color of the lower cover. There is also a video inspection room.

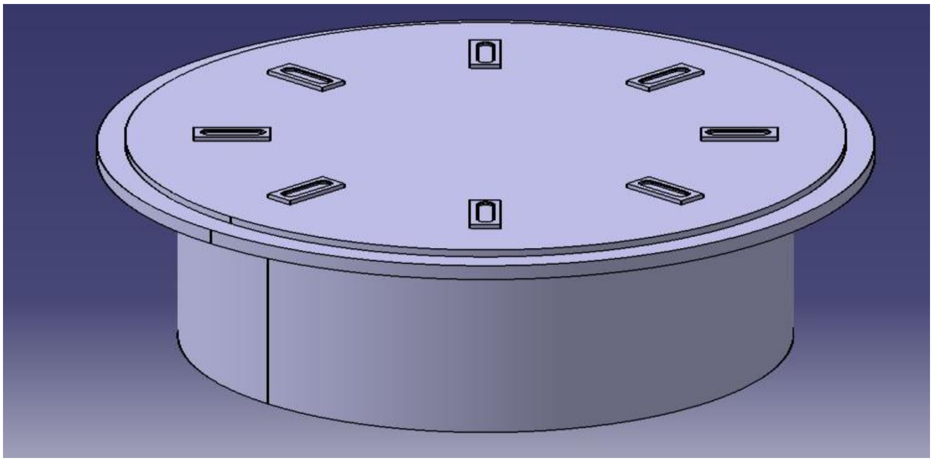


Fig. 5.3.4.13. The index table

For the index table we used a 710 MD series video inspection from Datalogic to check the product assembly and possible scrap.

At the extension part we used 4 industrial robots manufactured by ABB. IRB 2400 is one of the most used robots in the industry, from handling and assembly to painting, as it is easy to mount and has high repeatability and high precision.

The first robot is used to feed the indexing mass with the top cap because the assembly is reversed.

The second robot is used for assembling lamellas and loaves equipped with a special gripper for lamellas.

The third robot is used to mount the button module, while, also, the mounting of this module is done with a special gripper.

The last robot is used to complete the assembly of the product by mounting the lower cover. This robot is also equipped with a special gripper to easily catch the lid and a video inspecting camera is mounted on the gripper to see if the mounting has been done correctly. Otherwise, the product is thrown into the scrap robocar.

The in-foliation machine (Fig. 5.3.4.14.) consists of two conveyor belts and a central section consisting of the foil holder, the foil application mechanism and the sealing furnace.

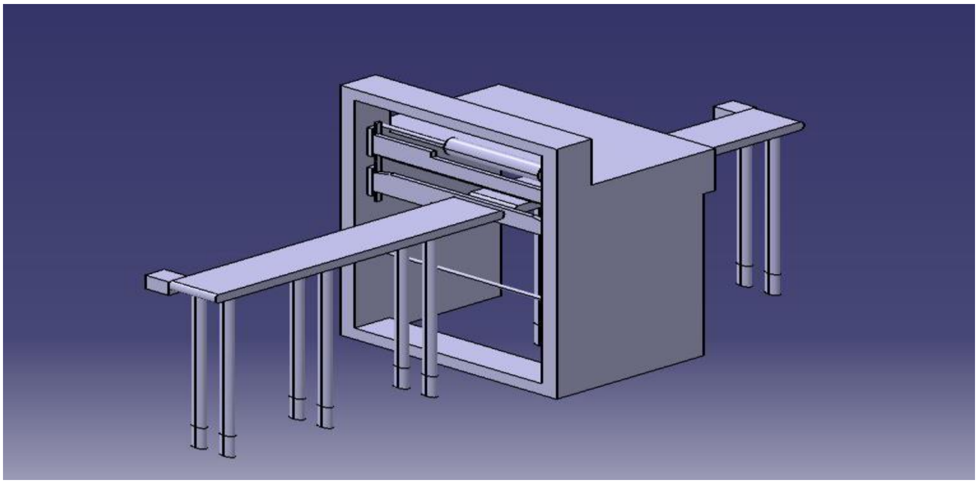


Fig. 5.3.4.14. The in-foliation machine

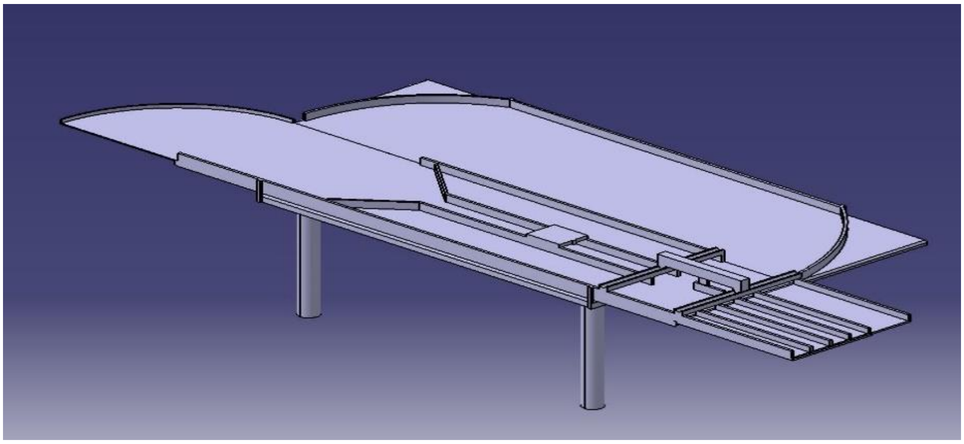


Fig. 5.3.4.15. Storage conveyor

Previously infoliated products reach the storage conveyor (Fig. 5.3.4.15.) that drives the pieces in a check area and also passes through a color separation zone. For color separation, we use an electric guideline that places the products on the respective color corridor, and then they are taken over by a handling robot and placed in boxes. Pieces that do not pass quality control are guided into a special lane for scrap.

A standard stacked cardboard stack is placed in the shape of the box. These cartons are passed through 4 pneumatic processes resulting in the box-like product (Fig. 5.3.4.16.).

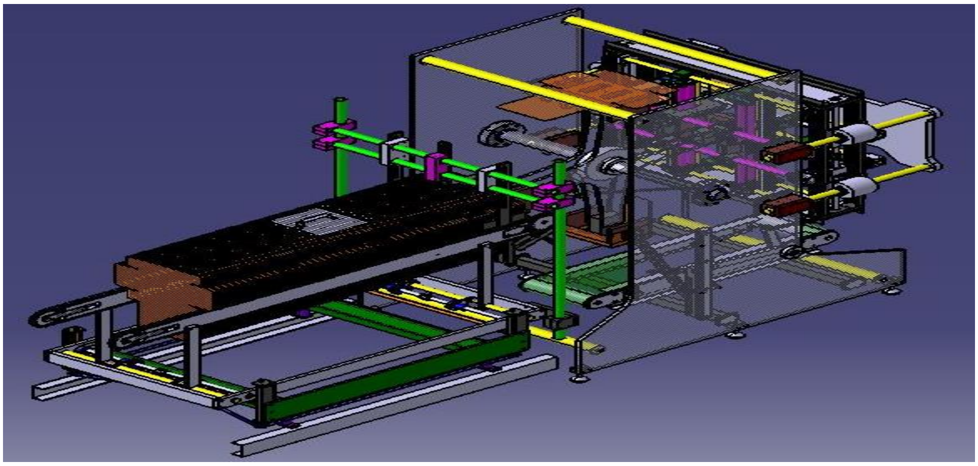


Fig. 5.3.4.16. Box formatting machine

Once formed, boxes are transported in front of the manipulator, a robot takes the products from the storage conveyor and puts them in the boxes, then the robocar takes a layer of cardboard and inserts it into the box. This process is repeated until the box is filled. Further, the box is transported to the sealing mechanism of the box, and then it is transported to the last handling robot that loads the boxes on pallets (Fig. 5.3.4.17).

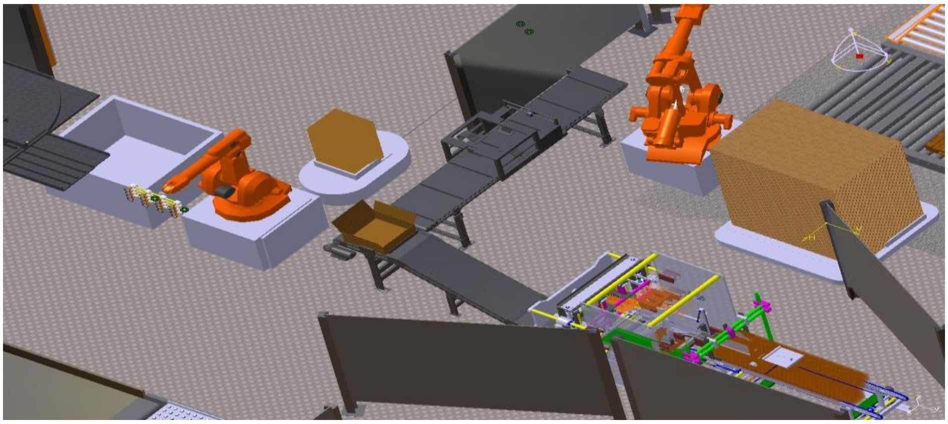


Fig. 5.3.4.17. Packing station

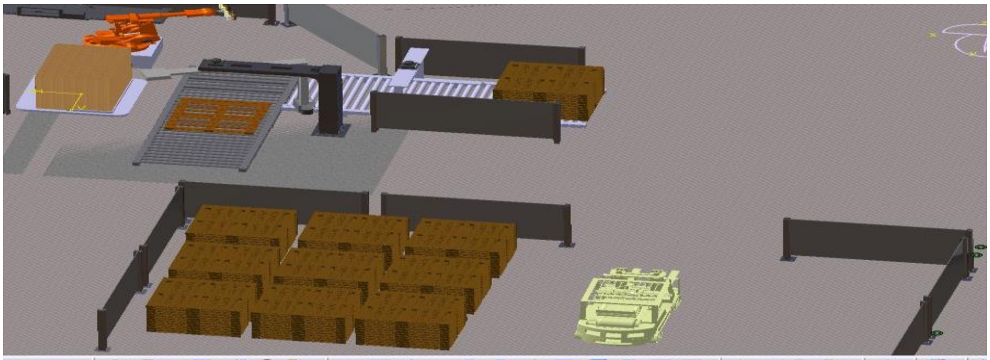


Fig. 5.3.4.18. Palletizing station

The sealed boxes arrive wet at the second handler robot, where they are loaded on pallets (Fig. 5.3.4.18.). After the first layer of boxes, the robot takes a layer of cardboard and puts on the boxes. This process is repeated four more times. After loading the pallet, it is inflated and then transported with the fork-lift truck in the warehouse.

The palletizing station is powered by pallets by a feeder that operates on the basic principle of a forklift, that is, the stack of pallets brought from the hopper and loaded on the feeder is transmitted to a lifting mechanism with which the used pallet is isolated from the rest of the stack, having the opportunity to proceed directly to the pallet station.

Economic evaluation of the robotic assembly cell:

- 6 x Industrial Robots - 6 x IRB 2400 - 20,000 Euros each.
- 2x roller conveyor for pallets - 4,000 euro.

- 1 x storage conveyor - 5,600 euro.
- 5 x conveyor belts - 5000 euro.
- 6 x robot for evacuation - 5000 euro.
- 2 x robots for carton supply - 4000 euro.
- 1 x car making box - 5000 euro.
- 1 x index table - 1,300 euros.
- 1 x infiltration machine - 12000 euro.
- 1 x forklift - 4000 euro.
- 13 x photoelectric sensors - 12 euros each.
- 5 x proximity sensors - 20 euros each.
- 3 x video inspecting rooms - 50 euros each.
- 2 x gripper with suction cups - 1100 euro.
- 1 x 8 Vacuum structure - 500 euros
- 1 x 2 gripper - 500 euro
- 1 x button gripper - 200 euro
- 1 x gripper for blades - 1000 euro
- 1 x protection bar 100m - 7000 euro
- 1 x PLC - 3500 euros

TOTAL: 183206 EURO.

Many thanks to our students, Ioan Petrovai, Mihai Pacurar and Vlad-Florin Burean, for enabling us to present their solution for this case study!

5.3.5. 5th Project Example

The initial product can be observed in figure 5.3.5.1 below.

Fig. 5.3.5.1. Initial product

From the DFAFD method, the level of assembly of the elongation, with the help of a robotic cell, resulted Qr = 57.53%. It can be noticed that the biggest problem is in the bolts, the assembling being much more difficult, so we have come to the conclusion that the electric extension must be redesigned so that the assembling is as easy as possible.

After redesigning the bolts have been replaced with clamps which are attached to the top cover on both sides in three places, and they are then pressed into the corresponding lids on the lower cover, as can be seen in Figures 5.3.5.2 and .63.5.3.

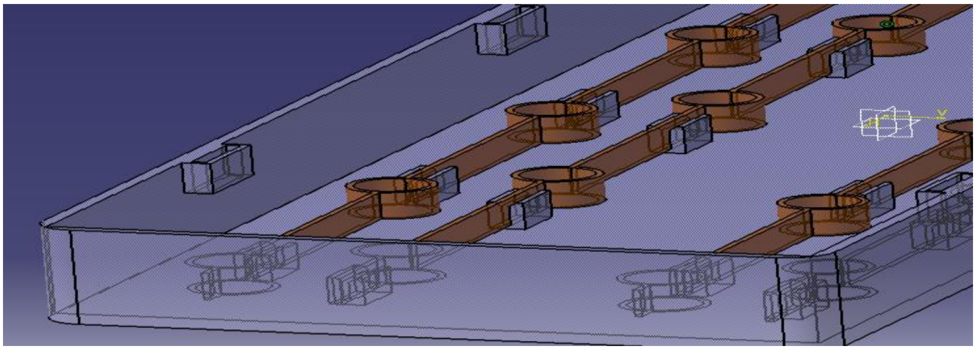


Fig. 5.3.5.2. Inferior lid after redesign

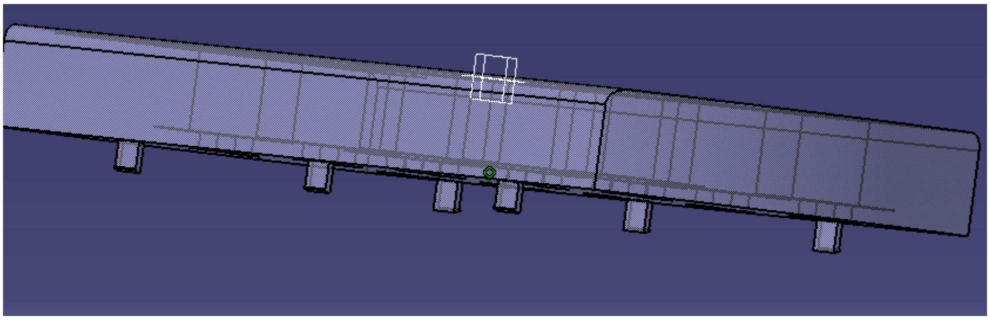


Fig. 5.3.5.3. Superior lid after redesign

The following figures (5.3.5.4, 5.3.5.5 and 5.3.5.6) show the electrical extension assembly steps.

First, fix the blades on the lower lid. Then assemble the switch module on the lower cover.

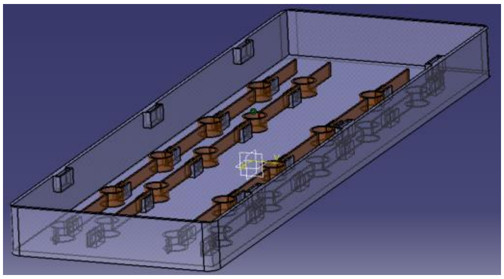


Fig. 5.3.5.4. Inferior cap with blades

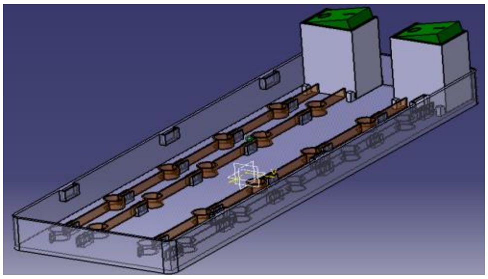


Fig. 5.3.5.5. Bottom cap with blades and switch mode

Following the last step, secure the top cover of the lower cover.

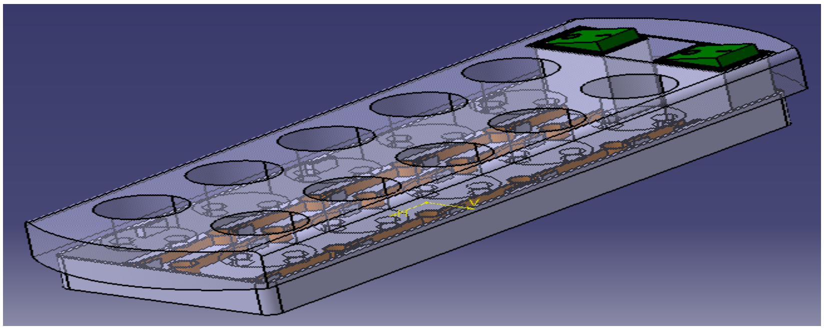


Fig. 5.3.5.6. Complete assembly

After assembly the final product is packed in bags and put in boxes.

After removing the bolts from the DFAFD chart, a higher level of quality resulted with an increase of 4.5%, therefore Qr = 62.07%.

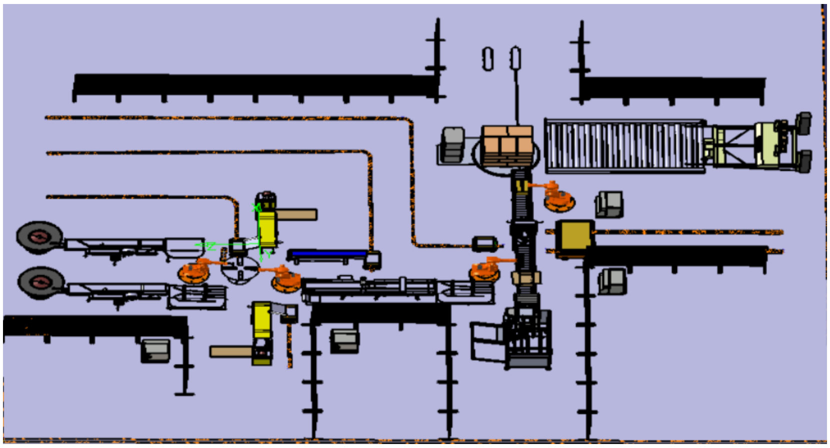


Fig. 5.3.5.7. Overview of the robotic cell

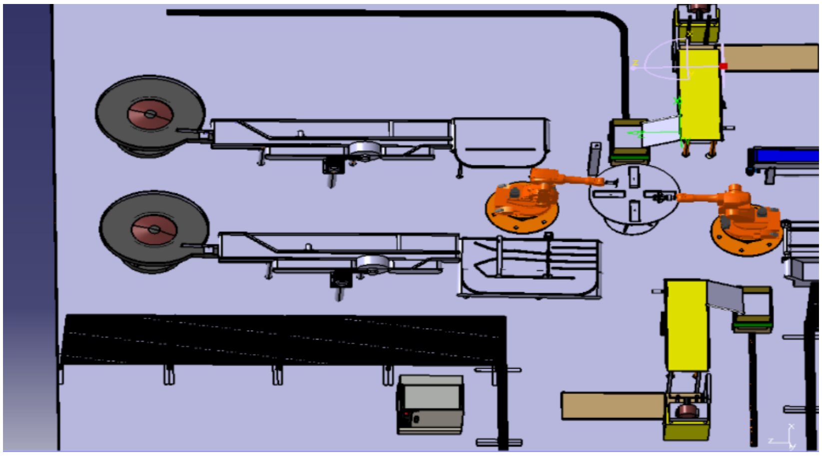


Fig. 5.3.5.8. Supply and assembly area

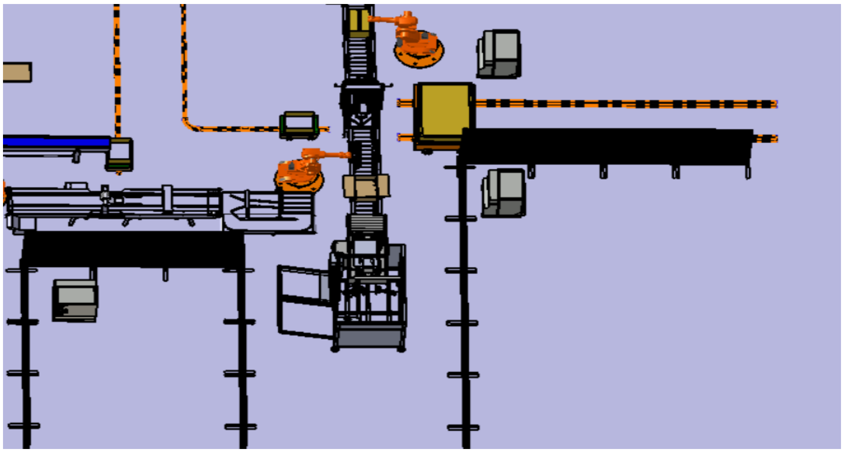


Fig. 5.3.5.9. Packaging and sorting area

The robotic cell (Fig. 5.3.5.7) is divided into 3 zones: supply and assembly area, packaging and sorting area, palletizing area (Fig. 5.3.5.8, 5.3.5.9 and 5.3.5.10).

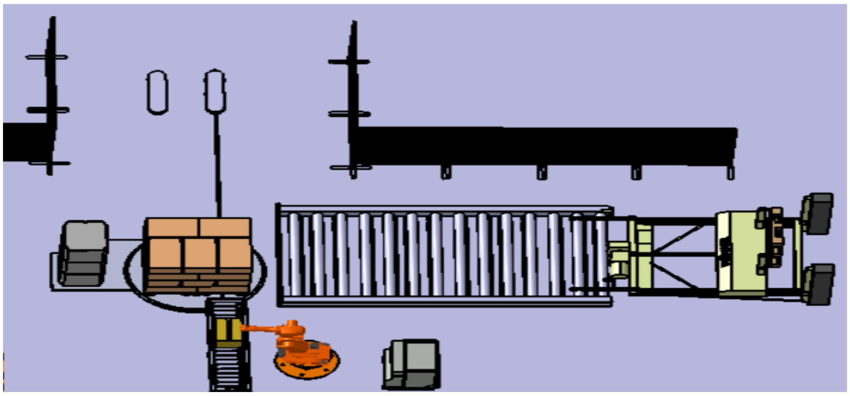


Fig. 5.3.5.10. Palletizing area

Each area is comprised of components that are specific to each and every one.

