Politecnico di Torino

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Control Technologies for Industry 4.0

Laser welding cell design for an industrial application: from 3D modelling to virtual validation

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ABSTRACT

The present thesis addresses the preliminary design of a laser welding cell for busbars in lithium-ion battery packs used in electric vehicles. The work focuses on the conceptual and functional design, aiming to define a company's standard station that has to be modular, flexible and customizable. The main topic of this project is the preliminary study of the digital twin and virtual commissioning methods, in fact, after the three-dimensional modelling phase, the digital model of the laser welding cell is developed using software Siemens Tecnomatix Process Simulate. The principal advantage of these approaches is the possibility of cycle time evaluation, especially in complex automated line cases. The simulation software used in this work has many suitable functions that help with the layout definition, such as the collision check and the reachability test for the robot path. The laser welding line results from an initial study about batteries and laser welding techniques, followed by a state-of-the-art analysis and market research to identify existing systems available for busbar applications; hence, the cell is designed taking into account different possible technological solutions and layout configurations, considering the pros and cons of each. Once the key features of the machine are defined, each component is modelled in Inventor and the complete station is then converted to the format required by the simulation software: all the objects are classified into specific categories that allow functionalities, special tools and operations based on their intended functions. The kinematic design, for each resource where applicable, allows the model to be animated by defining movements, specifying joint types between links, revolute or prismatic, imposing motion limits and setting speed and acceleration. The operations are determinate that means path planning for the robot and parts flow. The work cycle is built using Cyclic Event Evaluation (CEE) mode: the work sequence is cyclic and governed by the succession of operations defined in the Gantt diagram and controlled by transition conditions. The system is not connected to any controller yet. The code for the PLC is written and checked. It manages the input-output signals that the simulator will share with the digital model and runs the logic flow of operations. The thesis is a preliminary study of the application of the powerful digital twin technique in an industrial context.

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1. ELECTRIC VEHICLES AND BATTERIES

"By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology."
— United Nations, Goal 7: Affordable and Clean Energy [1]

Figure 1: United Nations, Goal 7 [1]

Decarbonization is a goal to be achieved: it is the process of reducing gas emissions through the gradual elimination of the use of fossil fuels and the transition to renewable energy sources such as sunlight, wind and geothermal heat.

The fight against climate change is a central issue of this era, in fact governments and institutions have imposed increasingly stringent limits on CO_2 emissions: the first step of the energy transition is the electrification of residential, commercial and mobility activities, based on clean energy production and the use of sustainable sources.

Electric mobility is one of the most significant changes in the transport and energy sector in recent decades. [2]

An electric vehicle converts the electrical energy stored in its batteries into mechanical motion through one or more electric motors. This system represents a sustainable alternative to conventional internal combustion engine vehicles, enabling efficient, quiet, and emission-free propulsion.

The core element of these vehicles is the battery pack, which represents the energy source: it is composed of lithium-ion cells, organized in modules and enclosed in a pack equipped with channels or cooling plates and mechanical structures to contain and protect the cells from stress, shocks and vibrations.

Since lithium-ion batteries are components that are potentially inclined to fire, such as in the event of an internal short circuit, mechanical damage, overcharging, or exposure to high temperatures, it is critical to keep them within a controlled temperature range to prevent overheating and ensure system safety.

1.1. Battery cell

A lithium-ion cell is a reservoir of chemical energy that can be transformed into electricity and it is composed of two electrodes: the anode (-), which is usually made of graphite, and the cathode (+), which is composed of lithium oxides and metals such as nickel, manganese, cobalt or iron.

Between the two there are the separator and the electrolyte. The first is a porous membrane, electrically insulating but permeable to ions, which serves to keep the anode and cathode physically separate, preventing internal short-circuiting, while allowing the passage of lithium ions during the charge and discharge cycles; it is generally made up of thermoplastic polymers such as polyethylene (PE), polypropylene (PP), or a multilayer combination of the two. These materials offer good mechanical properties, chemical stability and some thermal resistance; however, at high temperatures they can melt, favouring the loss of separation between the electrodes and therefore the risk of thermal runaway.

The electrolyte, on the other hand, is a conductive solution that allows the movement of lithium ions between the anode and cathode and consists of a lithium salt dissolved in a mixture of carbonated organic solvents; these solvents provide high ionic conductivity but are highly flammable, which is one of the main fire risk factors in lithium-ion batteries.