Supply and assembly area:

There are two circular feeders, one for the top cover, the other for the lower cover.

There also are two belt conveyors, one for the lower cover and the other for the upper cover. They have been added a steering mechanism because the products may not have the same orientation on the conveyor. On the vertical feeder there is a laser sensor that measures the size. If the size is small it means that the cap must be returned. The sensor transmits the signal to the pneumatic piston that sends it on a conveyor to a return system. The cap goes into a cylinder that is driven by an electric motor, it is transmitted through the strap by turning the cover 180°.

Two robocars are supposed to deliver the empty kits and one to carry the scrap. They are placed on a metallic rail, they have wheels that help for easy movement.

There are two vertical feeders for blade kits and switch modules. The kits support performs a bottom-up motion transmitted by an electric motor, the transmission being made with a pinion and a chain. At the end of the conveyor there is a touch sensor to stop the belt, the kit being pushed on the conveyor by means of a piston the pneumatic force being divided into 2 points for a good positioning on the conveyor, and when the kit is emptied it is removed from the belt by a pneumatic cylinder. Features: - 50 lamellae kits, 30 kits switch module.

There is an accumulation conveyor, that is a belt conveyor, powered by an electric motor with an accumulation part, used to feed the lower caps.

There are scrap conveyors that are belt conveyors driven by an electric motor.

The index table has 4 indexing positions, each provided with proximity sensors for presence detection. The rotation motion is performed using an electric motor.

We used the Omron FJ-SC5MG video inspection camera to check the product on the index table.

When assembling the extension, we chose two ABB IRB 1600 robots because they have higher reliability, speed and precision than other models.

The first robot assembles the inferior and superior cover, and the second assembles the switch modules, the kits, removes the scraps on the index table, and transmits the assembled product to the packing machine.

In the cell, IRB 1600 robots were used.

We used pneumatically driven grippers with a load capacity of 2kg, with a linear motor at the base of the movement and suction grippers with a carrying capacity of 500g, which will catch the caps with the vacuum.

Several types of sensors were used at the assembling and feeding area: laser sensor, touch sensor, optical sensor.

Packaging and sorting area:

For packing we chose a Flow Pack packing machine, which is an automatic machine with high productivity, the packaging is horizontal.

The sorting belt conveyor is equipped with a video detection system for color detection, it further sends the signal to the stepper driver that helps guide in a compartment through the ball screw according to the detected color. If the detected color already exists the compartments will be directed to the accumulation band.

The box making machine is equipped with a pneumatic actuator provided at the end with some suction cups, which simply draw from a stack of preformed boxes. The sealing box machine is an automatic machine that closes and stacks boxes with tape.

The magnetic robocar is used for transporting cardboard sheets.

The same sensors are used at the assembly area: optical sensor to be present on the assortment sorting conveyor after filling, at the end of the roller conveyor after sealing the boxes.

Palletizing area:

At the palletizing area I chose the ABB IRB 660 robot because it is a robot specially designed for palletizing, high production, high load bearing capacity and it is also robust.

For the palletizing area I used a gripper designed by me with a carrying capacity of 25 Kg. It can manipulate the boxes, the sheets between cartons with the help of the four suction cups and the pallets, thanks to the arms, on which there is a hook. For the safety of the product during the handling, two fixing plates are operated by three pistons each.

The pallet feeder has the function of feeding the cell automatically with pallets with the help of an optical sensor. When the pallets reach the end, they are stored in a feeder again by a human operator using a forklift. From the feeder, with the help of a conveyor roller, the pallet is carried to the proximity of the pallet infiltration machine.

The roller changer is driven by an electric motor that conveys the roller movement.

The wrapper has the role of infoliating the loaded pallets to secure the cargo on them during transportation. The pallets are infoliated with a multilayer wrap with stretch foil. At the bottom there are guides for correct positioning on the pallet station.

For the transport of box pallets, we have opted for an automatic conveyor with wireless connection because it occupies little space, has high manoeuvrability and it is very economical.

Economic evaluation of the robotic assembly cell:

If full productivity IP < 1 then the adopted solution is not profitable

IP > 1 then the adopted solution is profitable

$$\underline{IP} = \frac{\underline{OUP}}{\underline{INP}} = \frac{\sum_{i=1}^{N_p} P_{vi} * \underline{N_{ai}}}{C_{la} + C_{cap} + \underline{C_{ma}} + C_m}$$

where :

OUP – system outputs

N_p – number of products/year

P_{vi} – whole production value

N_{ai} – number of assemblies produced annually

INP – system inputs

C_{la} – labor costs

C_{cap} – capital consumption

C_{ma} – materials' cost

C_m – other costs (energy, rent)

Labor costs

$$C = n_s C_{las} l_f$$

Where l_f is a factor (l_f>=1) influenced by the frequency with which the human operator si able to supply the cell with materials; If l_f=1 the supply is not frequent; usually, when working, the following situations appear l_f = 1.1 ÷ 1.3 .

$\mathrm{n_s} = 3$ (shifts/day)

$\mathrm{C_{las}} = 12000$ €(annual labor cost /shift)

$\mathrm{l_f} = 1$

$\mathrm{C} = 3 * 12000 = 36000$ €

Consumption of capital

$$C_{cap} = \frac{r}{1-(1+r)^{-\mu}} I$$

where *I* is the total initial investment.

$$I = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7$$

$$I_1 = \sum_{k=1}^{H_r} I_{rob\ k}$$

$$I_2 = (0.1 + 0.35) C_{RS}$$

where C_{RS} is the cost of the entire robotic system.

$$I_3 = I_b + I_{so} + I_{om}$$

$$I_4 = I_{fg} + I_{mfg} + I_{mg} + I_{ge} + I_{ug} + I_t$$

$$I_5 = I_{it} + I_{tb} + I_{pft} + I_{AVG} + I_{fix}$$

$$I_6 = I_{ins} + I_{esp} + I_{ae} + I_{sen} + I_{cs} + I_{ep} + I_{ss} + I_{rwr}$$

$$I_7 = I_{eng} + I_{inst} + I_{train} + I_{red} = f_n I$$

where f_n is a proportion factor

I_1 =80000 € - cost robots

I_2=36000 € - cost software

$I_3 = 5000 + 7000 + 6000 = 18000$€ - cost supply system

$I_4 = 600 + 1200 + 2500 = 4300$€ - cost gripper

$I_5 = 800 + 1400 + 4400 + 1400 + 2300 + 3600 + 8500$ - cost conveyor and index table

$+14000 = 36400$€

I_6=5000+100+240+180+9000+650+40=15210 € - cost sensors and inspection system

I_7=11500 € - cost training and redesign

I=201410 € - total investment

$C_{cap} = \frac{2}{1-(1+2)^{-10}} * 201410 = 402827$ € - consumption capital

Other costs

$$C_m = C_{fi} + C_e + C_{main}$$

where C_{fi} is the cost of the work space, C_e energy costs, C_{main} maintenance costs.

$$C_{fi} = F_s C_{fm}$$

$$C_e = n_s f_e C_{cap}$$

where f_e este un factor de proportionalitate de la C_{cap} / schimb.

$$C_{main} = f_{main} C_{cap}$$

where f_{main} is a proportion factor from C_{cap}.

$$N_{ai} = f_i N_i$$

where f_i is the proportion of acceptable assemblies in variant i.

$$E(f_i) = \prod_{j=i}^{N_{ci}} \frac{1 - x_{ji}}{1 - x_{ij}[m_{ij} + (1 - m_{ij})cf_{ij}]}$$

C_{fi} =56000 €

C_e =3*465828 = 1397484 € €

$C_{main} = 11000$ €

C_m =56000+1397484+11000=1464484 €

N_{ai} =485200 pieces

$$T_{tot} = n_s n_d n_h 3600$$

Material costs

$$C_{ma} = \sum_{i=1}^{N_P} C_{mi} N_i$$

where N_i is the number of assemblies made in version i.

$$T_{tot} = n_s n_d n_h 3600$$

T_{tot} =3*240*8*3600=20736000 s

$$T_{ac} = \sum_{i=1}^{N_p} T_{ci} v_i$$

where T_{ac} is the average cycle time / assembly variant.

$$T_{ac} = 60 \text{ s}$$

$$C_{ap} = \frac{T_{tot}}{T_{ac}}$$

where C_{ac} is the cell's capacity.

$$C_{ap} = \frac{20736000}{60} = 345600 \text{ s}$$

where T_{OP} is time/operational year.

$$T_{OP} = T_{tot} - (T_{su} + T_{pf} + T_{sf})$$

$$T_{pf} = T_{jam} + T_{cf}$$

$$T_{jam} = \sum_{i=1}^{N_{jam}} T_{ji}$$

$T_{jam} = 600 * 40 = 24000$ s

$$T_{cf} = \sum_{i=1}^{N_{cf}} T_{cf\,i}$$

$T_{cf} = 300 * 40 = 12000$ s

$T_{pf} = 24000 + 12000 = 36000$ s

$$T_{sf} = \sum_{k=1}^{s} T_{sf\,k}$$

$T_{sf} = 1800 * 40 = 72000$ s

$T_{su} = 1200$ s

T_{op} =20736000-(1200+36000+72000)=20626800 s

$$A = \frac{T_{op}}{T_{tot}}$$

$$A = \frac{20626800}{20736000} = 0.99$$

$$N_i = C_{ap} Av_i$$

$N_i = 485200 * 0.99 = 480348$

C_{ma} =4*480348=1921392 €

$$IP = \frac{15 * 485200}{12000 \ + 465828 \ + 1921392 + 1464484} = 1.9$$

If IP<1 then the chosen solution is not profitable.

If IP>1 then the chosen solution is profitable.

Many thanks to our students, Alin-Dorin Burz and Manuel Ungureanu, for enabling us to present their solution for this case study!

5.3.6. 6th Project Example

The original product is assembled manually, in figure 5.3.6.1 the electrical extension is presented, before redesigning the product and applying the automation/robotization solutions to the process. Moreover, it is presented the way in which the product will be packaged.

Fig. 5.3.5.1. Initial product and packaged product (top to bottom)

Following the DFAFD analysis, a 55.96% ease of installation was obtained, which shows the degree of difficulty of assembling the electrical switch with the help of the robotic cell.

There are problems with assembling all parts of the original product, but the biggest problems arise in fitting the 6 bolts, making it difficult to screw correctly with the help of an assembly of prehension-orientation device, resulting in the need to change the assembly method. The elongator must be redesigned so that it can be easily mounted in a robotic cell.

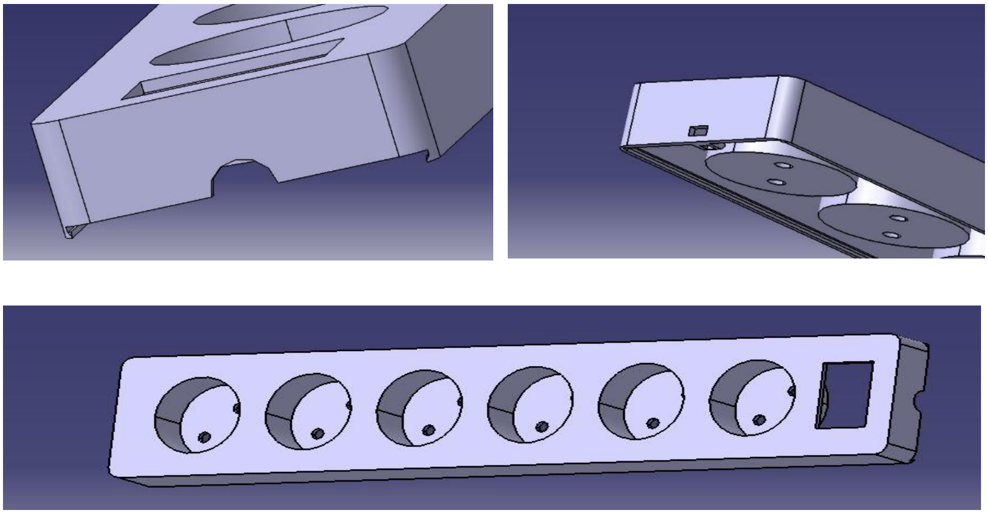


Fig. 5.3.5.2. Superior lid after redesign

Due to the need to remove the screws, we redesigned the design of the electric switch, therefore it became easy to mount and disassemble. The proposed solution is to mount the top cap on the lower cover through a rail system, the top cover has a channel in which the rail on the top of the lower cover is mounted. Keeping together the lids is ensured by a plastic clip that ensures the two parts are joined together, but also provides the possibility of dismantling.

In figures 5.3.6.2 and 5.3.6.3 one can see the mounting principle and the elements of the new assembly. Figure 5.3.6.4 presents the assembled product.

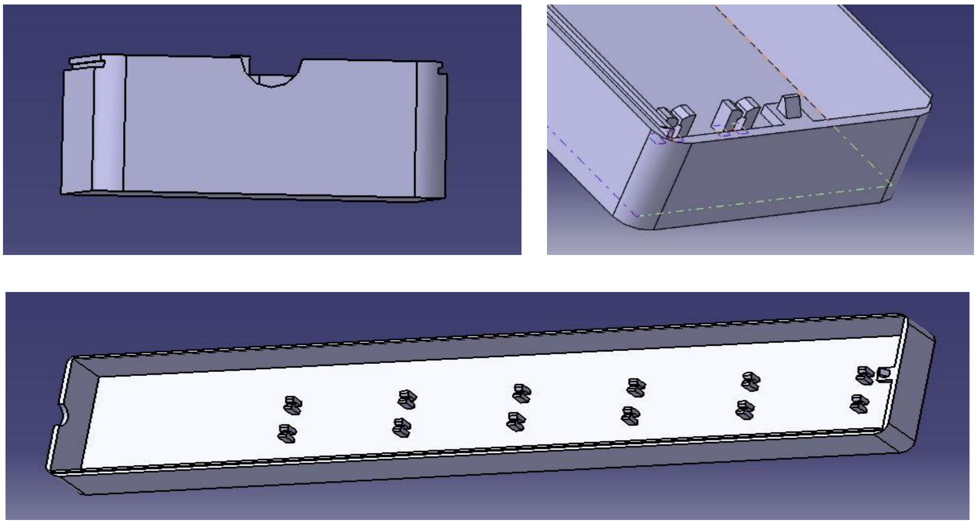


Fig. 5.3.5.3. Inferior lid after redesign

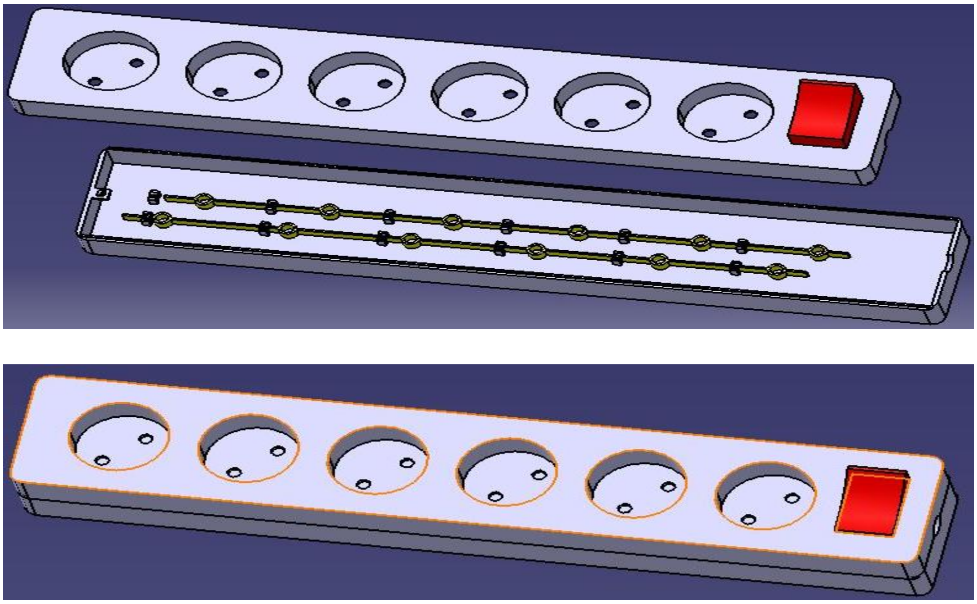


Fig. 5.3.5.4. Assembled switch

From a structural point of view, the robotic assembly cell is divided into three important areas:

- Supply and assembly area of component parts;
- Area of packaging and final product sorting;
- Palletizing area.

Fig. 5.3.5.5. Overview of the robotic cell

Supply and assembly area of component parts (Fig. 5.3.5.6.)

The main components of this area are:

- Vertical feeder for the lids;
- Belt conveyors;
- Robocars;

- Vertical feeders with kits;
- Video-inspection camera;
- ABB IRB 140 Robots
- Gripper with fingers;
- Controllers for the robots;
- Accumulating conveyor;
- Sensors.

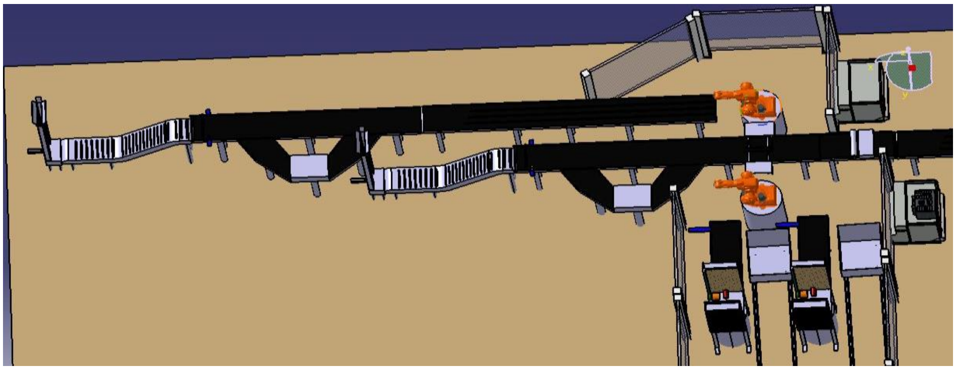


Fig. 5.3.5.6. Supply and assembly area of component parts

Two vertical feeders were used to feed the cell with the lower and top caps to provide the required position for the assembly of the two with special guides.

We used 2 belt conveyors, one for transporting the inferior and top cover, equipped with video inspection systems to check the color and position of the parts, electrical sensors placed on the conveyor ends to detect the existence of the parts and special guides for tracking the orientation.

The second conveyor also contains a system of guides specially designed for fixing the lower cap as long as the rest of the electrical switch components are secured. The guide also contains a proximity sensor for detecting the presence of the lower cover.

In the system, we included two other belt conveyors for transporting modules and blade kits by vertical feeders in the proximity of the robot to be assembled on the power switches.

These conveyors are equipped with an end stop to stop the kits, pistons to remove the empty kits in the robocars adjacent to the conveyors and proximity sensors to detect the presence of the kits at the stops.

We used 2 robocars on electro-magnetic rails to transport empty kits after they are removed from the conveyor belt of the vertical feeder.

To feed the lamellae and power switch modules, we chose vertical feeders that are powered by 18 kits, with the ability to rotate the kits for use after using the first set of 18 kits to deliver a system continuity and at the same time refueling with kits. The kit holder performs a bottom-up movement, driven by a ratchet sprocket and a motor.

For the indexing table we used a 1618 CHEPETH CMOS inspection video camera from IMPERX to check the position and color of the product.

We used two industrial robots manufactured by ABB IRB 140 at the electrical extension section. The first robot runs the upper cover assembly on the lower cover and the second robot is used to assemble the module and the lamellae.

Mounting the top cover, blades and modules is done using 2 high-prediction hydraulic grippers that ensure the assembly of the blades and modules of small size.

The conveyors used for the accumulation of upper caps and finished products are equipped with a color sorting system with data from the optical sensor located at the beginning of the conveyor of the caps, the pieces being sorted by means of a blade which drives the pieces on 4 trails where you can accumulate 15 pieces of each color. At the end of the conveyors there are 4 proximity sensors to detect the presence of the track on each track.

The sensors used at the supply area and the assembly of the extension are capacitive proximity sensors, as well as photoelectric sensors.

Area of packaging and final product sorting (Fig. 5.3.5.7.)

The main components of this area are:

- Packaging machine;
- Conveyor for sorting and storage;
- Robot ABB IRB 1600;
- Gripper with suction cups;
- Robot controller;
- Paper card holder;
- Box formatting machine;
- Rotary table with box sealing system;
- Roller conveyor for boxes;
- Sensors.

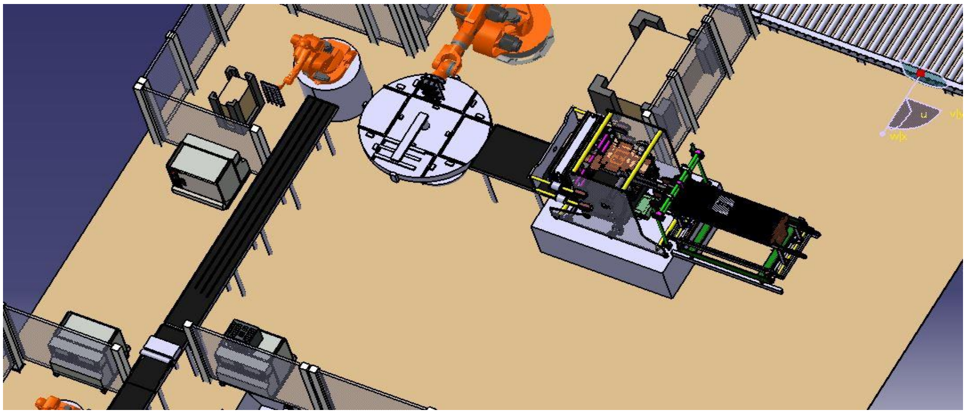


Fig. 5.3.5.7. Area of packaging and final product sorting

We used a packing machine to wrap the workpiece with a thermosensitive plastic sheeting, and then go through a hot air jet that will cause the foil to snap onto the parts, thus sealing.