When the cell is charged, most of the lithium ions are in the anode, but when the battery is used, the ions move from the anode to the cathode through the electrolyte and the electrons, on the other hand, which cannot follow the same path, travel through an external circuit: this movement of electrons is the electric current that powers the motor.

During charging, the process is reversed, in fact, thanks to the energy coming from the charger, the ions return to the anode and the cell is regenerated.

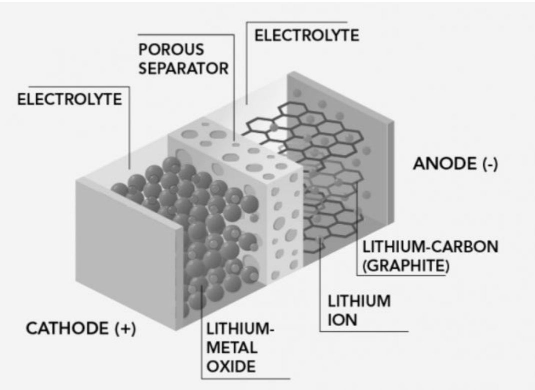


Figure 2: Battery components [8]

One of the main reasons why lithium batteries are so widely used is the reversibility of the charging and discharging process, which can be repeated thousands of times.

The energy provided by a single cell is not enough to guarantee a sufficient range of kilometres to a vehicle. This is the reason why batteries are made up of many cells connected to each other, which, each providing a fraction of energy, make up a battery pack capable of powering an entire vehicle. [3] [4] [5]

1.2. Battery typologies

There are different types of battery packs for electric vehicles and they are based on the different shapes of the cells of which they are made: cylindrical cells, prismatic cells and pouches. Each variant has advantages and disadvantages and characterizes the package design, thermal management, density and cost.

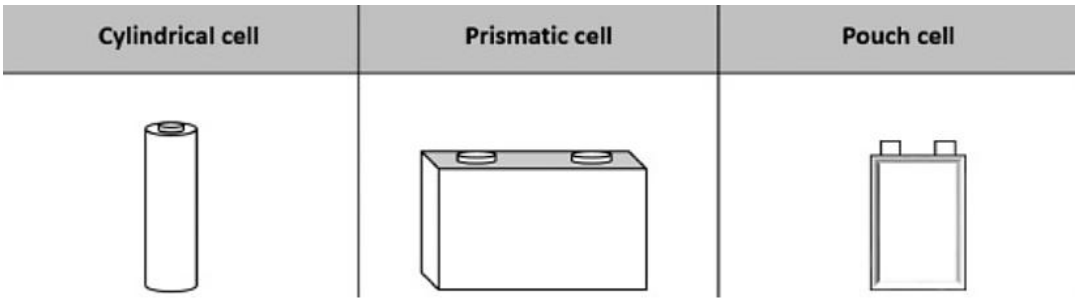


Figure 3: Battery typologies [7]

In cylindrical cells, the cathode-separator-anode layer is rolled into a cylindrical shape and inserted into a rigid metal container; this format has high mechanical robustness, ease of automated production and good thermal control due to the high exposed surface. However, it also has disadvantages because the filling of the space between cylinders is not optimal, with gaps that penalize the volumetric density.

Prismatic cells, on the other hand, have a rigid rectangular shape, often with a metal casing that gives structural support and contains the expansion of materials during the work cycle; this system allows for more effective packaging, i.e. better use of space and therefore greater volumetric density. However, due to the larger size and flat surfaces, thermal management can be more challenging: the implementation of a cooling system, such as plates or cooling channels between modules, is necessary to avoid hot zones.

In pouch cells, the electrode layers and separator are placed in a flexible casing and sealed; these are lightweight and able to adapt to irregular spaces. However, the casing of cells of this format can swell during charging and mechanical protective containment may be necessary to prevent deformation or penetration. [6] [7]

1.3. Battery busbars

In the battery pack, each cell or group of cells is electrically connected via busbars or conductive strips that allow current to flow between the various modules.

They are often made of copper or high conductivity alloys and sized to minimize resistance and energy losses; therefore, the layout of the busbar is essential since it must withstand high currents and it must be integrated with temperature sensors, fuses and contactors.

In terms of differences, packs using cylindrical cells often require more busbars and connections, but the round shape offers advantages in self-cooling, while packs with prismatic cells or pouches can use more compact busbars, but require more attention to heat dispersion and strain management.

Inside the battery pack modules there are also the "cell tabs" or connection plates that come out of each cell to be joined to the busbar. These interconnects must be robust to vibration and thermal stress, and typical joining techniques include ultrasonic welding, laser welding, resistance welding, brazing, as well as mechanical methods such as clamping or press fit.

Each method has advantages and disadvantages: ultrasonic welding is a solid-state process suitable for conductive materials but can generate high heat and vibrations that damage cells; laser and resistance welding offer joints with low electrical resistance and high repeatability, but the former requires high precision and higher costs. Mechanical joining by pressure or screwing generates little heat and low strength but introduces complexity and risk of loosening over time.

Among the various joining technologies used for the interconnection of busbars, a particularly important role is played by laser welding, which, considering the precision and reliability requirements of energy storage systems for vehicles, is now one of the most widely adopted solutions in the production of battery packs. [7]

2. LASER WELDING

Laser welding is a joining process in which a high-intensity laser beam fuses and joins two metal or plastic components; it concentrates a high amount of energy on a very small area, causing fast and precise melting of materials, and thanks to the millimetre-level focusing, clean, strong welds and robust connections are obtained, without overheating heat-sensitive elements such as battery cells.

2.1. Laser types

There are several types of laser sources.

The fiber laser is characterized by high efficiency and power, with a very precise beam, allowing deep welding and reliable electrical connections. With a wavelength of about 1064 nm, it enjoys excellent absorbency in metals, and is compatible with materials such as nickel, copper, stainless steel and aluminum. These lasers are ideal for high-speed welding.

The Nd:YAG laser (Neodymium: Yttrium Aluminum Garnet) is used for precision welding of small components such as in medical, jewellery and electronics sectors; it has compatibility with materials such as nickel, copper, gold, and silver, but lower efficiency than the fiber laser.

The diode laser is suitable for light welding, operating at lower powers than fiber and Nd:YAG lasers; it is used for high-speed welding in electronics manufacturing and plastic welding in the automotive sector. It has a wavelength between about 800-1000 nm and is suitable for nickel, copper and aluminum.

In contrast, the CO_2 (carbon dioxide) laser is less used in battery soldering, as its wavelength (10.6 μm) is not effectively absorbed by metals and it is more suitable for plastic or ceramic materials, or to perform cutting and welding of thick materials.

For battery packs welding, the fiber laser is the most widely used technology, offering a combination of precision, speed and quality of result; it enables extremely detailed machining on small components or complex geometries, allowing precise joints even on thicknesses of less than 0.1 mm. [9]

The high focusing of the optical beam ensures minimal heat input, reducing material deformations, making the technique particularly suitable for sensitive elements such as cell terminals.

The speed of the process, compared to other welding technologies, and the full compatibility with automated and robotic systems facilitate its integration into industrial production lines. In addition, since it is a non-contact process, there is almost no wear on the tools and the aesthetic appearance of the welds has high quality.

2.2. Laser welding parameters

The laser welding process provides two main mechanisms through which the laser beam interacts with the materials to be joined. The conduction mode is a way in which the energy of the beam is transferred mainly by thermal conduction through the metal, generating a relatively shallow weld pool and the width of the junction tends to be greater than the depth. In contrast, the keyhole mode involves a high-power density that vaporizes part of the material, forming a narrow cavity in the metal that the beam enters, enabling much deeper penetration and a smaller heat-affected zone.

The choice between these two modes of operation depends on factors such as material thickness, the need for penetration, minimization of the heat-affected zone (HAZ) and the tolerances of the joint geometry.

Among the process parameters that require accurate control, the laser power and the emission mode play a primary role. The emission can be continuous wave, which generates a constant beam and it is ideal for greater penetrations and high-speed production. In contrast, the pulsed mode allows the beam to be switched on and off in very short intervals, limiting the heat input to the area and being advantageous for thin materials and heat-sensitive components.

Another key parameter is spot size for which a smaller spot diameter generates a higher power density, therefore, higher penetration for the same power; for this reason it also requires extremely precise positioning and very tight tolerances not to compromise the result.