For the packing area we used a robot from ABB, IRB 1600. It takes over the electrically extruded packs from the conveyor and puts them in a box, eight at a time, on four levels; There are 32 electrical extension cords in the box.

For the robot weighing the elongators we chose a gripper with a total of 32 suction cups. It is able to take all eight electric extensions once and place them in the box.

The paper holder is located within the range of the IRB 1600 robot. Once it is emptied, it is reloaded with cardboard sheets by an operator.

The box making machine forms the boxes by means of rollers that take the properly cut carton, lead it to a system of guides where a piston forces the carton to take the shape of a box, and then the box is released on a conveyor at the bottom of the machine.

The index table moves the ready-made boxes to the product-handling robot, after which the table rotates to the box sealing system, and then moves to the palletizing robot that picks up the sealed box and transports it to the pallet.

Palletizing area:

The main components of this area are:

- Pallet feeder;
- Roller conveyor for the pallets;
- Sheet cardboard support;
- Robot ABB IRB 660;

- Palletizing gripper;
- Robot's controller;
- Palletizing station;
- Sensors;
- Euro pallets.

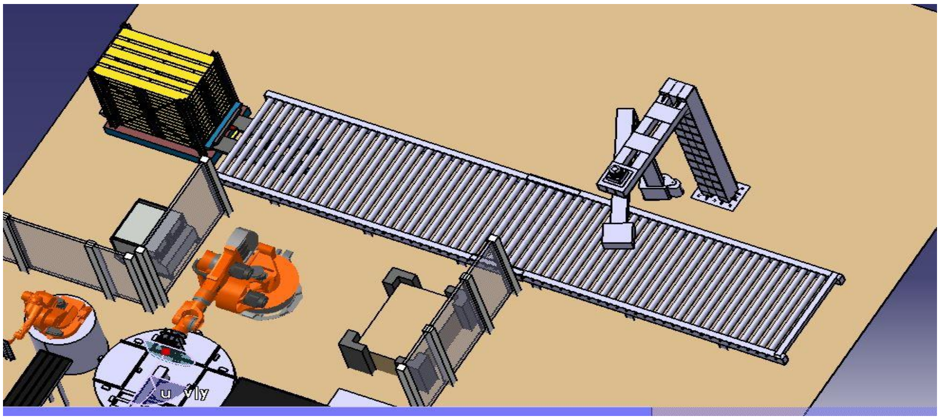


Fig. 5.3.5.8. Palletizing area

The pallet feeder is designed to store and feed the pallets for the palletizing area, while the robot will distribute the boxes evenly on them, so they can be further transported to the customer.

The gripper used for palletizing is designed specifically for this system by us in the project "Competitive Development of Robotic Systems"

The gripper is a pneumatic valve with suction cups for optimal handling of the boxes to be palletized. It has a total of 12 cups on an area of 660x240 [mm].

With the robot, the gripper is positioned above the box to be handled. The contact between the cups and the box is made. Thanks to the damping pistons and due to the fact that the suction cups are made of elastic material the contact is made smoothly, without noise and the structure or the shape of the boxes to be manipulated is not affected.

Once the cups are pulled through the vacuum pump by the vacuum generator, it is manipulated at the set point. The gripper releases the box and once it has reached the desired position, the process resumes.

The desks are located in the proximity of the KR 360 robot. After it is emptied, the carrier is reloaded with cardboard by an operator.

For the palletizing area we chose a KUKA robot built specifically for this specific activity, with just four axes, namely the KR 360.

As security elements we used fences in areas where there is a danger of injury, more precisely in the robot's action areas. They are standardized at 1500x2000 mm.

Economic evaluation of the robotic assembly cell:

Integrated productivity calculation

$$I = \frac{OUP}{INP} = \frac{Pvi*Nai}{Cla+Ccap+Cma+Cm}$$

OUP	- system's output;	INP	- system's input;
N_p	- number of products or assembly variants/year;	C_{la}	- labor cost;
P_{vi}	- production value per acceptable assembly variant i;	C_{cap}	- capital consumption;
N_{ai}	- number of acceptable assemblies of variant I which are produced annually;	C_{ma}	- material costs;
		C_m	- other costs (energy, workspace, etc.).

Pvi=9 eur (cost/piece)

Nai=250 days/year*1000 pieces /day= 250000

OUP= 2250000

ns – number of shifts/day =2

If - is a factor (If>=1) which is determined function of frequency the human operator has to supply the cell with materials; If=1

Cla=72000 EUR 6 persons

Capital Consumption

$$C_{cap} = \frac{r}{1-(1+r)^{-\mu}} I$$

r=0.15

µ=-10 years

R1, R2 = 30000EUR/piece

R3 = 20000EUR

R4= 30000EUR

Total = 80000EUR

Ccap= capital consumption

I = I1 + ... + I6

I1 = cost robot = 80000EUR

I2=0 .45 * cost-sistem-robotic = 0.45 * 200000EUR = 90000EUR

I3 = cost-gripper = 2000EUR

I4 = cost-stack-feeder-e = 41500EUR

I5 = cost-inspection-and-sensors = 20100EUR

I6 = cost-engineering-training-redesign = 1000EUR

I = 233700EUR

$$C_{cap} = \frac{4}{1-(1+4)^{-20}} * 233700 = 934800\ €$$

C.ma = C.mi * Ni = 2EUR * C.capacity * A.disponibilit * vi (100%)

Ni - the number of assemblies carried out in variant I

C.mi - direct and indirect material costs/assembly variant i excepting the tools

C.capacity = 250 days * 16 hrs * 60 mins / 3 mins = 84.000 units

A = 200 / 250 = 0.8

A – cell availability

C.ma = 2 * 84.000 * 0.8 = 134400EUR

C.others = 12 months * (800EUR + 300EUR + 300EUR) = 16800EUR

I = 2250000/(72000+ 934800 + 134400+ 16 800)=1,94

Conclusions:

After optimizing the assembly of the electric switch, we tried to create an economically efficient robotic cell to assemble, pack, pack and palletize the switch.

Following the calculations of full productivity, it was concluded that the adopted solution is economically profitable.

Many thanks to our students, Ciprian Cotoi and Krisztian Pomian, for enabling us to present their solution for this case study!

5.4. Third case study: assembly and palletization of the electric dose

The examples of the projects outlined below are the exclusive vision, conception, and implemented solutions developed by each student or team of students who have worked on each project.

5.4.1. 1st Project Example

Robotizing a process involves knowing the product in detail (material, components, assembly steps, etc.). Thus, a study of the electrical dose will be made up of component parts. To begin with, the 3D dose model is created using CATIA. The CAD variant of the initial subassembly and the component elements are shown in figure 5.4.1.1 (a, b, c).

The outline structure of the initial sub-assembly is shown in figure 5.4.1.2.

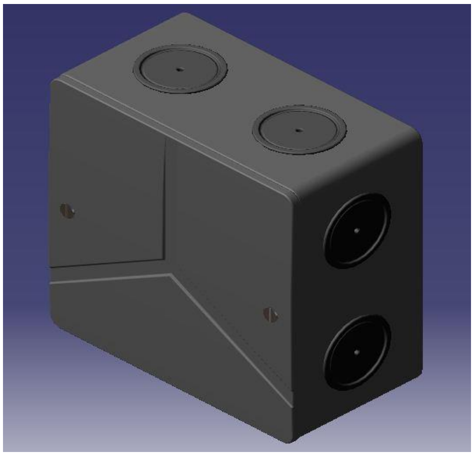


Fig. 5.4.1.1. a) Initial electrical dose - closed

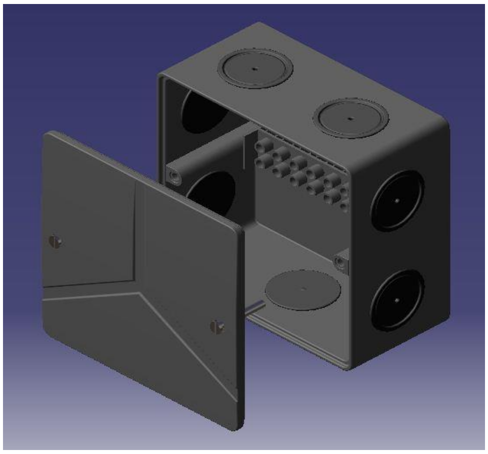


Fig. 5.4.1.1. b) Initial electrical dose - open

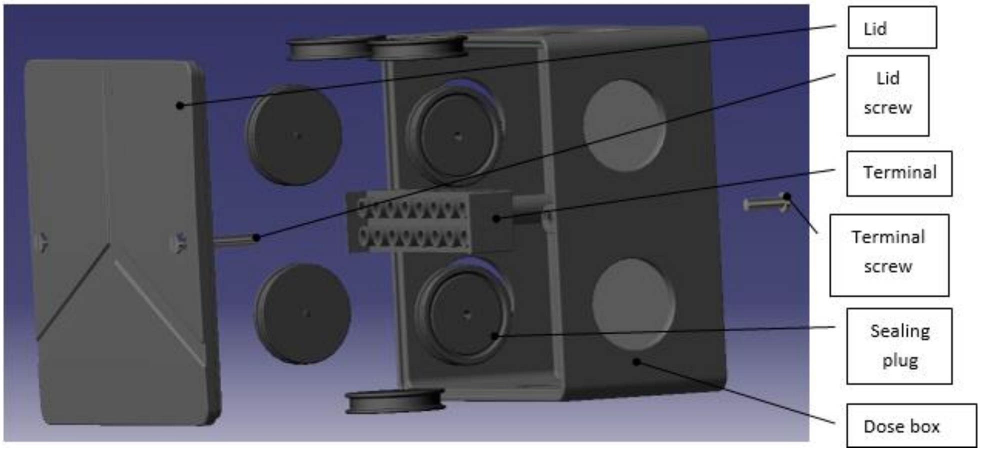


Fig. 5.4.1.1. c) Initial electrical dose - Exploded View

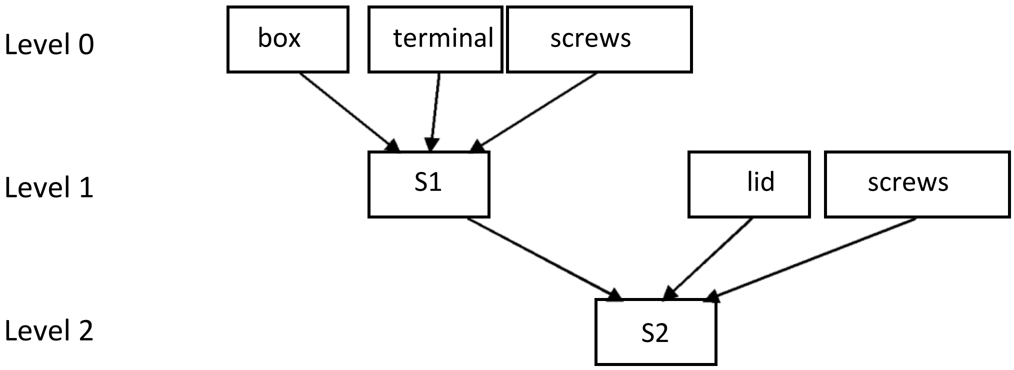


Fig. 5.4.1.2. Outline structure of the initial sub-assembly

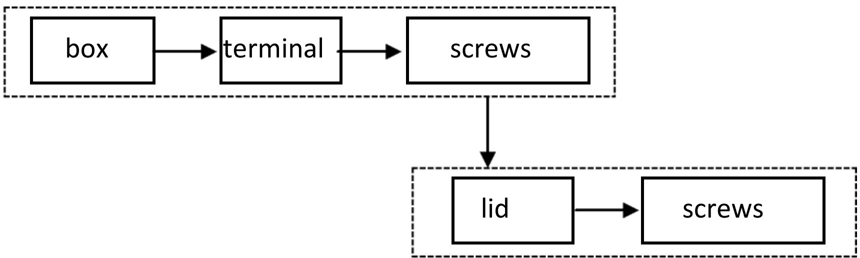


Fig. 5.4.1.3. Diagram of interdependence between component parts of the initial sub-assembly

The diagram of interdependence between component parts of the initial sub-assembly is shown in figure 5.4.1.3.

The diagram of the structure of the initial sub-assembly is shown in figure 5.4.3.

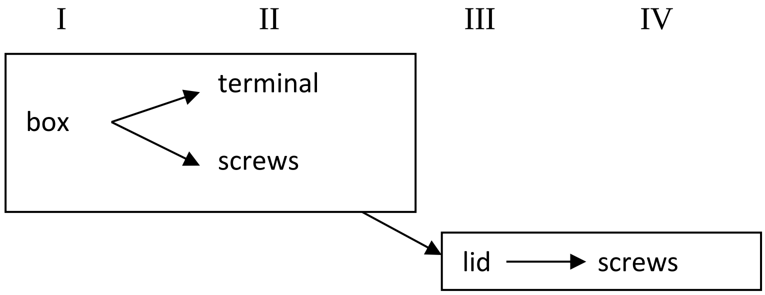


Fig. 5.4.1.4. Diagram of the structure of the initial sub-assembly

The outline of the assembly process for the original product, given through the project theme, is shown in figure 5.4.1.5.

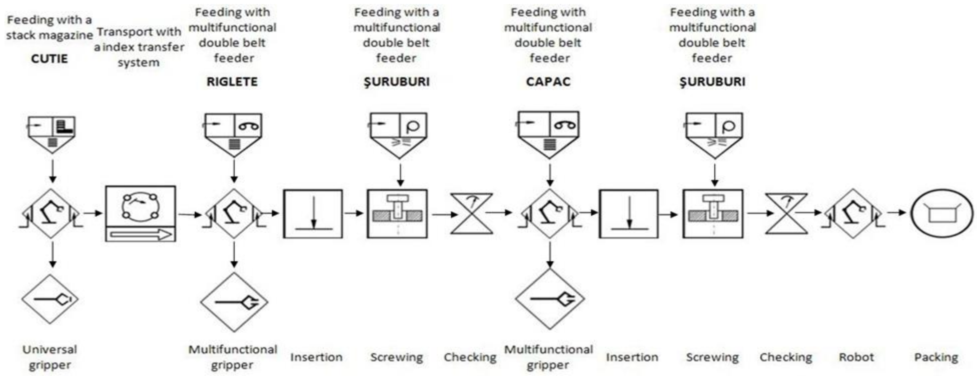


Fig. 5.4.1.5. Outline of the assembly process for the original product, given through the project theme

The simplified layout for the original product, received through the project theme is shown in figure 5.4.1.6.

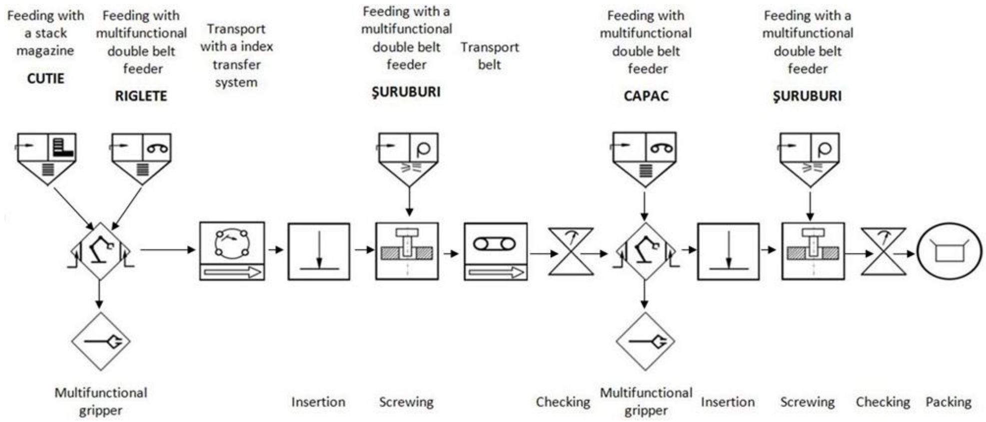


Fig. 5.4.1.6. Simplified layout for the original product, received through the project theme

Applying the DFAFD method to the original product, one can notice that the robotic process for this product can only be achieved at 55.39%. The low percentage of robotization is due to the presence of the screws for holding the reels in the electrical box.

The next step, in order to robotize the assembly of the electrical dose, is to remove the gripping screws of the reels, finding a favorable variant both functionally and qualitatively.

The improved version of the initial sub-assembly consists of removing the screws for holding the reels in the electrical box.

With the removal of the screws, we tried to find a low-cost-fitting method of roulette fastening and while attempting to facilitate the robotic assembly process.

This method consists of making guides inside the box where inserts will be inserted (having the negatives of the guides). The direction of the guides will be the same as the existing screws on the original product. The fastening of the shutters will be made by means of elastic elements which allow further removal (see figure 5.4.1.7. c).

The CAD model of the electrical dose obtained after the first modification is shown in figure 5.4.1.7. (a, b, c, d).

The outline of the structure of the modified sub-assembly is shown in figure 5.4.1.8.

The diagram of interdependence between component parts of the modified subassembly is shown in figure 5.4.1.9.

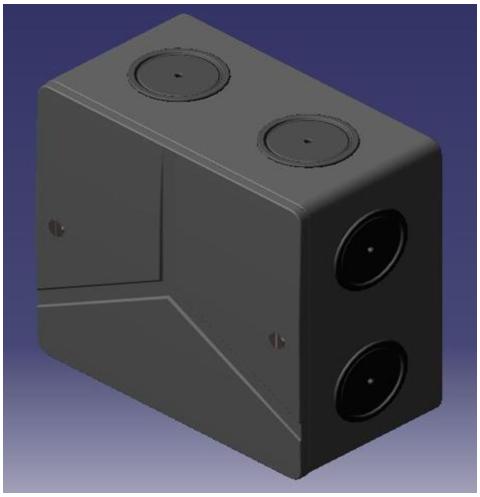


Fig. 5.4.1.7. a) Modified electrical dose - closed

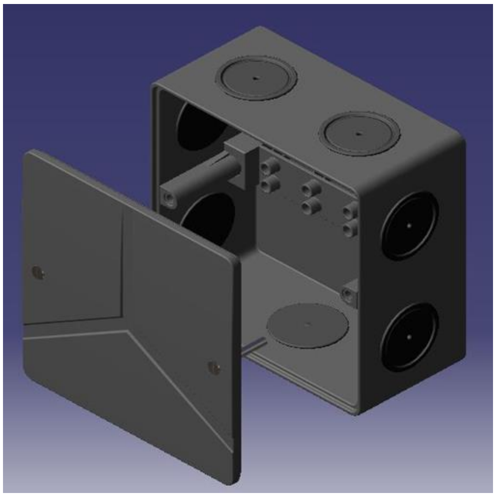


Fig. 5.4.1.7. b) Modified electrical dose - open

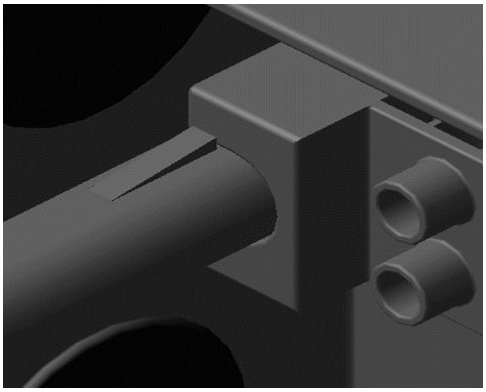


Fig. 5.4.1.7. c) Modified electrical dose - terminal detail

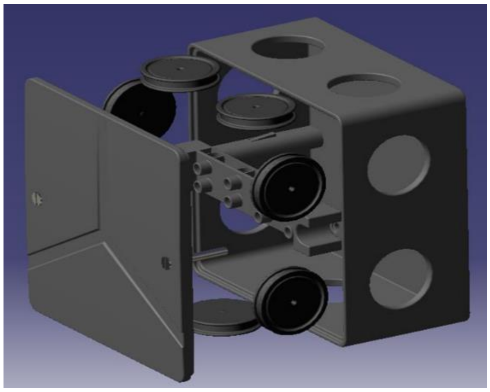


Fig. 5.4.1.7. d) Modified electrical dose - explored view

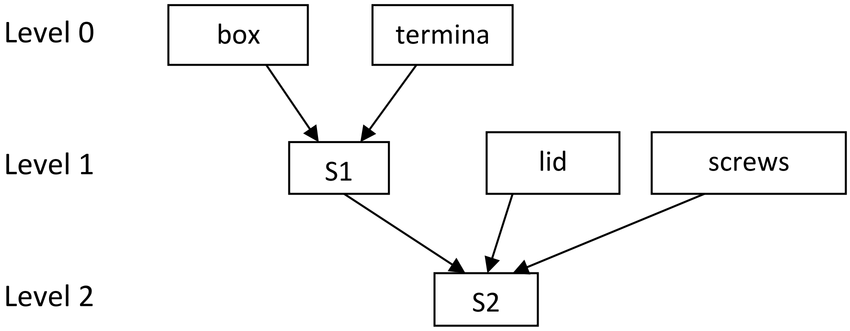


Fig. 5.4.1.8. Outline of the structure of the modified sub-assembly

The diagram of the structure of the modified sub-assembly is shown in figure 5.4.1.10.

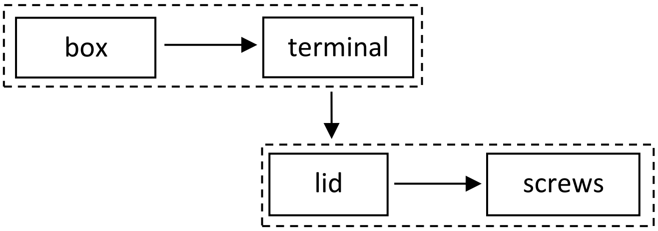


Fig. 5.4.1.9. Diagram of interdependence between component parts of the modified subassembly

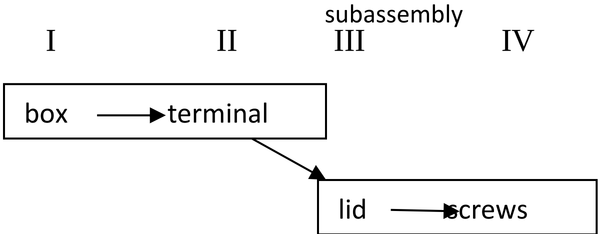


Fig. 5.4.1.10. Structure of the modified sub-assembly diagram

The outline of the assembly process of the modified subassembly is shown in figure 5.4.1.11.