The focus position relative to the surface allows to change the geometry of the weld, to manage spatter or porosity issues, and to improve the consistency of the joint. The speed of the weld head is another essential factor: if it is too high, it can prevent complete melt or desired penetration, while too low, can generate excessive heat input, thermal deformation and potential defect formation.

The management of the clamping and the gap control between the components to be welded is also crucial because an inaccurate alignment or a wide gap can generate a lack of melting, porosity, or even the formation of visible holes on the seam.

Another technology controlled in the laser welding is the protection of the zone by shielding gas. It consists in a flow of inert gas (argon, nitrogen, or others) that must be precisely regulated because an insufficient flux can allow oxidation or plasma generation that disturbs the beam, while excessive flow can create turbulence that degrades weld quality.

Other advanced techniques in welding operations include beam manipulation and wobble strategies, in which the laser beam is intentionally oscillated to increase the effective width of the weld, fill gaps, or accommodate materials with varying thicknesses. This oscillation, often following circular or figure-eight patterns, enhances melting, improves mixing of the molten metal, and helps reduce porosity.

The intrinsic properties of the material to be welded can influence the joining work: the composition of the alloys, thermal conductivity, reflectivity and the presence of oxides or surface contaminants strongly affect the ability of the laser beam to melt the metal efficiently.

In the specific area of electric vehicle batteries, laser welding requires additional attention. The system for clamping busbars on cells can be designed based on two main different approaches: the use of a mask that clamps several busbars at the same time offers high production speed but imposes very strict dimensional control, while cell-by-cell clamping allows greater tolerance but at the expense of speed. Cell placement in the battery fixture is an important detail because even small variations in alignment can compromise weld penetration and process repeatability.

The thickness and choice of busbar material (copper or aluminum) also have a direct impact on the process: thicker busbars require more energy and longer penetration times.

In conclusion, laser welding is a highly capable and versatile technology, but its effectiveness ultimately depends on the careful coordination of many parameters; in critical applications such as EV batteries, this also requires integrating suitable equipment design, appropriate material choices, and robust quality-control and monitoring systems. [10] [11]

3. BONETTO AUTOMATION COMPANY

Bonetto Automation, located in Pinerolo (TO), is a company, part of the Bonetto Group, specializing in the design and construction of automated lines, robotic cells and special machines.

Figure 4: Bonetto Automation logo [12]

Figure 5: Bonetto Group logo [12]

The sectors in which it operates are varied and range from medical to luxury, from automotive, electromechanical, to packaging.

It specializes in the design and production of assembly lines for various components, implementing different technologies; the company provides testing, welding, and screwing stations, robotic cells, palletizing systems, and filling stations for the medical sector, including clean room production when required.

The goal is to satisfy customer requirements at every stage: starting from the technical specifications and feasibility studies conducted by the sales and pre-project departments, through detailed design and construction, up to testing, inspection, and final shipment to the destination plant.

It is a company in which it is possible to observe a project from its birth, that is, from its conception, followed by mechanical, electrical, pneumatic, technical design, software design, up to the assembly and operation of the entire system.

During the internship carried out in the sales office, technical section for preliminary projects, offers were produced that range over various sectors and involve the use of different technologies.

How is an industrial line born?

The first step in the design of an industrial automation is carried out by the company sales manager who approaches potential customers and proposes the company as a possible supplier; once a Request For Quotation (RFQ) has been received, the phase of in-depth analysis of the specifications, and the study of the product to be managed, begin, through technical drawings, 3D models and research.

The designer then organizes the ideas to propose a solution that can best meet the needs. The technologies adopted can be different as can as the machine to be built, but by evaluating and weighing advantages and disadvantages, economic costs and technical details, the shape to be given to the system is chosen.

Using AutoCAD, the components of the line are schematized and the overall dimensions of the system are defined in the layout: the feasibility of the project is analysed by measuring distances, comparing velocities and estimating the cycle times of the stations.

The project is divided into stations in which the various operations necessary for the task are carried out; a technical-economic offer of the system is then drawn up, describing each group and component inserted.

The Bonetto company aims to keep up with the evolution of the industry, closely following technological innovations; with this in mind, it intends to enter the battery market as a specialist supplier and reference in the field of laser welding. It invests resources in research and development with the objective of creating a standard company laser welding cell: a solid basis, for offering customers a ready and reliable proposal, to be presented in the first stage and, subsequently, customizable in the order acquisition phases.

The standards to be worked on are modular, meaning they are designed to be easily scalable, allowing the integration of additional components or the duplication of stations as needed. This flexibility makes it possible to adapt to specific project constraints, such as tighter cycle times or the need to integrate additional control stations.

During the offer phase, a document is sent to the customer containing a detailed description of the solution proposal and the related costs in the form of an economic offer of the system; the complete layout of the line is also attached.

A goal to be achieved is the enrichment of the offer that is sent to the customer with a 3D simulation of the proposed automated line. The schematic 3D modelling of the system components and the representative assembly of the plant allow a global view and control of spaces and dimensions, as well as a more immediate understanding of the solution. If the kinematics and the movements to be performed in the work cycle are defined and then assigned to the various objects in the assembly, the virtual proposed plant simulation is obtained, operating in a virtual environment.

The digital model allows simulating and analyzing the real behavior of the plant by verifying cycle times, checking for any collisions and evaluating the overall efficiency of the system. This approach offers a great advantage, as it allows visualizing and understanding the operation of the proposed plant, even if it is still in the concept phase, providing a realistic and interactive representation useful both for technical validation and for presentation to the customer.

4. DIGITAL TWIN AND VIRTUAL COMMISSIONING

The concept of digital twin refers to a virtual representation of a physical system that integrates models, sensor data and dynamic logic to reproduce the behaviour of the real asset over time. In the manufacturing sector, the term has been the subject of numerous definitions and classifications: it is frequently distinguished between a simple digital model, a digital shadow model and a real digital twin characterized by bidirectional data flows and real-time updates between the physical element and its virtual counterpart.

The digital model is the virtual representation of a physical object, system or process, but it is not automatically linked to its real equivalent: any change in reality is not automatically reflected in the model, and vice versa; it can therefore be useful for analysis, rough simulations or initial design, but it does not allow real-time monitoring.

The digital shadow is an intermediate level: in this case the digital representation is automatically updated through data from the physical object, i.e. there is a unidirectional flow of data, from the physical to the digital, but not vice versa; this allows monitoring the physical state in real time, but not to intervene directly from the digital model on the physical asset.

Finally, the digital twin represents the highest level of integration: it provides a bidirectional flow of data and information between the physical and digital objects, so that changes or decisions in the digital component can affect the real object, and vice versa. The digital twin is not just a copy of the physical system, but an active simulation, control and optimization platform, capable of dynamically representing the life cycle of the asset, collecting data in real time and implementing corrective actions.

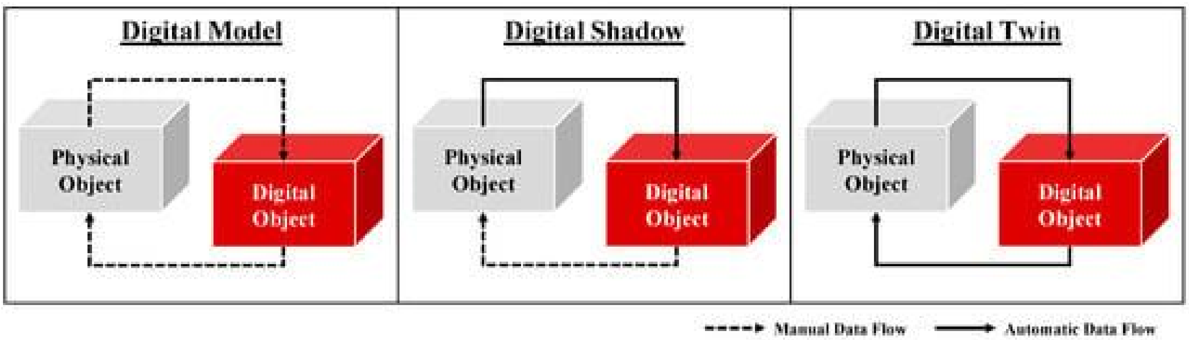


Figure 6: Digital Model, Digital Shadow and Digital Twin differences [14]

This classification is important to accurately define the level of implementation of the system, in fact, only digital models or digital shadows are often found in industrial contexts, and the evolution towards a fully operational digital twin requires IoT infrastructures and sophisticated skills.