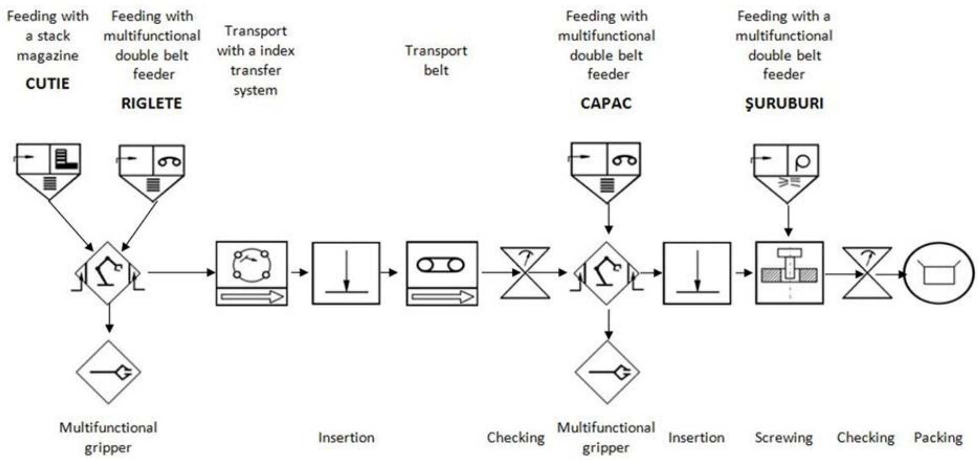


Fig. 5.4.1.11. Outline of the assembly process of the modified subassembly

Applying the DFAFD method for the electrical dose after the first change, an increase of ease in the robotic assembling of 60.67 is observed. Considering this increase, it can be deduced that the presence of the screws has a negative influence on the ease of robotic assembling.

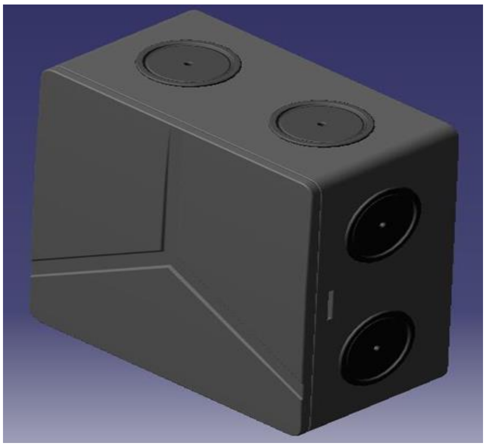


Fig. 5.4.1.12. a) Electrical dose (final version) - closed

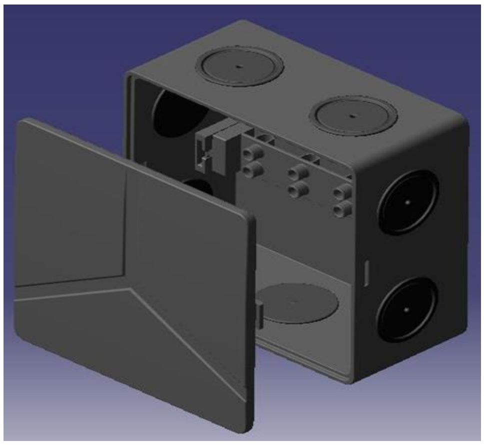


Fig. 5.4.1.12. b) Electrical dose (final version) - open

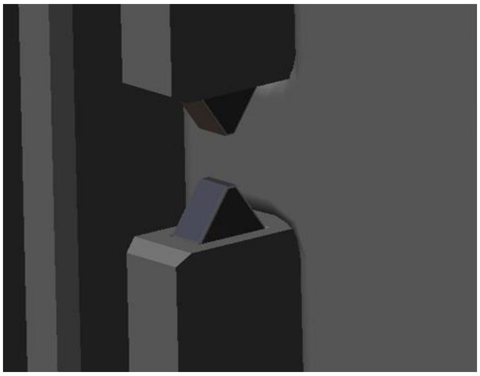


Fig. 5.4.1.12. c) Electrical dose (final version) – terminal fixing detail

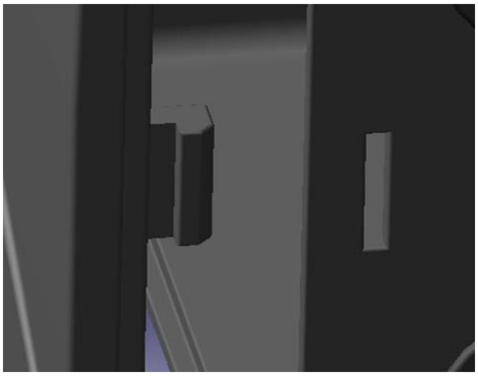


Fig. 5.4.1.12. d) Electrical dose (final version) – detachable cap fastening

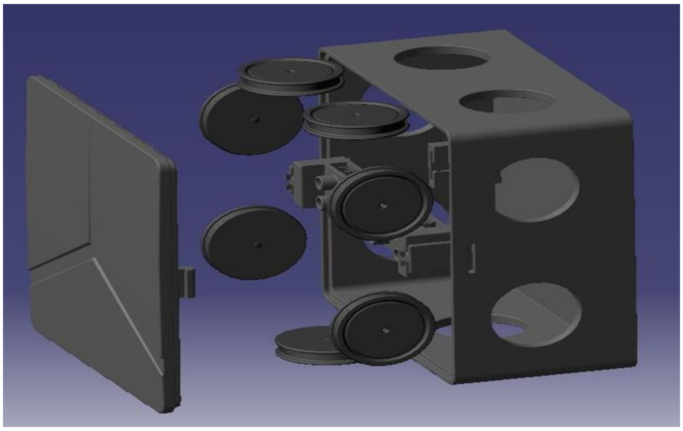


Fig. 5.4.1.12. e) Electrical dose (final version) – explored view

Currently, there are other screws used to clamp the lid of the electrical box into the assembly process. In order to increase the percentage and facilitate the robotic assembly of the electrical dose, remove the cap fastening screws as a result of the DFAFD application. The final version of the sub-assembly consists of removing the caps of the lid of the electrical box.

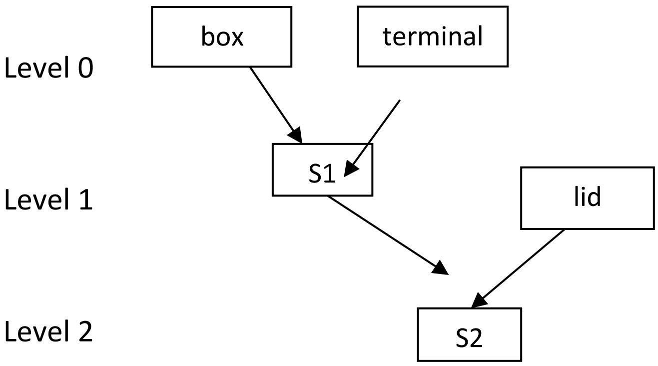


Fig. 5.4.1.13. Outline of the sub-assembly

The diagram of interdependence between component parts is shown in figure 5.4.1.14.

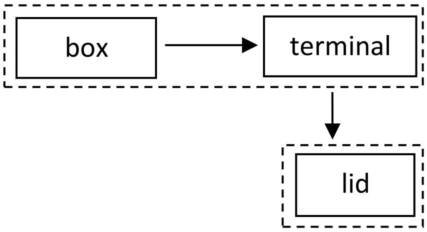


Fig. 5.4.1.14. Diagram of interdependence between component parts

With the removal of these screws, attempts were made to find a low-extra cost-fitting method for the lid and attempt to facilitate the robotic assembly process. The fastening of the cover is made by means of elastic elements (clamps) that allow the opening of the electric dose (Fig. 5.4.1.12.d). These elastic elements will be made of the same material as the lid.

Changing the method of clamping the lid on the electric dose box had an influence on the shelves because they had the support as a support for the screws in the dose box. Thus, a method of fixing the shutters has been found. This consists in the existence of two mirrored clamps, the movement of which is made by the arc at their base (Fig. 5.4.1.12.c).

The CAD model of the electrical dose obtained from the two modifications can be found in figure 5.4.1.12. (a, b, e).

The outline of the sub-assembly is shown in figure 5.4.1.13.

The diagram of sub-assembly structure is shown in figure 5.4.1.15.

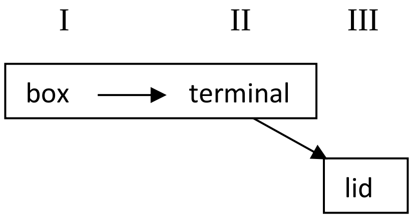


Fig. 5.4.1.15. Diagram of sub-assembly structure

The outline of the assembly process is shown in figure 5.4.1.16.

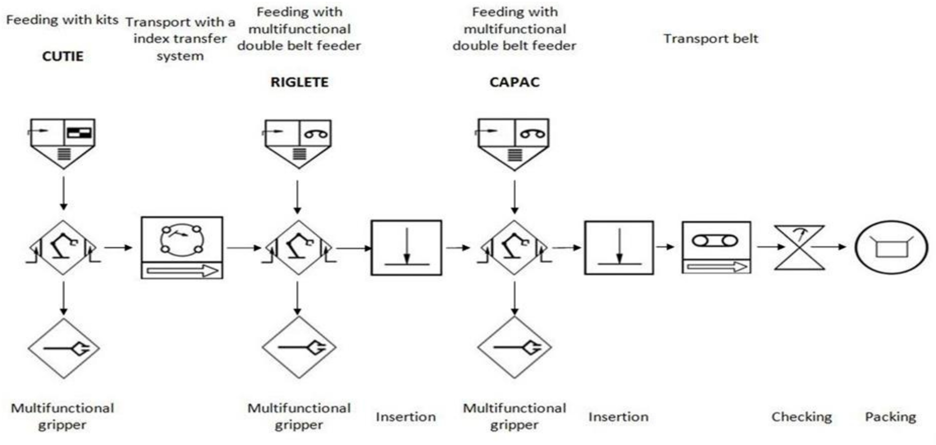


Fig. 5.4.1.16. Outline of the assembly process

After the initial product passes through two modifications, it can be seen that the robotic assembling of this product can be accomplished by 70.30%, therefore, the results obtained following the application of the DFAFD method.

Changes to the original product to increase the level of robotic assembly consist of removing the fasteners (screws) from both the shelves and the lid. Improvements to the product are:

a. The shuttles will be mounted in specially designed guides and will be fastened using metal elastic clamps that allow disassembly
b. The cover will be fitted with elastic clamps made of the same material as the lid and the box

List of equipment and sensors required for the design of the robotic assembly cell for an electric dose:

a) equipment:

- 1 ABB IRB1600 industrial robot
- 1 ABB IRC5 controller
- 1 multipurpose gripper
- 1 PLC
- 1 indexing table at 120 °
- 3 conveyors
- 1 kit feeders
- 2 devices for feeding the shutters and covers

b) sensors:

- 3 photoelectric sensors
- 1 optical sensor
- 1 force sensors
- 1 video systems

Robotic assembly is an operation that cannot be done without the control elements of the sensors. They are chosen based on the operation that takes place and the characteristics of the assembly type.

In this case, the sensors used are:

- photoelectric sensors - at each feed of the process with the required assemblies (boxes, shutters, cover); a photoelectric sensor will also be used at the end of the assembly (before the packing area, on the transport system area) for counting the number of assembled products; 4 photoelectric sensors are required
- optical sensors - at the index table to detect the presence of elements on the index table; 1 optical sensor is used
- force sensor - mounted on the gripper; use in the insertion area of the shelves and caps; 1 force sensor is required
- video system - used for the verification area, which is after completion of the product assembly (1 video system required)

In order to make the robotic cell of the final product, besides the product, sensitive elements and components, equipment and devices are required to perform the robotic assembly process.

A first important element in any robotic system is the robot that will replace the human operator and assemble the product. In this case, a serial robot with a small carrying capacity (small and light items handled) and a reduced working area will be used. A multifunctional gripper will be attached, as there are 3 close-fitting components.

The connection between the assembly steps will be done by means of an index table at 120° (the second component of the robotic cell), with $\varnothing$1300 mm, on which the entire assembly process will be carried out. Once the dose has been assembled, it will be transported to packaging using a strip conveyor, of at least 3 meters long.

The boxes will be powered by kits, their orientation and guidance being indicated from the beginning. The trays and caps will come on a dual multipurpose tape, and guidance and guiding will be done using automated systems (feeders) specifically designed for this purpose. Both the terminals and the caps will be mounted by insertion.

With regard to the gripping devices used, these are represented, during the assembly process, by the specially designed pockets (according to the box dimensions) on the index table. The presence of the index table facilitates the positioning and orientation of the final product that is going to pack.

For the robotic assembly of an electric dose, use an ABB IRB1600 robot to which a multifunctional gripper is attached, together with an index table, three conveyors, feeders for each component (box, routers, lid), sensors (for force, photoelectric, optical) and a video system.

The entire assembly process will be performed on the index table by the robot. The first step is to place a box on the index table in the specially designed places (the same size as the box). Once the box is in place, the optical sensor (will only work on the first feed - the first box) will detect its presence and so the table will rotate 120° to make the next step.

The index table will remain in position 2 until the product is assembled completely. The complete assembling consists of mounting the shutters inside the box that will be transported from the router power supply system to the robot (to the right of the robot) by means of a conveyor. On the left side of the robot they will reach the lids. These are also introduced in this process by a special power system designed for caps, via a conveyor. Mounting the caps is the final step in assembling the electrical dose. Each conveyor (for shutters and caps) has finally mounted photoelectric sensors by which the presence or absence of the element is detected in the desired position, so the robot will know whether or not the element is in the desired position.

Once the assembly process has come to an end, the same robot will take over the final product and transport it to a conveyor to pass through the verification and packaging steps.

Once the final product has been transported on the exhaust conveyor, the photoelectric sensors located at the beginning of the product will send the PLC signal and, thus, start the assembly of the second product (electrical dose). The signal will reach each feeder (component) in part, in order to provide the robot with the following items for assembly.

Product verification will be carried out using a video system placed in the middle of the conveyor. This system is equipped with 2 lamps (one red and one green), which will inform you if the product is correctly or incorrectly assembled.

The correct assembly of the product is indicated by the green light of the optical system. Thus, the product will go further towards packaging. At the end of the exhaust conveyer there is a device specially designed for packaging the finished product (the finished product will fall into the box where it will be transported for storage). This device consists of a table on which the product packaging (box) is located and which then slides on a rail. Once the table has reached the end of the rail, a human operator will close the box, which will go to storage.

In the figures below there are different views of the mounting cell, specially designed to assemble the required dose. There is a 3D view of the cell (Fig. 5.4.1.17) and a top view (Fig. 5.4.1.18), where the components of the assembly cell are indicated.

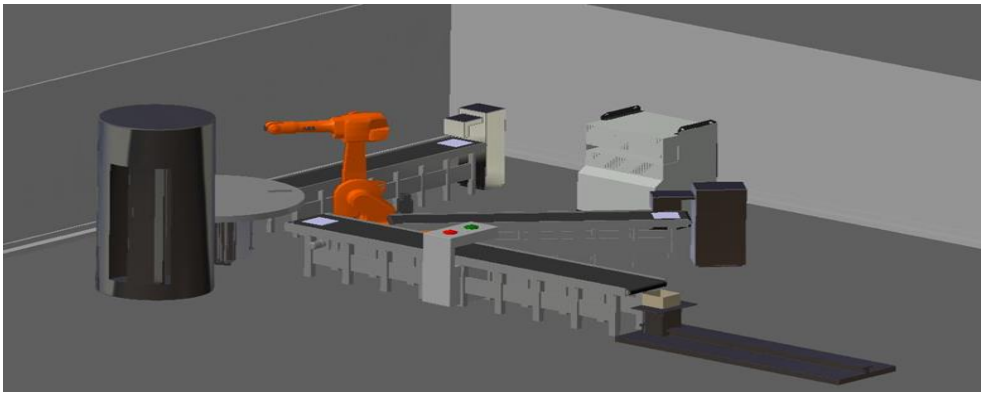


Fig. 5.4.1.17. Layout robotic cell - 3D view

Economic evaluation of the robotic assembly cell

The economic profitability of a certain robotic assembly cell concept is defined by the coefficient called total IP productivity.

The value of this coefficient indicates whether the solution adopted is economically profitable or not.

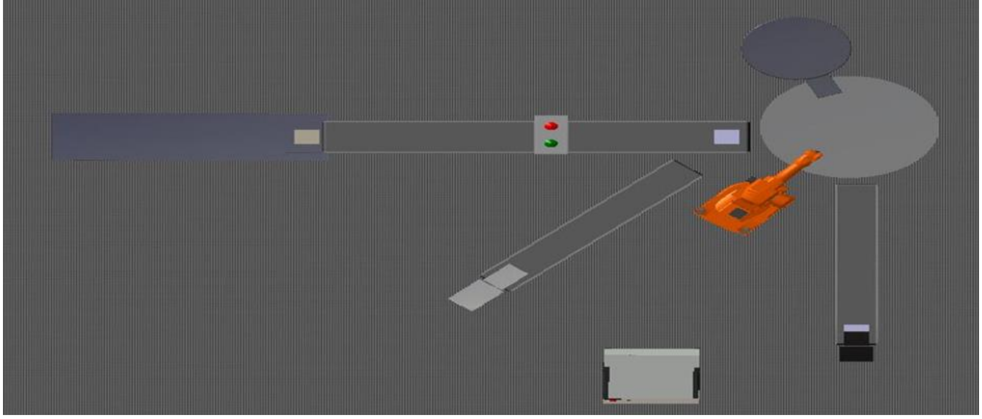


Fig. 5.4.1.18. Robotic cell layout - Top view

If: IP < 1 then the adopted solution is not economically profitable

IP ≥ 1 then the adopted solution is economically profitable

In order to make the economic assessment, we need to have some input data, which consists of the purchase prices for each equipment, sensor and the devices used to make the assembly cell. This data is presented in table 5.4.1.1.

Table 5.4.1.1. Equipment prices

Equipment	Price (€)
Feeders (3 pieces)	1800
Conveyor (3 pieces)	21000
Index table	2200
Sensors (5 pieces)	500
PLC	2000
Gripper	700
Video system	5000
Robot ABB IRB1600 (+ controller)	25000
TOTAL	**116400 €**

$n_s := 1$ - Number of shifts

$C_{las} := 1 \cdot 12 \cdot 10000$ - Annual cost/shift

$I_f := 1.2$ - Factor by which it is represented how many times the human operator needs to supply

$C := n_s \cdot C_{las} \cdot I_f = 1.44 \times 10^5$ the cell with material (has values between 1.1 and 1.3)

Capital for consumption

$r := 0.13$ - Interest rate

$\mu := 6$ - Economic life span of the system

$I_1 := 25000$ - Cost for the robot

$I_2 := 0.45 \cdot 25000 = 1.125 \times 10^4$ - Cost for the software (PLC)

$I_3 := 6000 + 4000 = 1 \times 10^4$ - Cost for the supply system

$I_4 := 700$ - Cost for the gripper

$I_5 := 2200 + 21000 + 100 = 2.33 \times 10^4$ - Cost for the conveyor and the index table

$I_6 := 5000 + 500 + 400 + 100 = 6 \times 10^3$ - Cost for the sensors and the inspection system

$I_7 := 15000 + 5000 + 10000 + 8000 = 3.8 \times 10^4$ - Costs of training and redesigning

$I := I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7 = 1.143 \times 10^5$ - Total initial investment

$C_{cap} := \dfrac{r}{1 - (1 + r)^{-\mu}} \cdot I = 2.858 \times 10^4$ - Consumption cost

Cost of material

$C_m := 1.6$ - Cost for the material/piece

$C_{cap} := \dfrac{240 \cdot 8 \cdot 60}{1.5} = 7.68 \times 10^4$ - Cell capacity

$v_1 := 1$ - Percentage of annual production volume

$A := \dfrac{200}{240} = 0.833$ - Cell availability

$N1 := C_{cap} \cdot A \cdot v_1 = 6.4 \times 10^4$ - Number of assemblies made

$C_{ma} := C_m \cdot N1 = 1.024 \times 10^5$ - Cost of material

Other costs

$C_{fi} := 7500$ - Cost of the used space

$C_e := 2000$ - Energy costs

$C_{main} := 500$ - Maintenance costs

$C_{others} := 12 \cdot (C_{fi} + C_e + C_{main}) = 1.2 \times 10^5$

$OUT := 15 \cdot 250 \cdot 200 = 7.5 \times 10^5$ 15 lei/dose * 250 days/year * 500 doze/zi

$IN := C + C_{cap} + C_{ma} + C_{others} = 4.432 \times 10^5$

$IP := \dfrac{OUT}{IN} = 1.692$

Taking into account the obtained data, namely that IP ≥ 1, it means that the adopted solution is economically profitable.

Many thanks to our student, Sanda Timoftei, for enabling us to present her solution for this case study!

5.4.2. 2nd Project Example

The product in the initial state presents some problems in its assembly. Complete automation cannot be done because it presents elements that make it difficult to assemble with industrial robots. These are the fastening screws of the connection rods and the cap fastening screws. Also, the cover of the original product has to be positioned very precisely because it does not have guides to allow easy mounting with the help of robots.

These elements will need to be removed and replaced or improved with another gripping system, and this will make possible the robotic assembly.

The sketch of the structure of the sub-assembly, the diagrams of the sub-assembly structure, the sketch of the assembly process must be elaborated.