This distinction helps to assess the degree of technological adoption and the objectives that the company can set itself in the context of the digitization of its assets. [13] [14] [15]

Virtual commissioning is a specific practice that uses detailed virtual models to test, validate, and tune control software and automation sequences before the physical system is connected or put into production; with virtual commissioning it is possible to perform the commissioning of automation virtually: the PLC program is executed on a simulated model of the machine or line, allowing logical errors to be detected, the integration between components can be verified and the time and risks associated with real commissioning can be verified.

This approach also allows for parallelization of mechanical and automation activities, speeding up project times.

The concrete applications and functionalities offered by these technologies are numerous and concern different phases of the life cycle of the plant; among the most relevant features are: verification of cycle times and analysis of production performance (cycle time analysis), collision detection and avoidance thanks to kinematic simulations, validation of PLC (Hardware/Software-in-the-loop) logic, validation of safety logics, optimization of layouts, ergonomics and testing of product changeover scenarios or line reconfiguration.

These features make it possible to visualize the operational cycle of a plant even when the design is still at a conceptual level, improving the understanding of design choices and enabling simulation-based decisions; in addition, the joint use of digital twin and virtual commissioning allows the virtual model to be reused throughout the plant's useful life, facilitating upgrades.

The practical benefits deriving from this are numerous: reduction of on-site commissioning times, reduction of the risk of downtime and accidents during the start-up phase, possibility of identifying and correcting logical defects before they cause material damage, greater reliability of production and cost estimates, and better decision support for the sizing of resources and stocks.

For plant suppliers and system integrators, these tools allow them to present more complete and less risky proposals to the customer, with virtual prototypes that can already be demonstrated and tested in the conceptual phase.

However, there is no shortage of critical issues and limitations that must be considered during design and investment for this technology such as, for example, the creation of a sufficiently accurate digital model requires time, interdisciplinary skills (mechatronics, simulation, software, automation) and initial economic resources that are not negligible. [16] [17] [18]

5. CASE STUDY AND OBJECTIVES

The thesis work addresses the preliminary design, i.e. the conceptual design phase, of a laser welding cell for battery pack busbars intended for electric vehicles. The goal is not to develop the detailed technical design of the plant, but to define a functional concept that can be validated already in the preliminary phase, useful as a basis for the subsequent development steps and the technical-economic evaluation during the quotation stage.

The main aspects of three-dimensional modelling are handled, with the aim of building a digital model that realistically represents the layout and operation of the cell; this model serves as a starting point for a virtual simulation of the process, with the purpose of verifying the feasibility of the system and supporting the preliminary validation of the design.

There is also a part dedicated to programming the PLC controller, in which the basic logic of the cell operating cycle is set; this aspect introduces the topic of virtual commissioning, i.e. the possibility of testing and validating control software in a virtual environment through the Software-in-the-Loop (SiL) approach. Although this phase has not been fully completed, the work lays the conceptual and methodological foundations for its future development.

The thesis addresses mechanical design, digital simulation and industrial automation, with the aim of exploring the potential of virtual prototyping tools in the design process of complex production plants.

5.1. Software

Autodesk Inventor Professional 2025 is used as CAD software for the three-dimensional modelling of the cell components, while the simulation of the plant's operations is carried out in Siemens' Tecnomatix Process Simulate 2502.

The PLC logic program is written in Ladder Diagram (LD) and Structured Text (ST) using CODESYS V3.5 SP16 Patch 3 and validated with a simulated plant in FluidSIM 6.

5.2. Market analysis

The first approach to a new project usually consists of an analysis of the solutions already existing in the market proposed for the given target. In the field of laser welding of battery packs, stations based on SCARA robots with fixed laser head represent one of the most popular configurations, especially for the welding of cylindrical cells; such systems are often designed with pass-through conveyors, a solution that allows integration into automated production lines and ensures a continuous flow of modules.

In other cases, the laser head is mounted on a cartesian robot, but this design always favors the welding of cylindrical cells batteries.

The objective of this phase is to understand the state of the art of existing technologies and the main design approaches, to be able to align with industry standards and, at the same time, identify any margins for improvement on which to base the project proposal.

5.3. Ideas and machine proposal

The first phase of the design of the laser welding system is the analysis of the product and the task.

In this thesis, it is chosen to base the simulation and the design on a prismatic cells battery pack as example of cell operation. The station can also be used to manage other types of batteries.

With the prismatic cells battery pack the goal is to imprint welding points on the side faces of the parallelepiped, and, in some cases, also on the top face.

The aim is to try to create a standard capable of accommodating products of different types, for example also adaptable to batteries with cylindrical cells.

A first choice of layout is made regarding the positioning of the welding head; it is decided to attach it to the end of an anthropomorphic robot, as end-effector, so that it is mobile and can, thanks to the manipulator, reach all welding positions while keeping the piece stationary on a pallet. The variant to this solution could be the fixing of the laser head on a structure and the movement of the object to process using the robot, but picking the battery via the robot's gripper can hide welding points, so the design choice is different.

Important note: there is no single correct way to design a system. The design solutions for an industrial plant can be many and all potentially valid; the choice of the way to act depends on the technician, who bases it on personal and technical experience, knowledge of available technologies, costs, design preferences, but also on the functional objective and future vision of the station, for example whether it is to be versatile, scalable or reconfigurable. The direction taken in this work represents one of the possible choices.

Choosing to move the laser head with a robot, it is necessary to think about the feeding and unloading of the batteries: the solution adopted consists of a belt conveyor for pallets flowing on which the battery packs are fixed. The conveyor is pass-through to avoid wasting time for changing batteries on the pallet and it is closed loop; thus, the linear parts of the conveyors are connected by lifters.

There is a manual loading and unloading station.

Another design choice concerns the clamping method, since it is necessary to press the surfaces to be joined together before welding operations to avoid or reduce defects.

There are two main techniques adopted for this functioning: the first involves the use of a single mask, therefore specific for each battery model, which must be pressed against the busbars to be welded; the mask pushes all busbars present in the face at the same time. The robot will then be able to carry out all the welding points of the entire face without interruption. It is a solution that has advantages in terms of cycle time, but limits on versatility and applications since each battery has its own specific mask, so if a cell has to process different models, many tool changes will be necessary for the clamping system (unless there are special cases in which the differences between the models are minimal and allow the use of the same mask for them).

The second technology is based on a mobile pusher tool, designed to perform the welding of one point at a time (or a small number of points): the pusher is dynamically moved along the workpiece according to the positions to be welded, making the system adaptable to multiple battery models. This architecture is adopted in this project as it provides greater operational flexibility and simplifies the management of product variants.

Another station design choice that is taken at the initial stage of the project is about the two variants that are conceived for the robot's position; the robotic arm could be placed on the base on the floor (or on the bench), or hung from the structure ceiling, with the idea that the latter version could save space. Subsequently, only the version with the robot on the base is carried forward.

It is also decided to conceive the system according to the principle of modularity and scalability.

In this perspective, two configurations are developed:

- single robot configuration, in which a single manipulator performs the entire welding cycle on both side faces of the battery pack (V1);
- double robot configuration, which maintains the same basic architecture but integrates a second manipulator and a second laser head, allowing the simultaneous welding of the two faces and a consequent reduction in cycle time (V2).

5.4. Operations and work cycle

The work cycle of the station is subdivided into operations.

At the beginning the operator manually loads the battery pack onto the pallet in the manual station, the object is then secured in the reference fixture and the pallet is ready to flow inside the welding station.

The conveyor belt transfers the pallet to the welding position where it is centered and referenced, then the clamping system, that is composed of a specific pusher tool and two linear actuators, presses the busbars onto the cells to ensure proper contact between the parts to be welded.

The robot starts the mission and goes to the first welding location where two laser points are applied; then, the robot proceeds to weld other two points. After four welds, the clamping system moves to the next pressing pose and the robot moves to the next welding location.

Once the joining process is completed on both sides, the conveyor transfers the pallet to the temperature checking zone, that is inside the lifter area, and another battery pack reaches the welding position.

If the temperature sensor detects overheating, the battery pack is immediately moved away from the cell through the emergency conveyor that brings it to a safe zone; conversely, if the check is successful, the pallet moves along the recirculation conveyor to the manual station where the battery pack is unloaded.

6. 3D MODELLING

Following the analysis of the cell regarding how to structure the layout and which technologies to adopt, the three-dimensional modelling of the system's parts and the creation of the representative assembly is carried out. The 3D modelling is done using the software Autodesk Inventor Professional 2025.