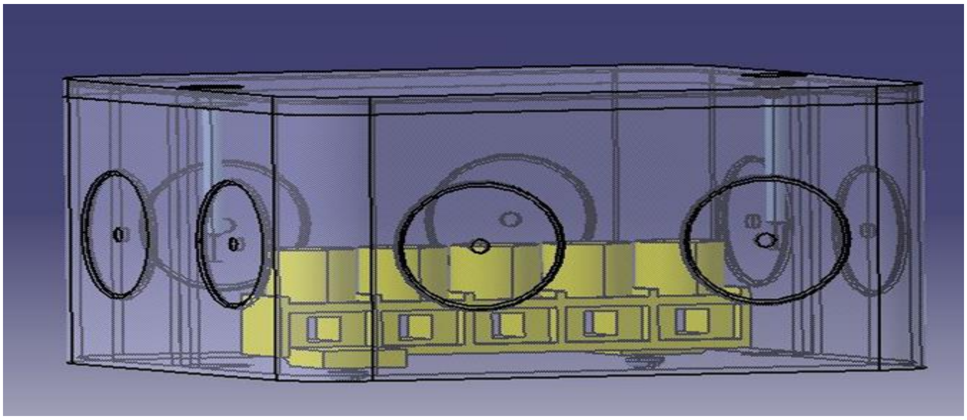


Fig. 5.2.4.1. The initial version of the subassembly

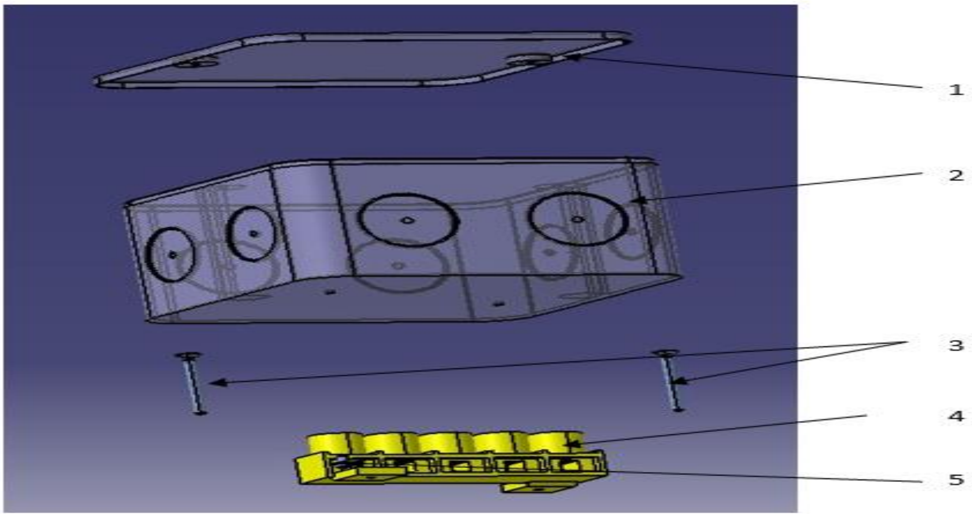


Fig. 5.2.4.2. The constituent elements of the electrical dose - initial version

Additionally, a list of weaknesses of the sub-assembly in the results of the DFAFD application is elaborated.

The initial version of the subassembly is shown in figure 5.4.2.1.

The constituent elements of the electrical dose in the initial version are shown in figure 5.4.2.2. These are:

1. cover
2. box
3. 2 M4x45 head screws
4. Connection terminals
5. 2 M4x5 screws - to fix the reels

The sketch of the product structure is shown in figure 5.2.4.3.

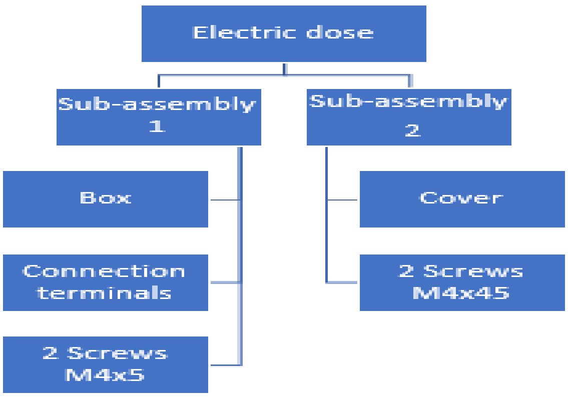


Fig. 5.2.4.3. The product's structure

Diagram of interdependencies between the components of the original product is shown in figure 5.2.4.4.

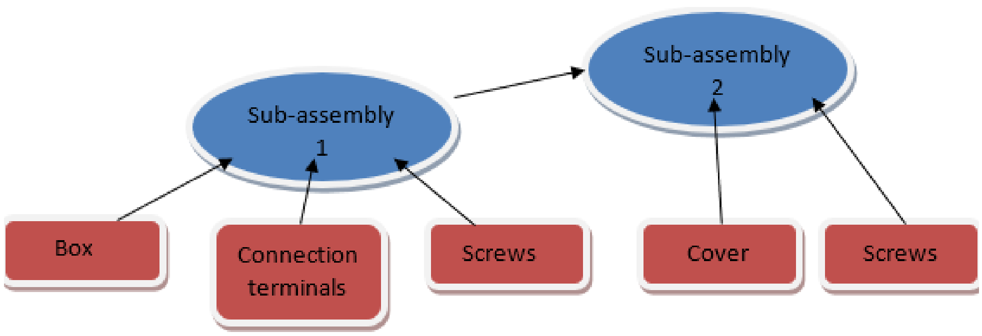


Fig. 5.2.4.4. Diagram of interdependencies between the components of the original product

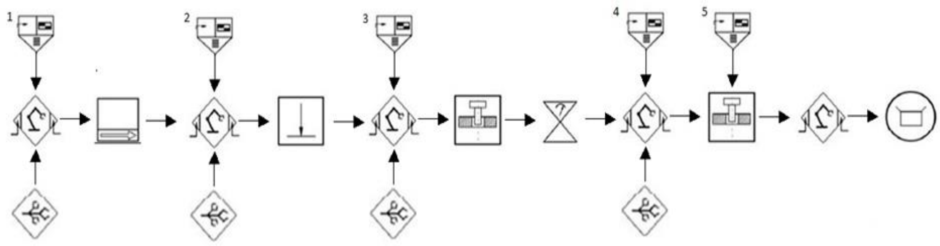


Fig. 5.2.4.5. Outline of the assembly process

The outline of the assembly process is shown in figure 5.2.4.5.

In the figure above (Fig. 5.2.4.5) the numbered items are:

1. box
2. connection terminals
3. M4x5 screws
4. cover
5. M4x45 screws

The lid is assembled with screws in the initial version. This operation involves changing the type of gripper or using a specialized gripper that is more expensive and requires more time to change. A solution to the problem can be to replace the lid clamping system by removing the screws and changing them with flexible clamps attached to the cover. You also need to change the box at the top by adding a frame to clamp the clamps.

The assembling of the rods in the initial product phase is also done with the screws. In this situation, we also have the problem of turning the box upside down because these screws are placed on its back. Changing the box and reels can easily replace this problem. The new clamping system is clipped.

When elaborating the improved variants of the subassembly, the elements that are difficult to assemble are taken into consideration, each element removes one element and makes the DFAFD analysis method.

The structure sketch of the sub-assembly, the diagrams of the sub-assembly structure and the sketch of the assembly process must be recalled.

Taking into account the weaknesses of the original product, I considered that the caps of the cover should be removed and modified by this clamping system with one clipping. The changes are, as follows, in the following figures. Figure 5.2.4.6 highlights the new assembly.

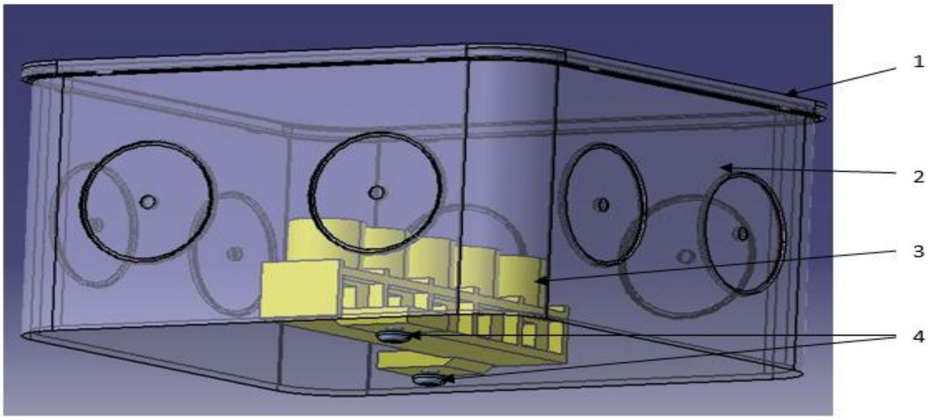


Fig. 5.2.4.6 The new assembly

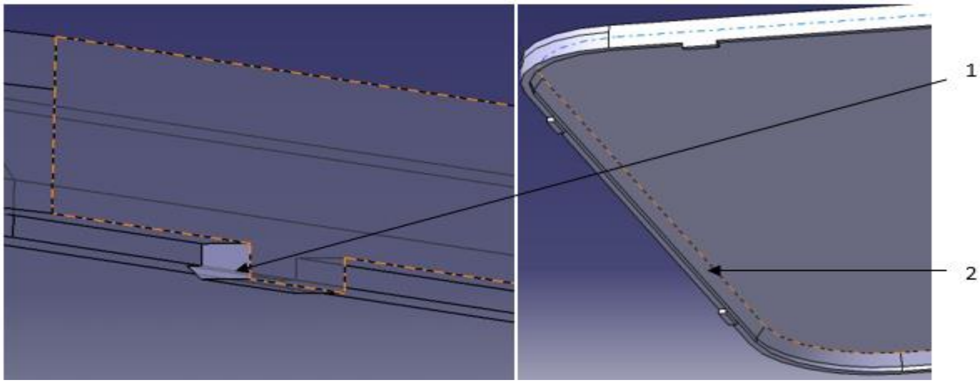


Fig. 5.2.4.7 The changes made to the cover

Figure 5.2.4.7 highlights the changes made to the cover. These are the insertion of 2 clamps (1) on each face of the lid and one inclined plane (2) around the edge of the box edge, which will make assembly easier for the robot.

Figure 5.2.4.8. shows the change to the box. The channel (1) has a bead to help position the cover.

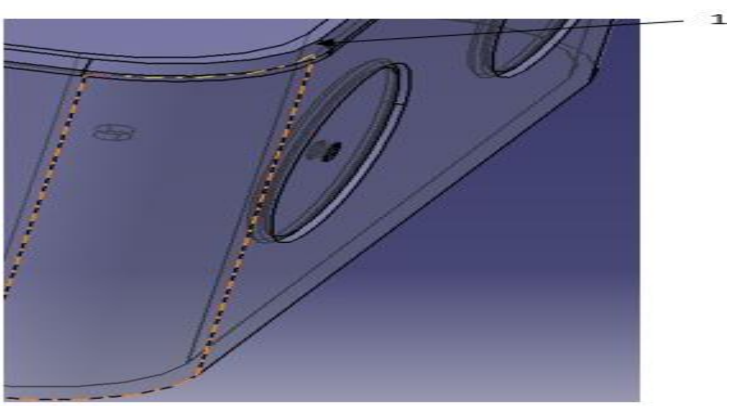


Fig. 5.2.4.8. The change to the box

The outline of improved product structure can be observed in figure 5.2.4.9, while the diagram of the interdependencies between the components of the improved product can be observed in figure 5.2.4.10.

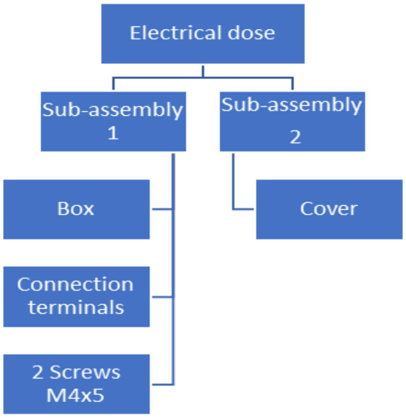


Fig. 5.2.4.9. Outline of improved product structure

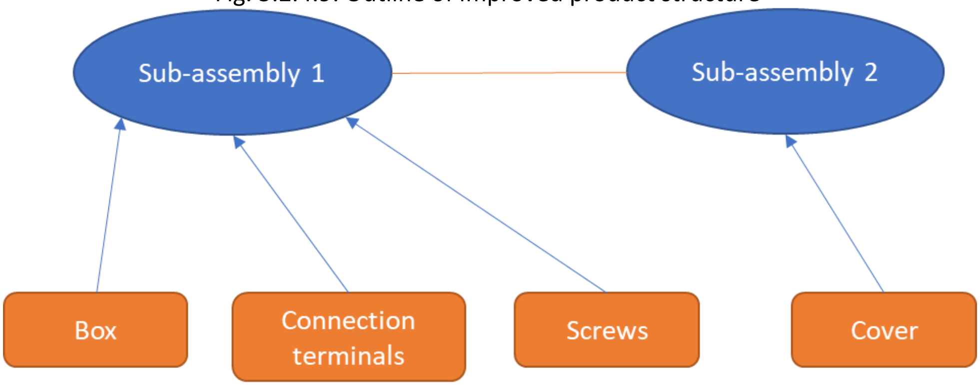


Fig. 5.2.4.10. Diagram of the interdependencies between the components of the improved product

The outline of the assembly process is shown in figure 5.2.4.11.

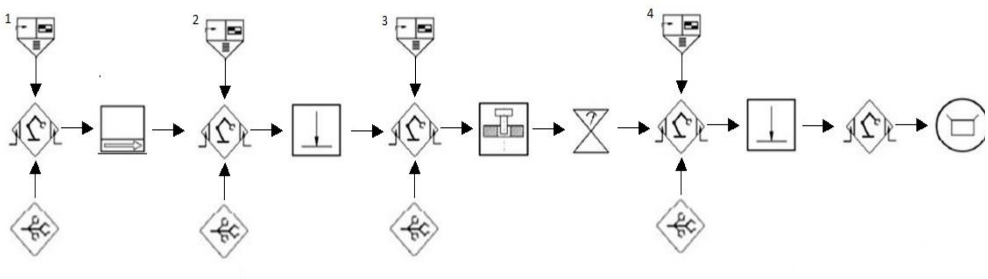


Fig. 5.2.4.11. Outline of the assembly process

In the figure above the items numbered are:

1. box
2. connection terminals
3. M4x30 screws
4. the cover

The only removed items are the M4x45 screw fastening screws. Also, as it can be seen from figure 5.2.4.10, the cover is now fixed by clipping.

As follows from the second DFAFD, the only remaining problem is the second set of M4x5 screws for fixing the connection roulettes.

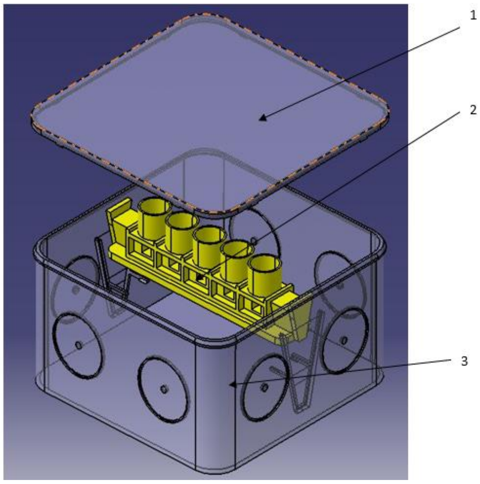


Fig. 5.2.4.12. The new assembly

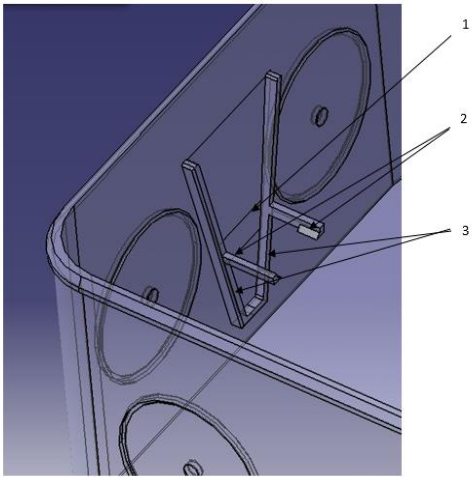


Fig. 5.2.4.13. The changes made to the box

I will modify the fastening system from one with screws to a clip system.

Starting from the DFAFD of the improved product, we notice that the last change in the dose set-up should be made to the clamping system. We will make it to cap 2, namely the replacement of the screw fastening system with a clamping system. The changes are, as follows, in the following figures. Figure 5.2.4.12 highlights the new assembly.

Figure 5.2.4.13 highlights the changes made to the box. These are the creation of a tilted plane on the side walls of the box (1) in the place where the ribbons enter. This creates a guide that ends with a tightening at the bottom, and at the top of the box remains a 2mm positioning game. Also, through the guide in V (3), an exact positioning of the ribs is ensured against the sides of the box. Clamps (2) do not let the ribbons come out vertically from the final position.

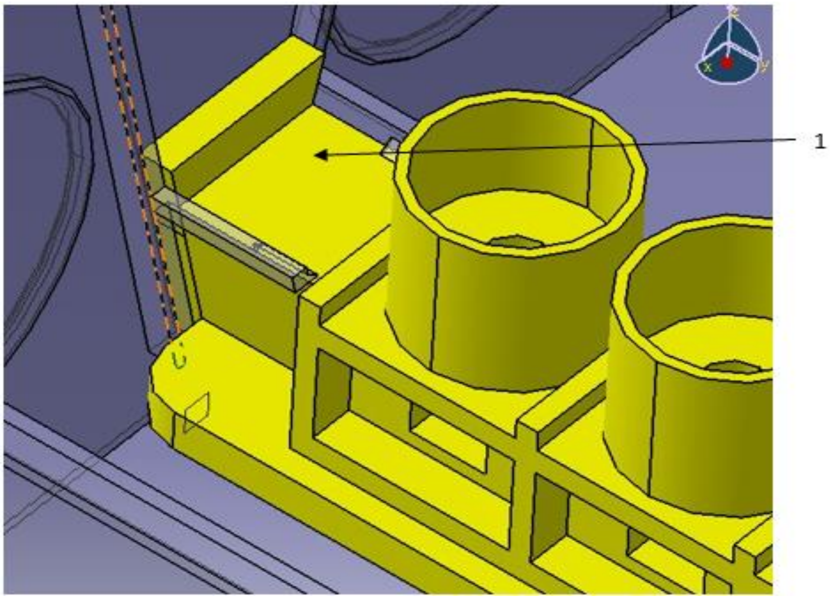


Fig. 5.2.4.14. The change to the terminals

Figure 5.2.4.14 shows the change to the terminals. The insertion of the extension (1) with the prismatic shape helps positioning the rectangles in the V-channel of the box. Also, by its shape, a rigidity of the terminal's structure was made. Therefore, they can be assembled robotically much easier, even at the middle of the assembly process.

The outline of the final product structure is shown in figure 5.2.15, while the diagram of interdependencies between the components of the final product is shown in figure 5.2.4.16.

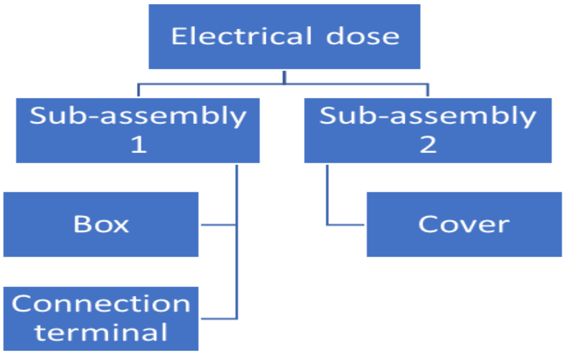


Fig. 5.2.4.15. Outline of the final product structure

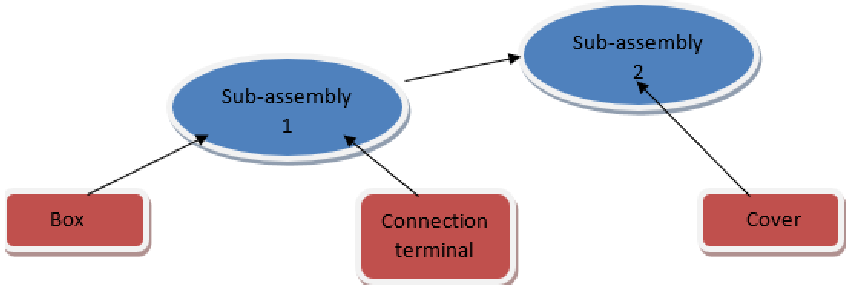


Fig. 5.2.4.16. Diagram of interdependencies between the components of the final product

The outline of the assembly process is shown in figure 5.2.4.17.

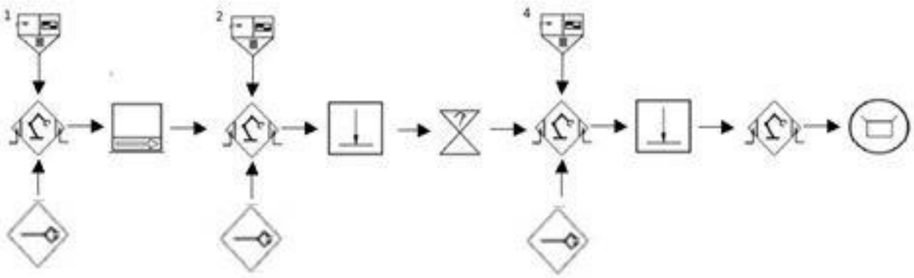


Fig. 5.2.4.17. Outline of the assembly process

In figure 5.2.4.17 the items that are numbered signify:

1. box
2. connection terminals
3. cap

The only items removed are the M4x5 clamping screws. Also, as can be seen from figure 5.2.4.20, the terminals are fixed at the moment by clipping. In order to improve the robotic cell, I changed the type of gripper from a multi-gripper into a multifunctional gripper that is cheaper. This change was made because all the pieces are clipped and there is no need for screw driving to fix them.

As can be seen from applying the DFAFD method, there are no further improvements that can be made to the product, without radically altering the remaining components. Also, the percentage of robotization has increased significantly from the initial state of the product, which translates into lower costs, fewer time and number of operations.

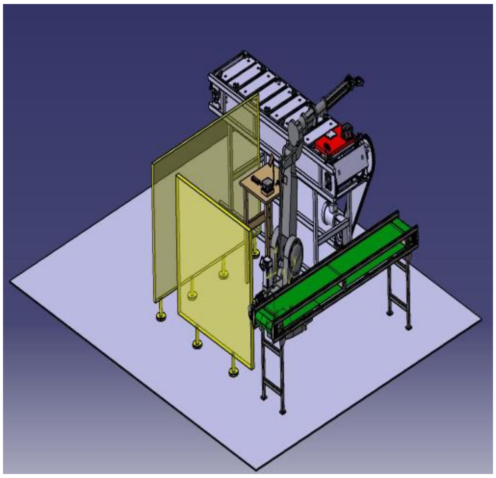


Fig. 5.2.4.18. Manufacturing cell – 1st view

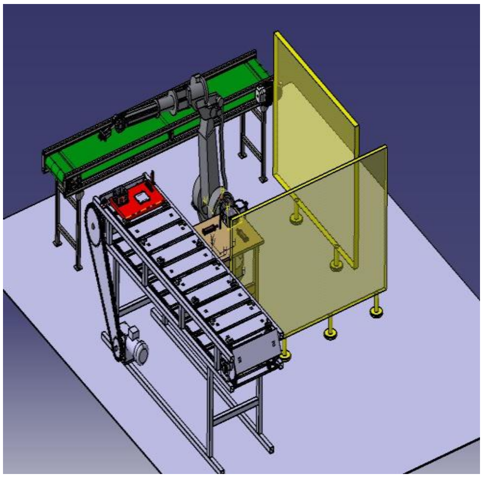


Fig. 5.2.4.19. Manufacturing cell – 2nd view

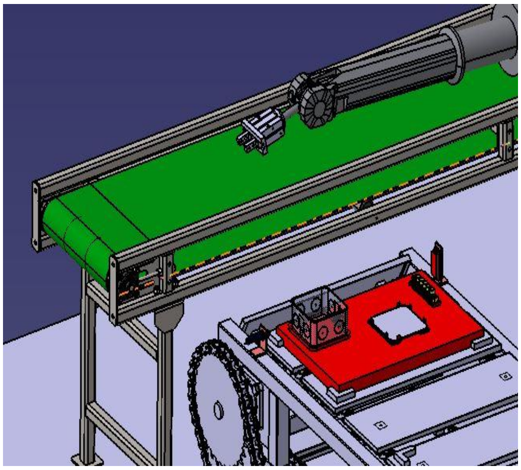


Fig. 5.2.4.20. Gripper and kit

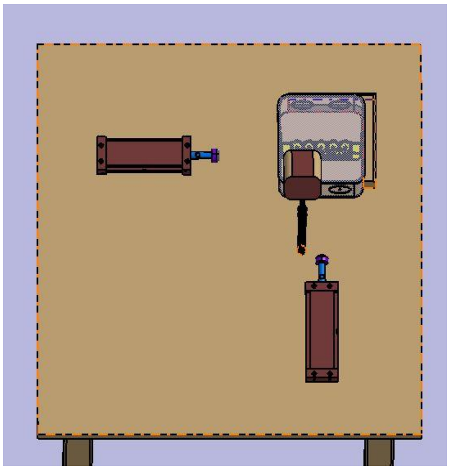


Fig. 5.2.4.21. Dose fixings

In figures 5.2.4.18 and 5.2.4.19, we represented the manufacturing cell from two different angles to see all of the components. Figure 5.2.4.20 shows the type of gripper used and the shape of the kit. In figure 5.2.4.21 one can see the dose fixings on the work table and the process control element.

The final version of the product offered the opportunity to greatly simplify the robotic cell for assembling the dose.

Costs have been significantly reduced by using a single type of gripper without special features, and a single robot is also used in the process. The gripper is a mechanic one with two fingers that can be opened sufficiently to catch all three parts of the assembly.

By not using the screw clamping system and replacing it with a clipping system, the process was simplified by reducing the number of operations.

The process is limited to:

- the assembly parts come in a single kit on a process input conveyor. Once the kit has reached the infrared sensor, the conveyor stops, and the robot takes the pieces in the default order: box - ruler - cap.
- the robot moves the box to the work table, where it will be fixed with a guide and two pneumatic pistons in a fixed position. Next, the robot will also mount the other pieces.
- Before installing the cover, the 2D camera system visually checks if the assembled product has defects
- if the product is defective, the robot will remove it and put it in the recycling area (box)
- If the product has no defects, then the robot will mount the cover and then place the finished product on the output conveyor in the process.

Economic evaluation of the robotic assembly cell:

Equipment/device	Price
kit	20 euro
conveyor + command	900 euro
working table	20 euro
pneumatic piston + command	150 euro
force sensor	150 euro
Infrared proximity sensor	180 euro
PLC	2000 euro
mechanic gripper	750 euro
video inspection system	14000 euro
robot IRB 2400	37500 euro

We have made an improvement in the process of assembling an electric dose for the purpose of assembling it with the help of robots. We did this by altering the fastening systems with screws with snap fasteners. We also modified the main dose items to make the clipping process easier.

With these changes, the operation scheme has been reduced and costs have been diminished.

Many thanks to our student, Vlad Florian, for enabling us to present his solution for this case study!

5.4.3. 3rd Project Example

In the first step we will analyze the junction box to be remodeled in order to facilitate its robotic assembly (Fig. 5.4.3.1).

ume student	A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm
omokos zilard	200	200	7.5	103	35	10	50

Fig. 5.4.3.1. Initial product and its dimensions

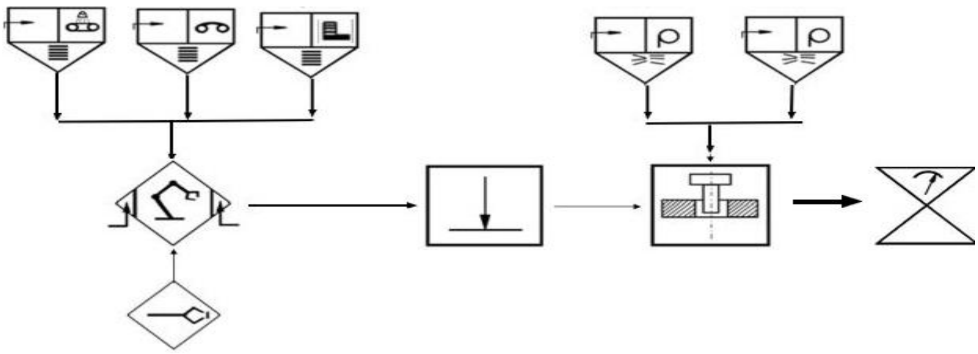


Fig. 5.4.3.2. Outline of the component assembly process - initial phase

The sketch of the component assembly process is presented in figure 5.4.3.2.

The use of screws to fix the connection routers is inappropriate for robotic assembling. First, screwing is an operation that takes a long time, and, secondly, it requires the purchase of a specialized gripper that raises the cost of the robotic cell.

At this stage we will replace the two screws with two components similar to the RAM memories. The advantage of these components is that the mounting is done by pressing rather than by screwing, thus reducing the assembly time.

For ease of assembly with the robot, we will design a channel on the bottom of the box and test the bottom of the terminal connections to obtain proper auto centration. At this stage we will design the required fitting locations.

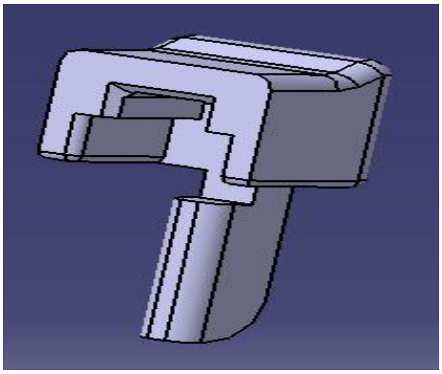


Fig. 5.4.3.3. Fixing element for fastening the connection terminals

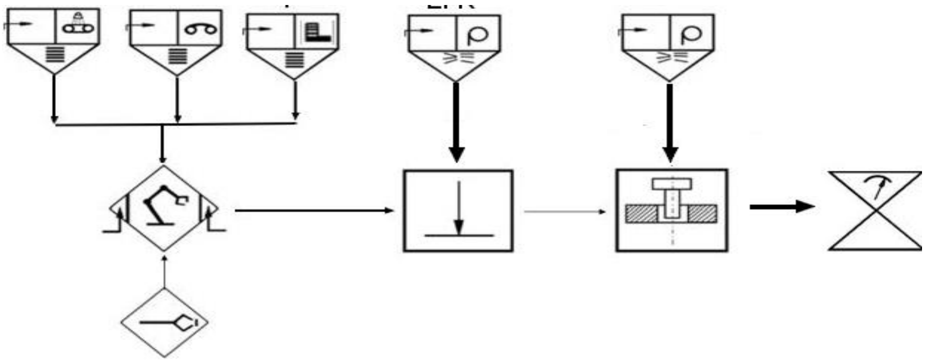


Fig. 5.4.3.4. Schematic of the assembly process after the first step of improvement

After designing the fixing element for the fastening of the connection terminals (Fig. 5.4.3.3), we will then develop an improved product version.

Thus, the new product will be easy to assemble using the same type of gripper.

Figure 5.4.3.4. shows the schematic of the assembly process after the first step of improvement.

In the next step, we remove the cap fastening screws, redesigning the cover (Fig. 5.4.3.5), and making small changes to the box. Thus, the lid will have a channel on the edge of the wall and two extruded profiles for fixing it. In order to achieve a necessary auto centering, we will test the edges of the extruded profiles. On the edge of the cover we will project an extruded profile that enters the channel on the lid, thus allowing the junction box to be insulated by clamping the two components (channel, extruded profile).

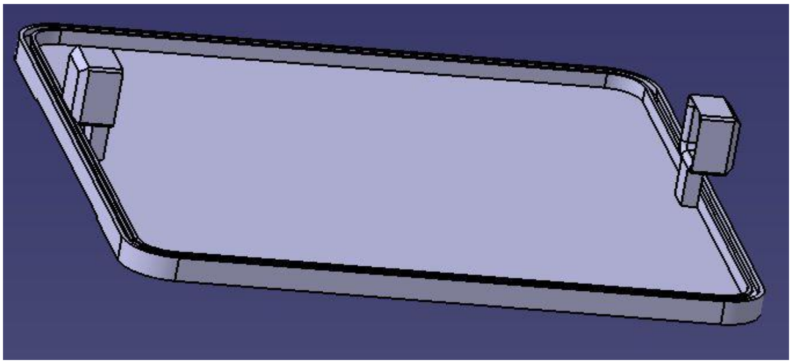


Fig. 5.4.3.5. The redesigned cover

Thus, the new product will be easy to assemble by using the same type of gripper as well as by using fewer assembly components. By removing the screw, the assembly time of the product is also reduced.

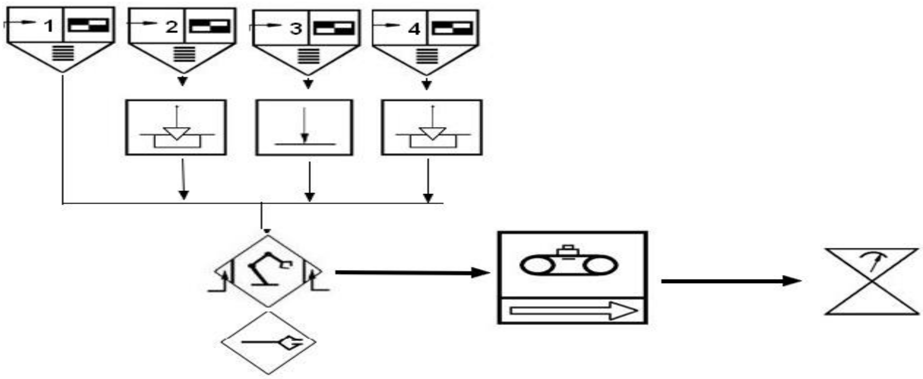


Fig. 5.4.3.6. Outline of the finishing process

The outline of the finishing process is presented in figure 5.4.3.6. Explanations for the numbering in the figure are shown below:

- 1 represents the box
- 2 represent the joining elements
- 3 represent the connection terminal
- 4 is the cover

If at the earlier stages the feed was made using feeders that were not organized in the sense that the orientation of the parts was not known, now the components are placed in a well-defined container. The used gripper is a multifunctional one that can have between 2-5 functions. In this case, the gripper is used to perform 4 operations. The finished assembled product (Fig. 5.4.3.7) will be transported by means of a conveyor to quality technic control and inspection.

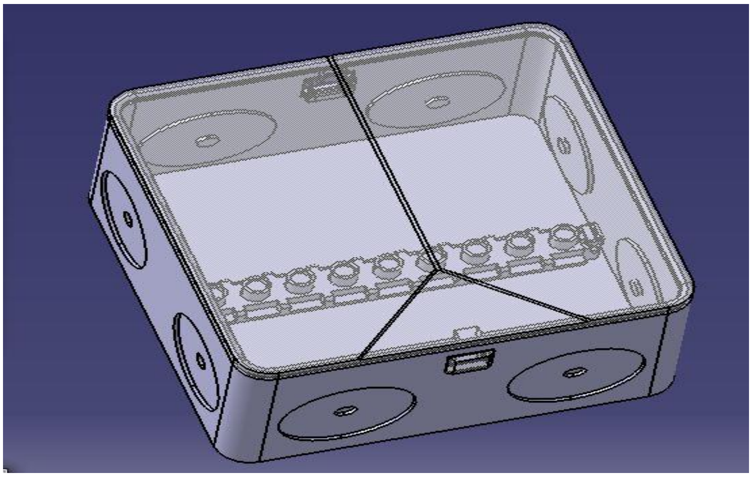


Fig. 5.4.3.7. Finished assembled product

Calculation of Total Productivity (IP):

If IP <1 - the solution chosen is not profitable

If IP> 1 - the solution chosen is justified

$$\underline{IP} = \frac{\underline{OUP}}{\underline{INP}} = \frac{\sum_{i=1}^{N_p} P_{vi} \cdot \underline{N_{ai}}}{C_{la} + C_{cap} + \underline{C_{ma}} + C_m} \qquad (1)$$

Where:

$\underline{OUP}$ - system's output;
N_p - number of products or assembly variants/year;
P_{vi} - production value per acceptable assembly variant i;
$\underline{N_{ai}}$ - number of acceptable assemblies of variant I which are produced annually;

$\underline{INP}$ - system's input;
C_{la} - labor cost;
C_{cap} - capital consumption;
$\underline{C_{ma}}$ - material costs;
C_m - other costs (energy, workspace, etc.).

Table 5.4.3.1. Costs of the elements of the robotic cell

No	The elements of the robotic cell	Price(€)
1	The parts store with kits	800-1000
2	Conveyor + command	9000-10000
3	Bar code reader	100
4	Proximity sensor	50
5	PLC	1200
6	Multifunctional gripper	900
7	Robot ABB IRB 1600	48000

OUP:

Pvi=5eur (cost/piece)

Nai=250 days/year*200 piece /day

INP:

$$C = n_s C_{Ias} I_f$$

I_f=1.2

n_s=1

C_{Ia}=1*1.2*1000=1200 €

Capital consumption

$$C_{cap} = \frac{r}{1-(1+r)^{-\mu}} I$$

r=0.15

μ=10 years

I = I1 + ... + I7

I1 = cost robot = 48 000 €

I2= .45 * cost-robotic-system = 0.45 * 1500 eur = 675€

I3 = 3600 € (4 warehouses)

I4 = cost-gripper = 900 €

I5 = conveyoare = 20000 €

I6 = cost-inspection-and-sensors = 9500 €

I7 = cost-enginnering-training-redesign = 1000.€

I = 83675 €

C_{cap}=16688.32 €

Cost of the material

$$\underline{C_{ma}} = \sum_{i=1}^{N_p} C_{mi} \underline{N_i}$$

$C_{ma} = C_{mi} * N_i = 2$ eur $* C._{capacity} * A._{disponibilit} * v_i$ (100%)

$C_{capacity}$ = 250 days * 8 hrs * 60 mins / 3 mins = 40.000 unitati

A = 200 / 250 = 0.8

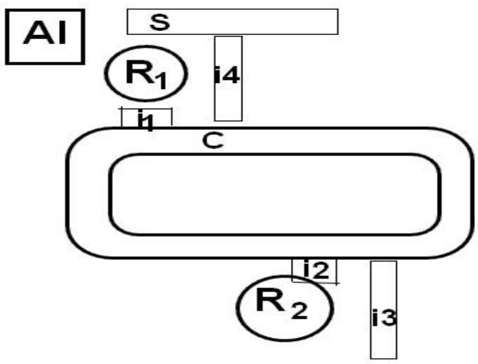
$C_{materials}$ = 2 * 40.000 * 0.8 = 64 000 €

$C._{others}$ = 12 months * (800 eur + 300 eur + 300 eur) = 16800 €

IP = 250 000/(1 200+ 16688.4 + 64 000+ 16 800)=2.53

IP> 1 which means that the robotic assembly is justified.

We will further elaborate the assembly process's scheme (Fig. 5.4.3.8).



Where
- R1,R2 are robots
- i1 and i2 barcode readers
- i3 and i4 proximity sensors
- AI- feeder
- S palletizing station

Fig. 5.4.3.8. The assembly process's scheme

The component parts are inserted into a container with seats, so-called kits. These kits are made available to the handling robot by a kits feeder. The handling robot takes the piece kit and puts it on the conveyor that has a circular shape. On the side of the kit we will print barcodes. When the bar code reader recognizes the sign, it sends a signal to the PLC, which, depending on the bar code, will know the exact position of the kit and depending on it will condition the switching on or off. The component piece kit, via the conveyor, will reach the robot assembling the product according to the process design sketch. The advantage of kits is that we know exactly the orientation and position of the assembled elements. A multifunctional gripper is used for assembly. After assembling, by recirculation, the finished piece will get back to the handling robot that puts it on the palletizing station. From here it will be sent to CTC and here is the download of kits.

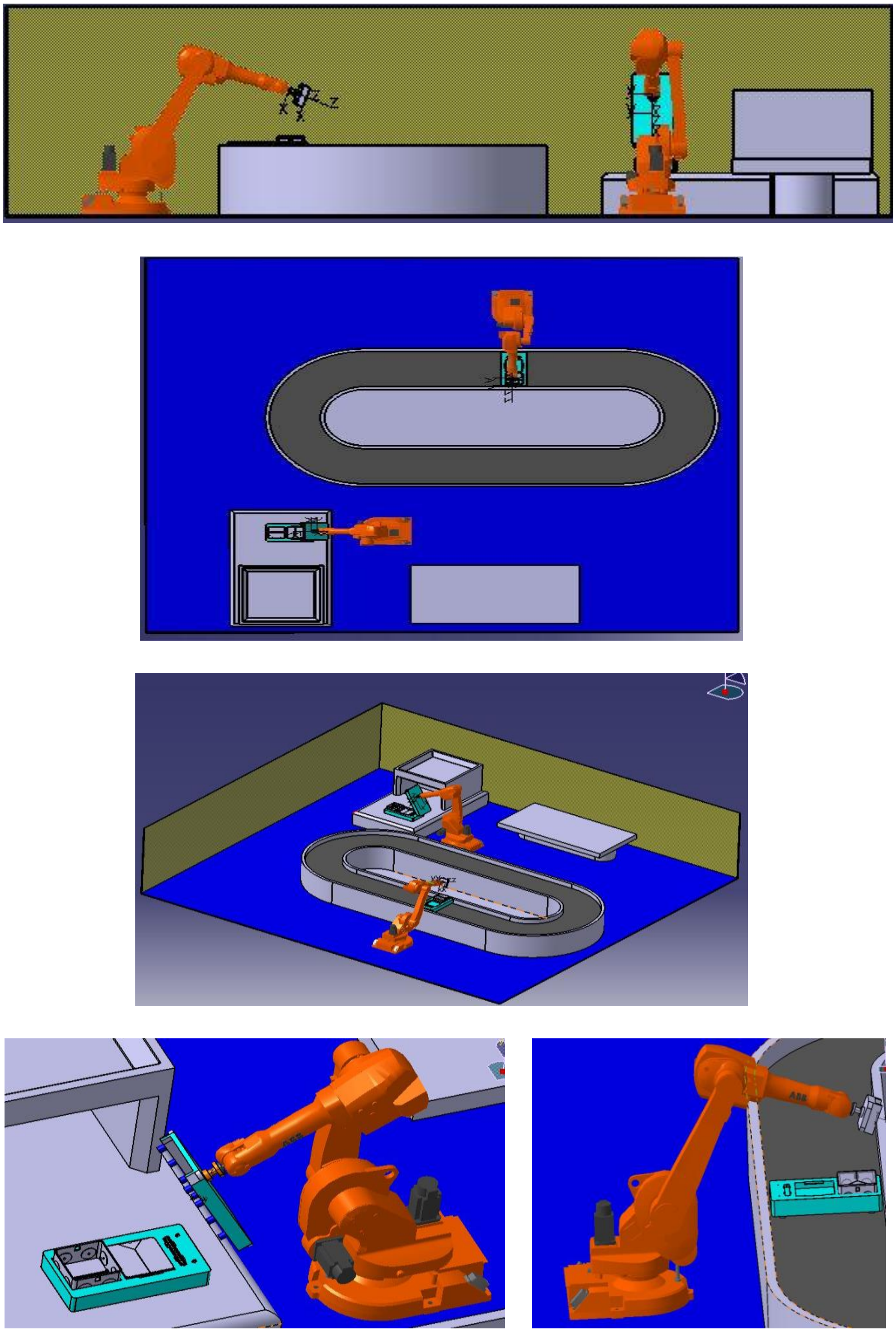


Fig. 5.4.3.9. The 3D prototype of the robotic cell

To ensure the safety of human operators in the robotic cell, two proximity sensors have been implemented, which when detecting objects in the robot workspace send signals to the PLC, which stops the robot.

Figure 5.4.3.9 shows the 3D prototype of the cell.

Ladder type diagram (Fig. 5.4.3.10)

Input data:

- A - the start button
- I1, I2 - bar code reader
- I3, I4, - proximity sensors

Output data:

- C1 - conveyors
- R1 – handling robot
- R2 - asembly robot
- S - palletizing station
- Ev - evacuator

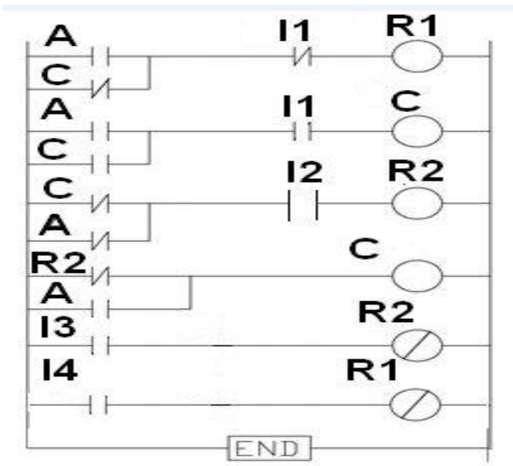
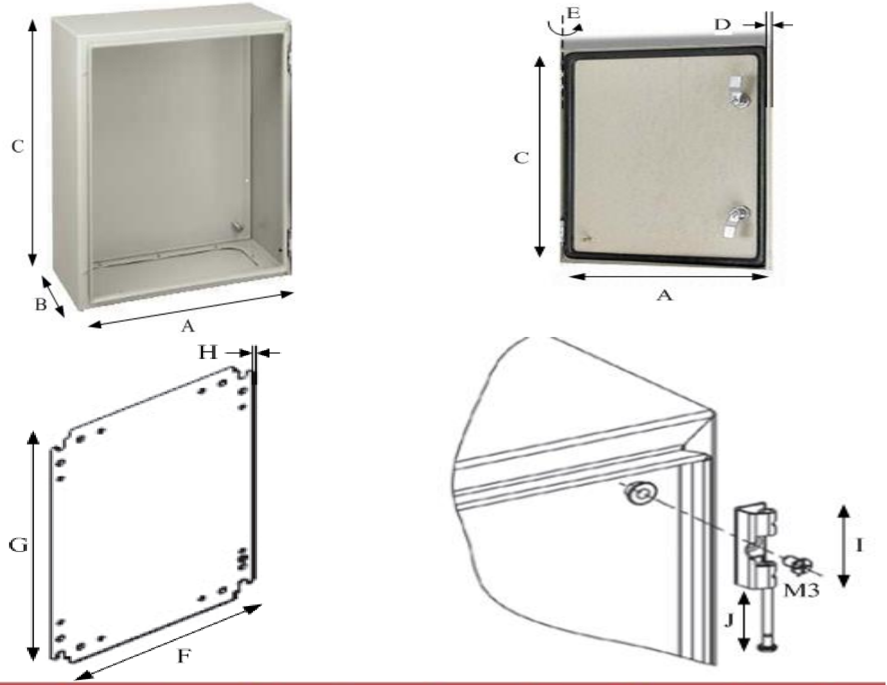


Fig. 5.4.3.9. Ladder (sequence) diagram for process control

Many thanks to our student, Szilard Domokos, for enabling us to present his solution for this case study!

5.4.4. 4th Project Example



A [mm]	B [mm]	C [mm]	D [mm]	E [°]	F [mm]	G [mm]	H [mm]	I [mm]	J [mm]
800	250	1200	5	120	780	1180	5	45	50

Fig. 5.4.4.1. Details of sub-assembly 1 and dimensions

The details of sub-assembly 1 and its dimensions are presented in figure 5.4.4.1, while the sketch of the component assembly process is shown in figure 5.4.4.2.

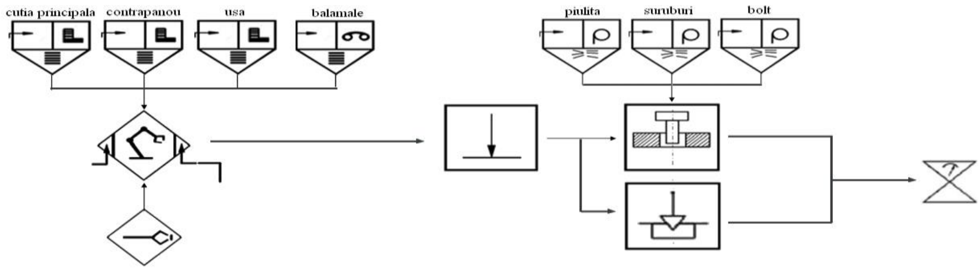


Fig. 5.4.4.2. The sketch of the component assembly process

The use of the internal screw to fix the fob makes the assembling more difficult and takes longer.

When using hinges and overhangs to catch it, in this case, too much time is lost and screwing is hard to do.

One method of raising productivity is to have some fasteners already fitted in the main box, which, if the bracket is inserted in place, is fixed.

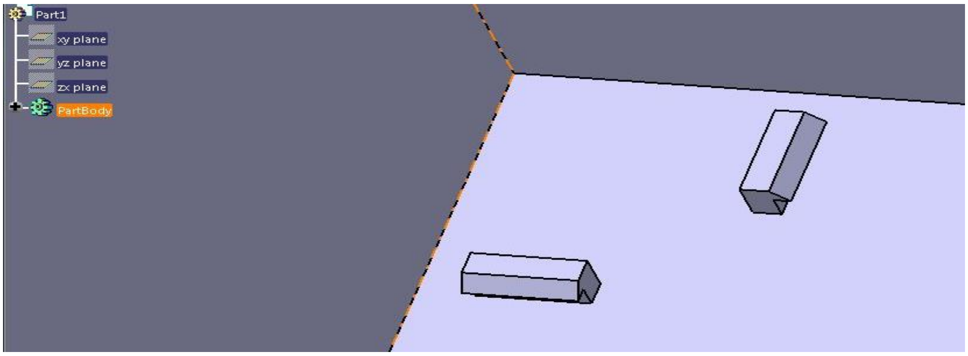


Fig. 5.4.4.3. The main box to be changed

If you change the main box (Fig. 5.4.4.3), the product will be easier to assemble, and will be assembled in shorter time because there will be fewer parts to assemble.

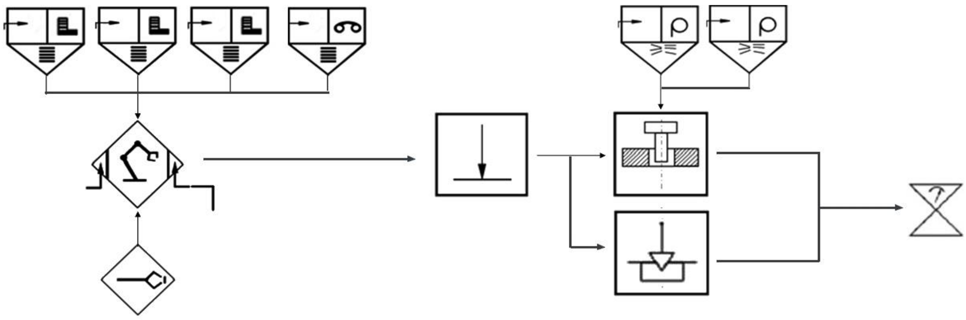


Fig. 5.4.4.4. Assembly sketch after the first change

The outline of the component assembly process, after the first change, is shown in figure 5.4.4.4.

The second stage involves modifying the main box and the door (Fig. 5.4.4.5).

By removing bolts, bolts and hinges, there will be fewer components, so assembling will be easier and shorter.

In this case, the sketch of the assembly process will be as shown in figure 5.4.4.6.

With the same gripper (with suction cups) we can handle the three components: the main box, the bracket and the door. Each component is in a stack of stores, from where the robot can take. First, the main box is pushed by a pneumatic actuator, and the robot will take a paddle and put it back inside the box. After this first operation is completed, the robot will take the door and mount it.

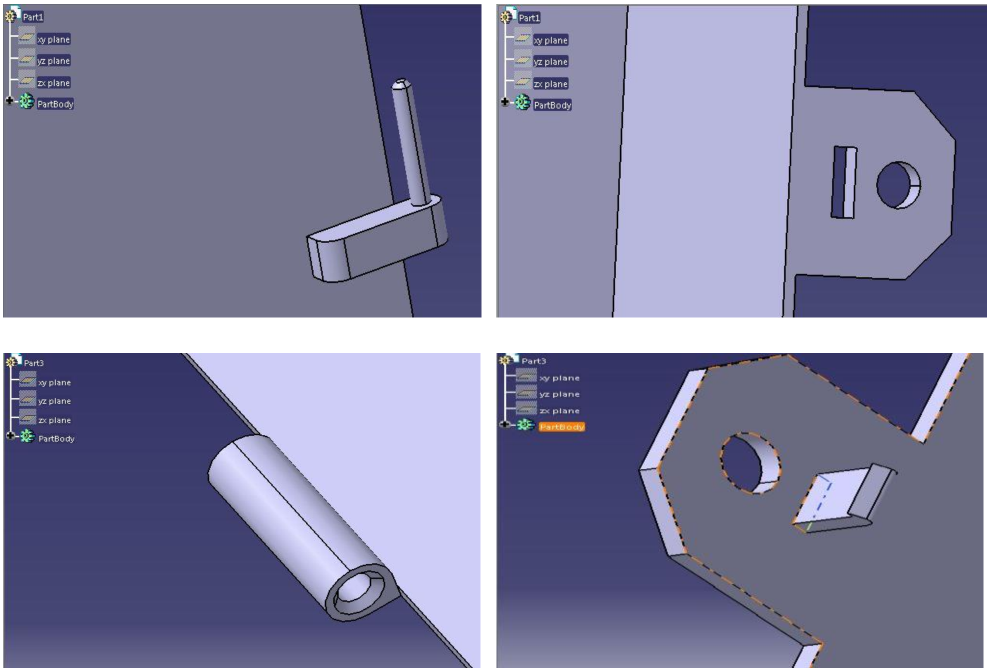


Fig. 5.4.4.5. Modified main box and the door (top to bottom)

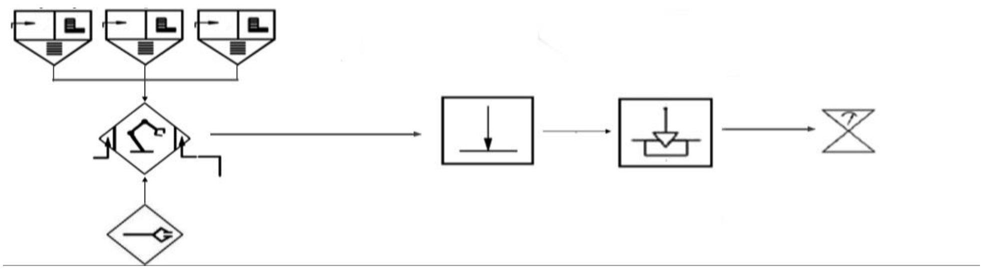


Fig. 5.4.4.6. Sketch of the assembly process

<u>Computational productivity calculation</u>

$$I = \frac{OUP}{INP} = \frac{Pvi * Nai}{Cla + Ccap + Cma + Cm}$$

<u>OUP</u> - system's output;

N_p - number of products or assembly variants/year;

P_{vi} - production value per acceptable assembly variant i;

<u>N_{ai}</u> - number of acceptable assemblies of variant I which are produced annually;

<u>INP</u> - system's input;

C_{la} - labor cost;

C_{cap} - capital consumption;

<u>C_{ma}</u> - material costs;

C_m - other costs (energy, workspace, etc.).

OUP:

Pvi=50 euro (cost/piece)

Nai=250 days/year*200 pieces /day

INP:

<u>*Labor Costs*</u>

$$C = n_s C_{las} I_f$$

Cla=1*1.1*1000=1 100 euro

<u>*Capital Consumption*</u>

$$C_{cap} = \frac{r}{1-(1+r)^{-\mu}} I$$

r=0.15

μ=-10 years

I = I1 + ... + I6

I1 = cost robot = 45 000 euro

I2= 0.45 * cost-robotic-systesm = 0.45 * 3000 euro = 1350 euro

I3 = 3000 euro (3 warehouses)

I4 = cost-gripper = 700 euro

I5 = cost-inspection-and-sensors = 10 000 euro

I6 = cost-engineering-training-redesign = 1000euro

I = 61 050 euro

Ccap= 12 026.85 Euro

C.ma = C.mi * Ni = 2 eur * C.capacity * A.disponibilit * vi (100%)

C.capacity = 250 days * 8 hrs * 60 mins / 3 mins = 40.000 units

A = 200 / 250 = 0.8

C.materials = 2 * 40.000 * 0.8 = 64 000 euro

C.others = 12 months* (800 euro + 300 euro + 300 euro) = 16 800 euro

IP = 250 000/(1 100+ 12 026.85 + 64 000+ 16 800)=2.66

Elaboration scheme of the assembly process is shown in figure 5.4.4.7. and the 3D model of the cell is presented in figure 5.4.4.8.

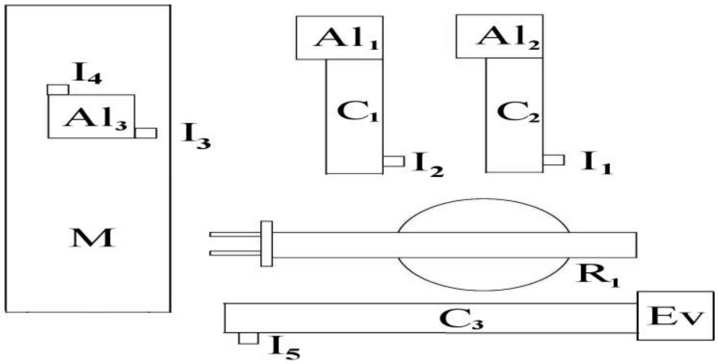


Fig. 5.4.4.7. Scheme of the assembly process

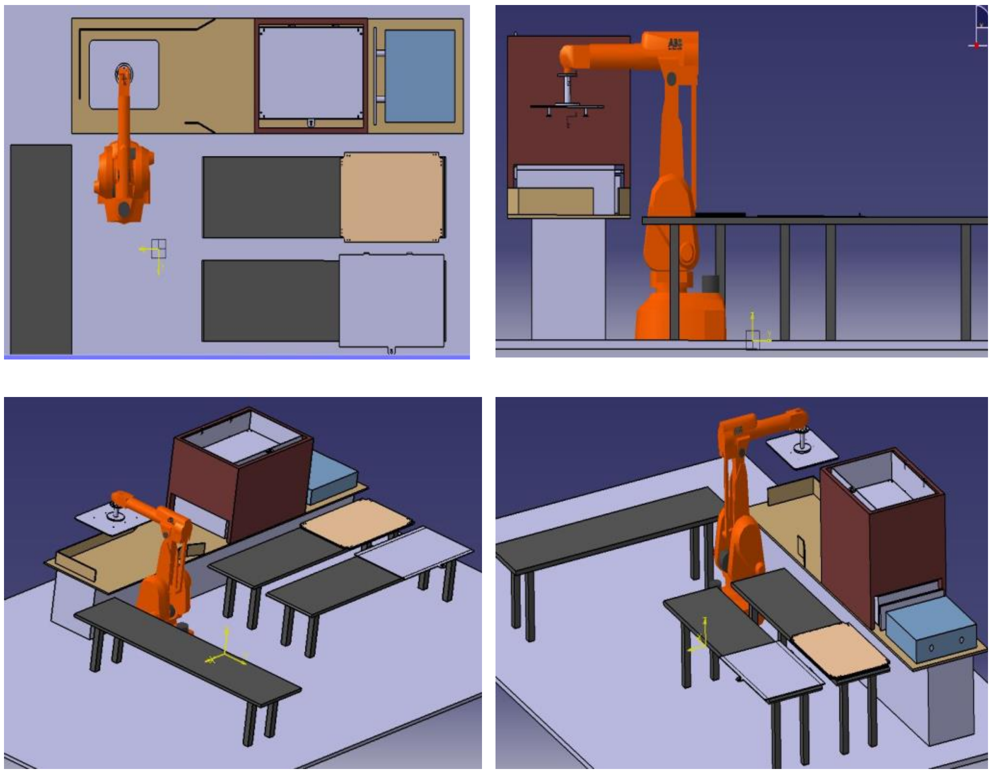


Fig. 5.4.4.8. The 3D model of the robotic cell

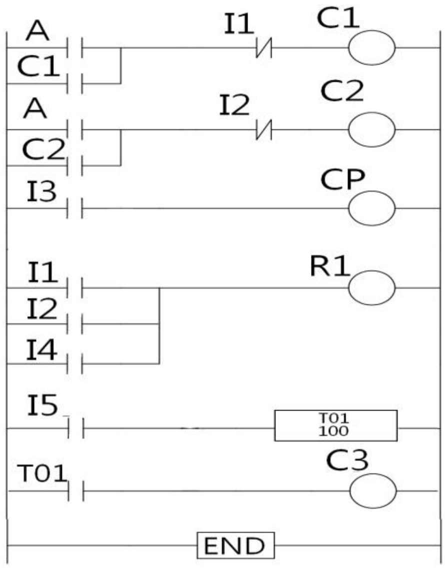
The cell works as follows:

- the first actuator actuates the pneumatic actuator, which pushes a box after its proximity sensor (I4) is detected. The box gets to the right place, this is confirmed by the magnetic sensor, which gives a signal that the rod has come to an end.

- the conveyors 1 and 2 are put into operation, so the door reaches the robot (conveyor feed is made from "stack stores" and a robot puts them on the conveyor). The robot will know when the proximity sensors (I1, I2) sense the parts and send the signal to the PLC. First, the robot will take the countertop and insert it inside the main box, then take the door and mount it. Self-centering is assured that assists the assembly process.

- the door that mounts the door, the robot closes it, and then takes the assembly and puts it on another conveyor, where it is checked by a video sensor if it was assembled correctly.

Ladder type diagram (Fig. 5.4.4.9):



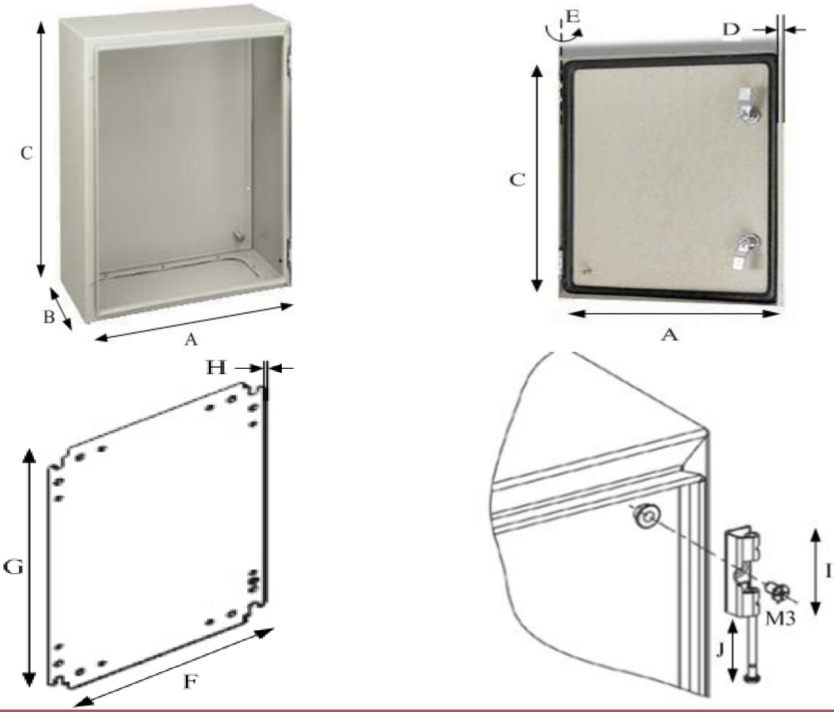
Where:
A- start button
C1, C2, C3 – conveyors
I1, I2, I3, I4, I5 – sensors
CP –pneumatic actuator
R1 – robot
T01 – timer on delay

Fig. 5.4.4.9. Ladder (sequence) diagram for process control

Many thanks to our student, Hunyadi Norbert, for enabling us to present his solution for this case study!

5.4.5. 5th Project Example

The details of the sub-assembly are shown in figure 5.4.5.1, as well as its dimensions.



Nume student	A [mm]	B [mm]	C [mm]	D [mm]	E [º]	F [mm]	G [mm]	H [mm]	I [mm]	J [mm]
Molitorisz Andor	800	300	1000	5	120	780	980	5	45	50

Fig. 5.4.5.1. Details and dimensions of the sub-assembly

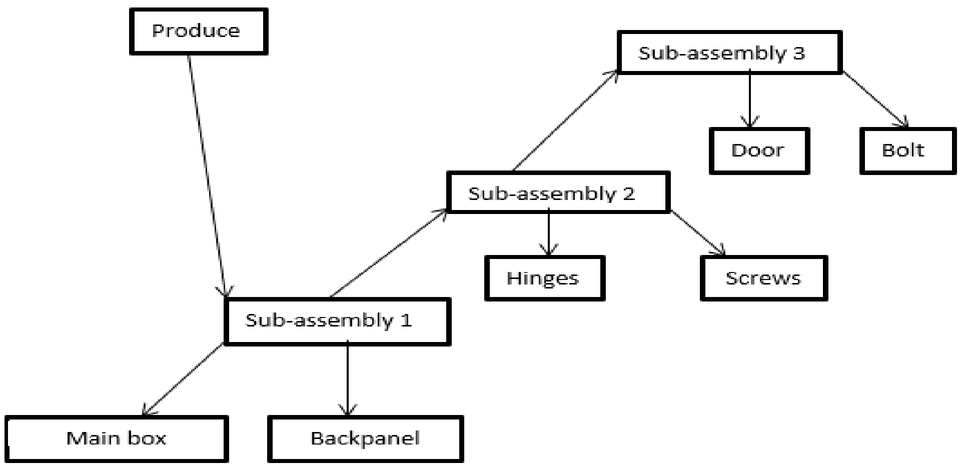


Fig. 5.4.5.2. Outline of the structure of the initial sub-assembly

The outline of the structure of the initial sub-assembly can be observed in figure 5.4.5.2, while the diagram of interdependence between component parts can be observed in figure 5.4.5.3.

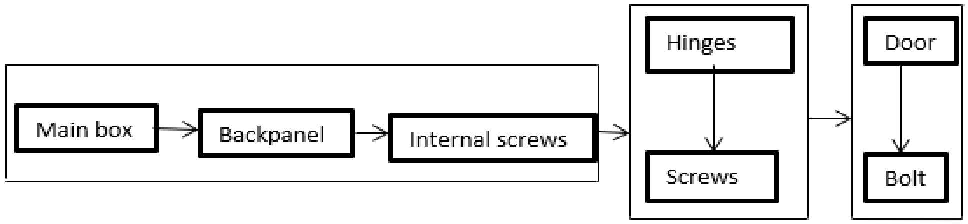


Fig. 5.4.5.3. Diagram of interdependence between component parts

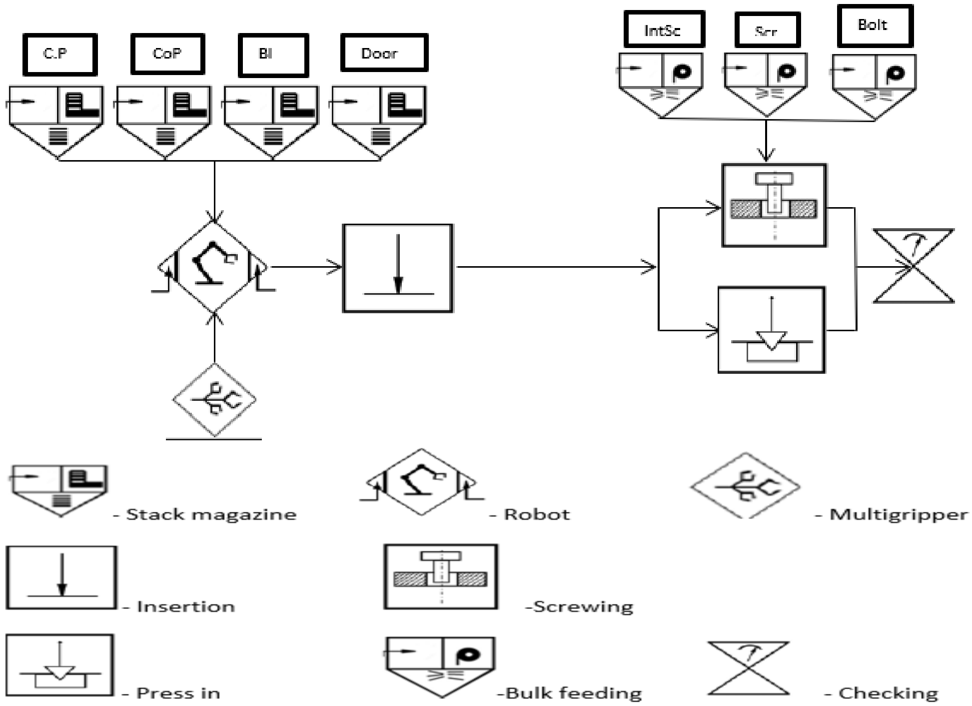


Fig. 5.4.5.4. Outline of the initial assembly process

The outline of the initial assembly process can be seen in figure 5.4.5.4.

By applying the DFAFD method to the original product we can identify some weaknesses of the originally assembled product that can be eliminated, such as:

- the four internal screws that hold the main box support.
- the two hinges, screws and bolts with which the door is tightened to the main box

Taking into account one of the weaknesses of the originally assembled product, we remove the four internal screws that hold the main box support, making an improved design by redesigning the original product. Its structure outline can be observed in figure 5.4.5.5, its diagram of interdependence between the component parts in figure 5.4.5.6 and its outline of the assembly process in figure 5.4.5.7.

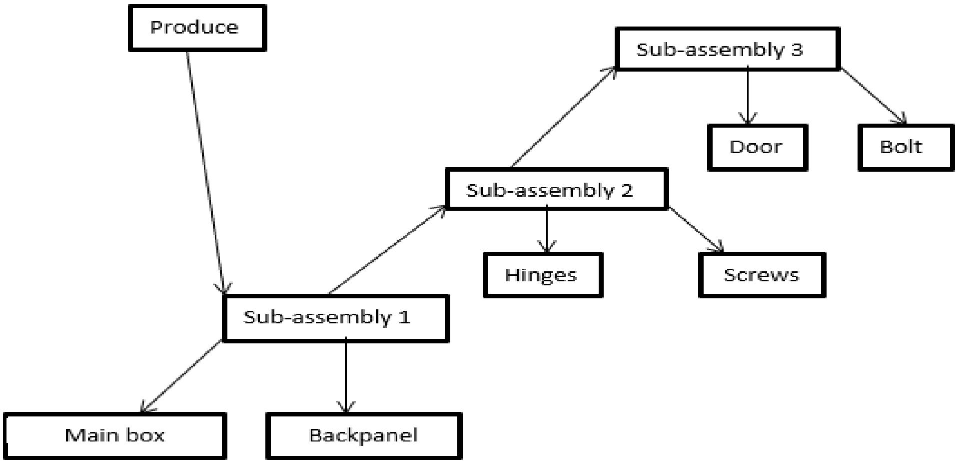


Fig. 5.4.5.5. Outline of the structure of the initial sub-assembly

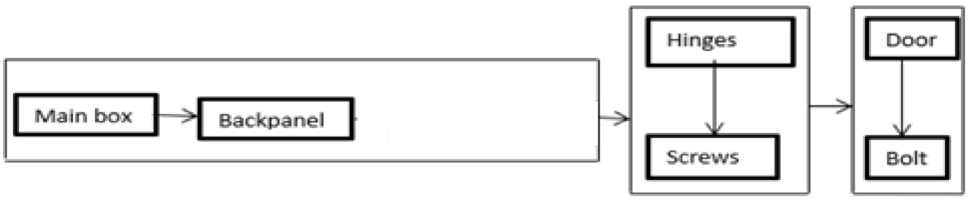


Fig. 5.4.5.6. Diagram of interdependence between component parts

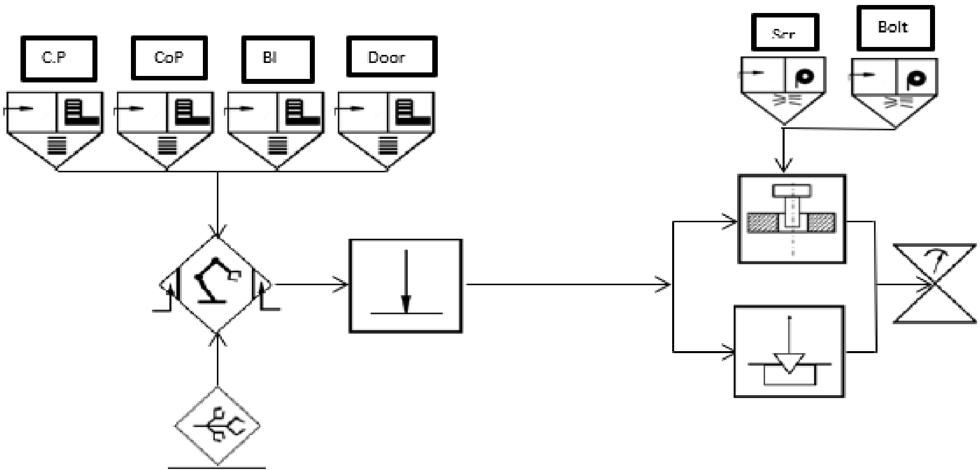


Fig. 5.4.5.7. Outline of the assembly process

By removing the internal screws, you can see an increase in Qr by 7%.

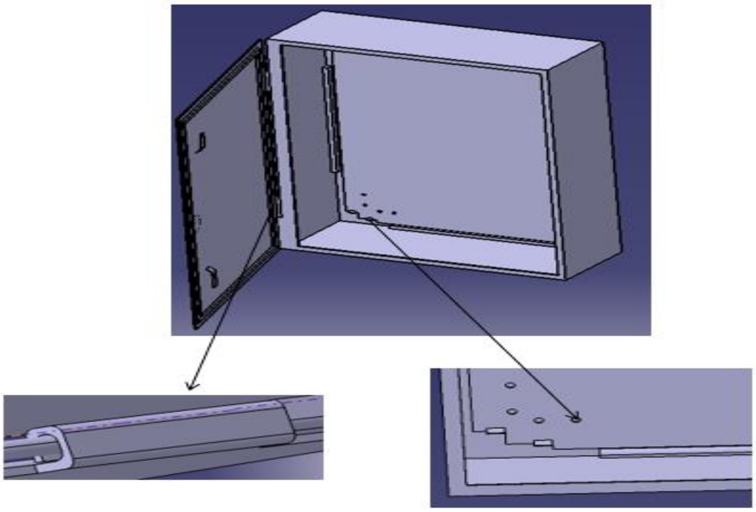


Fig. 5.4.5.8. The metal box redesigned in Catia V5

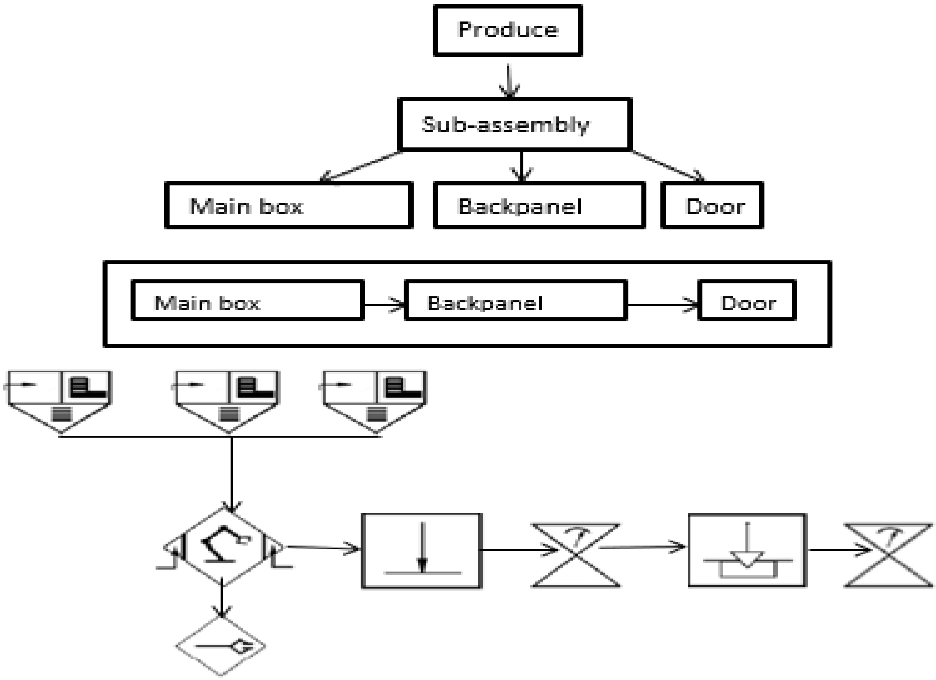


Fig. 5.4.5.9. The final structure outline, final diagram of interdependence between the component parts and the outline of the assembly process (top to bottom)

Taking into account the weaknesses highlighted in the previous chapters, we are making an improvement and developing a final version of the product. By redesigning it, we improve the initial assembly.

The redesign of the metal box can be observed in figure 5.4.5.8.

The final structure outline, final diagram of interdependence between the component parts and the outline of the assembly process can be observed in figure 5.4.5.9.

Equipment:

- 3 stack feeders with pneumatic drive: Al1; Al 2; Al3;

Sensors:

- proximity sensor (photoelectric sensors positioned at each stack stores to signal the presence of components): s1; s2; s3;
- a vacuum sensor (detects based on the vacuum level if the piece is picked up by the gripper): s4
- video sensor (above the worktable, checks the correct placement of the parts): s5

Orientation, guiding and fastening devices:

- Robot with multifunctional vacuum gripper: R1

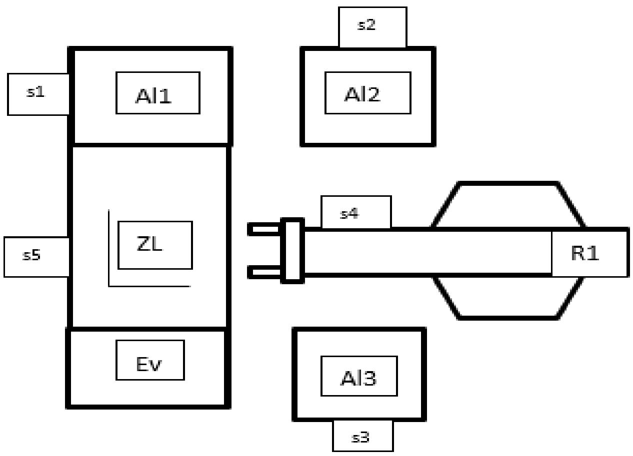


Fig. 5.4.5.10. The cell scheme

The scheme of the cell can be observed in figure 5.4.5.10, while its view can be seen in figure 5.4.5.11.

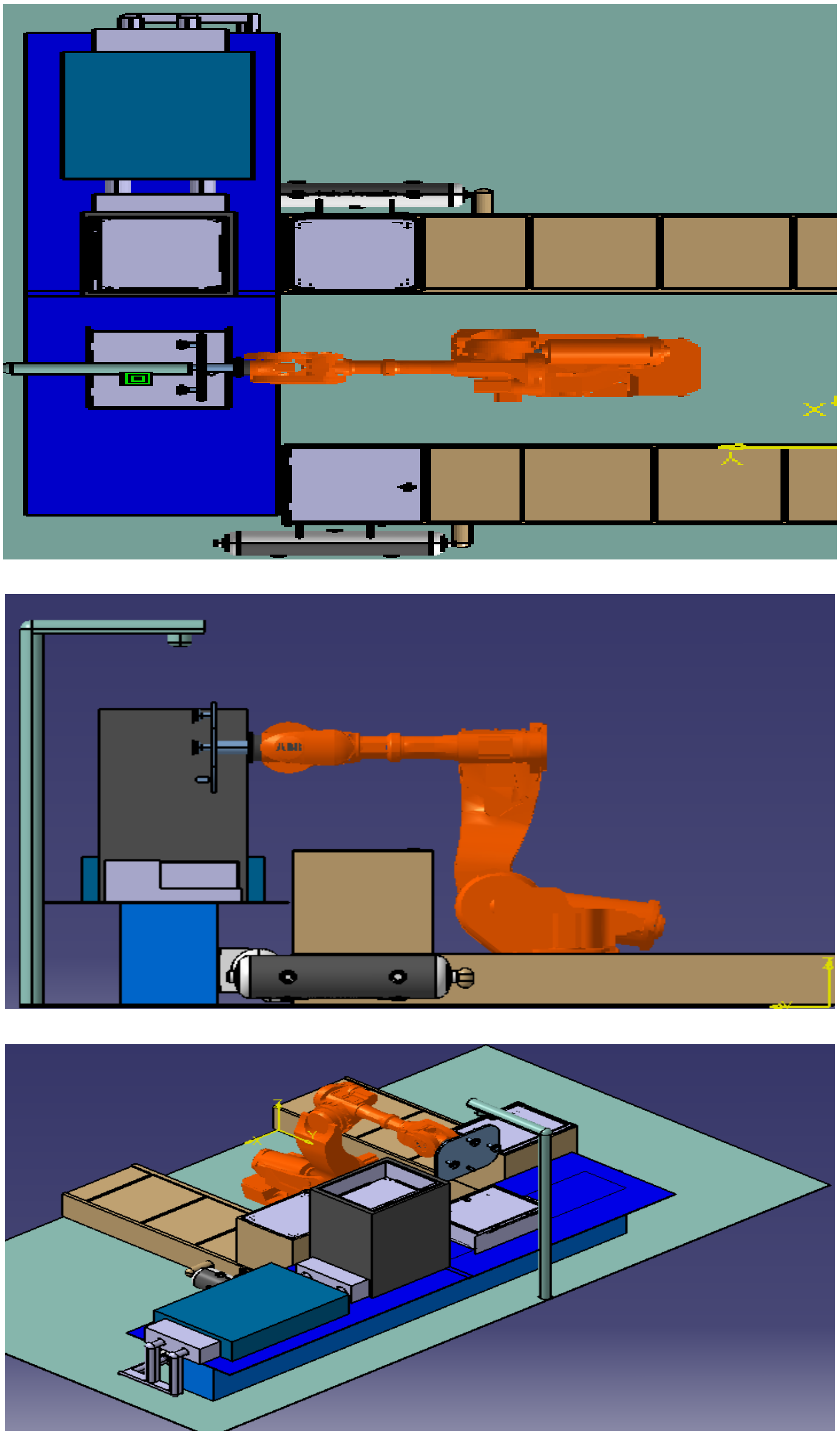


Fig. 5.4.5.11. Top view, side view and isometric view of the robotic cell using DelmiaV5

The way in which the assembly process works:

The first Al1 feeder, which is a stack feeder that detects the presence of the first component and the metal box by means of a photoelectric sensor s1, conditions the actuator of the pneumatic motor of the feeder that pushes the metal box into the assembly area in front of the robot R1.

The s5 sensor detects if the metal box has reached the ZL assembly area and is seated properly. Condition the robot actuation with the proximity sensor s2 in the Al2 feeder to take the next piece, the bracket with the gripper, detecting by the vacuum level s4, if the piece is picked up, taken to the work table and released after being assembled in the metal box. If adjustment is needed, then the s5 video sensor detects this.

After receiving the signal from the s5 video sensor, and the proximity sensor s3 from the Al3 feeder, the robot goes and takes the next component, the door. The vacuum sensor s4 signals the pickup and release of the piece after its assembly on the main box.

After assembly, the product is attached to the robot's gripper and is placed near the working area ZL in the Ev evacuation area, from where it is picked up by either another robot or a person.

Economic evaluation of the robotic assembly cell:

Computational productivity calculation:

$$I = \frac{OUP}{INP} = \frac{Pvi * Nai}{Cla + Ccap + Cma + Cm}$$

<u>OUP</u>	- system's output;	<u>INP</u>	- system's input;
N_p	- number of products or assembly variants/year;	C_{la}	- labor cost;
P_{vi}	- production value per acceptable assembly variant i;	C_{cap}	- capital consumption;
<u>N_{ai}</u>	- number of acceptable assemblies of variant I which are produced annually;	<u>C_{ma}</u>	- material costs;
		C_m	- other costs (energy, workspace, etc.).

OUP:

Pvi=5 euro (cost/piece)

Nai=250 days/year*200 pieces /day

Labor Costs

INP: $C = n_s C_{las} I_f$

ns - Number of shifts/day

If - is a factor (If>=1) which is determined function of frequency the human operator has to supply the cell with materials; If=1

Cla=1*1.1*1000=1 100 euro

Capital Consumption

$$C_{cap} = \frac{r}{1-(1+r)^{-\mu}} I$$

Interest rate

r=0.15
Economic life time of system
μ=-10 years
I = I1 + ... + I6
I1 = cost robot = 15 000 euro
I2= .45 * cost-robotic-system = 0.45 * 2000 eur = 900 euro
I3 = cost-gripper = 700 euro
I4 = cost-stack-feeder-e = 41 500 euro
I5 = cost-inspection-and-sensors = 10 100 euro
I6 = cost-engineering-training-redesign = 1000 euro
I = 69 200 euro
Ccap= 13 632.4 euro
C.ma = C.mi * Ni = 2 euro * C.capacity * A.disponibilit * vi (100%)

Ni - the number of assemblies carried out in variant I

C.mi - direct and indirect material costs/assembly variant i excepting the tools

C.capacity = 250 days * 8 hrs * 60 mins / 3 mins = 40.000 units

A = 200 / 250 = 0.8

A - the cell disposability

C.ma = 2 * 40.000 * 0.8 = 64 000 eur

C.others = 12 months * (800 eur + 300 eur + 300 eur) = 16 800 eur

I = 250 000/(1 100+ 13632.4 + 64 000+ 16 800)=2.61

The scale diagram for the process's control can be seen in figure 5.4.5.12.

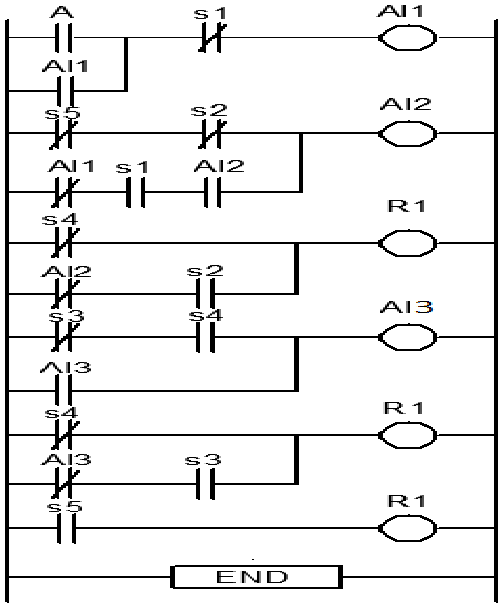


Fig. 5.4.5.12. Ladder diagram (sequence) for process control

In conclusion, when designing a robotic assembly cell for a sealed metal box for electrical panels, it is primarily necessary to redesign the original product to reduce assembly time and to recover production costs.

Redesigning is effective in this case, moreover, it is not at all costly. Removing internal screws, screws, hinges and bolts allows for greater flexibility and "ventilation" in the process, leads to better product quality by eliminating errors due to too many components being assembled, involving a too complicated assembly process and is much more costlier.

Many thanks to our student, Molitorisz Andor, for enabling us to present his solution for this case study!

5.5 Conclusions

The case studies presented above are students' semester projects and the aim of such projects is to familiarize students with the specific issues of automated production systems. The objectives and the input data within these projects are purely theoretical and have to be treated as such. The maturity level of the projects and the generated solutions are reduce, because for our students is the first exercise of its kind and of this magnitude. On the other hand these projects demonstrate the ability of our students to approach complex projects and highlight their technical creativity and ability to find innovative solutions to the problems they encounter.

Analyzing these projects is highlighted the magnitude of such a project and the effort required to achieve the establish objectives. These projects start with the assessment of the difficulty of assembling the product (the given product) within an automatic system, and continue with the mechanical and electrical design or selection the necessary equipment and robots. The project continues with sensors selection, layout and control design and finally with and economic evaluation of the generated solution.

To develop the above-mentioned projects, a wide range of software applications have been used, for example: Solid Works©, Solid Edge©, Catia©, Delmia©, Robot Studio©, Inventor©, Auto CAD©, Process Simulator©, Plant Simulation© from Siemens, Creo©, etc..

Finally, the bellow presented projects represents a collection of possible solutions for the new generation of students as well as a source of inspiration and identification of the necessary stages to be fulfilled.