Starting from components present in the company database and adding commercial parts obtained from suppliers, a first version of the welding cell is developed.

What follows is a description of all the components that make up the system.

The robot chosen, according to the payload and the working range, is the YASKAWA GP25 which handles up to 25 kg within a work area of 1730 mm.

The robot is a six-axis anthropomorphic manipulator, meaning it has six degrees of freedom: it consists of six rotary joints, which enable angular motion between the links, and seven links that are the rigid segments connecting the joints and forming the robot's kinematic chain.

The 3D model of the robot is downloaded from the official YASKAWA website and inserted into the cell assembly, together with the YASKAWA YRC1000 controller.

Figure 7: YASKAWA GP25 robot [19]

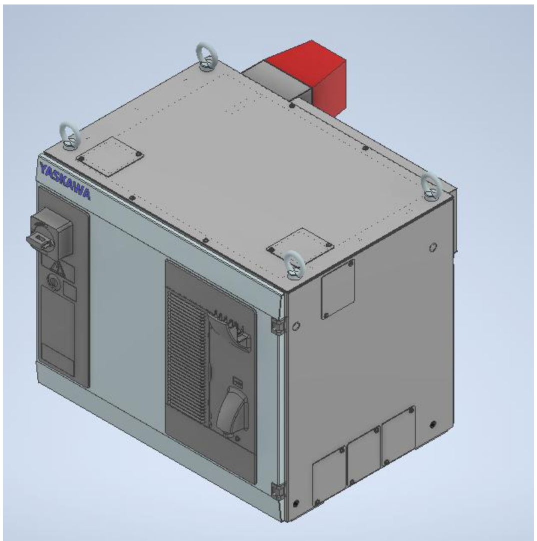


Figure 8: YASKAWA YRC1000 controller [20]

Another commercial component that is part of the system is the laser head. The three-dimensional model of the object is provided by the company and it works with a focal distance of 400 mm.

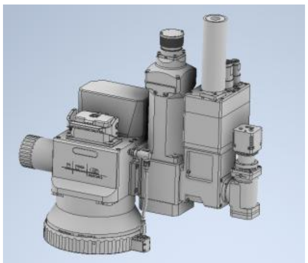


Figure 9: Laser welding head [21]

The laser is generated from a source and the model of the generator is provided by the company, as well as the chiller, necessary and fundamental for cooling the system during welding.

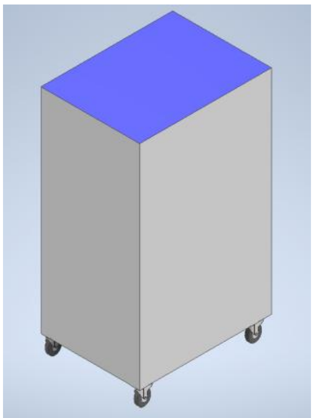


Figure 10: Laser source

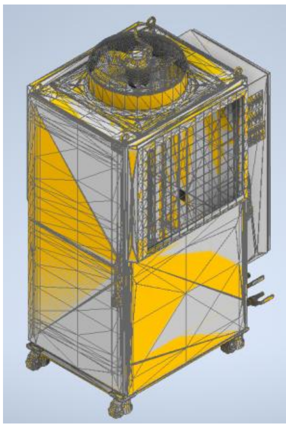


Figure 11: Chiller

The part to be processed, the battery pack, is composed of prismatic cells and the model is provided by the company as a prototype for the study of the station, but the system is able to process, with the necessary settings and specific recipes, even different batteries.

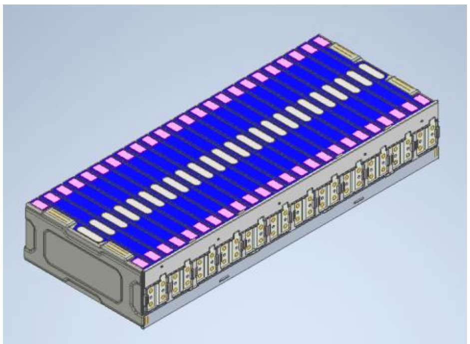


Figure 12: Case study battery pack

The battery is manually loaded and unloaded on pallets equipped with references and locking systems. The pallet is derived from a company model, adapted to the working principle; the dimensions are 1038 mm x 315 mm.

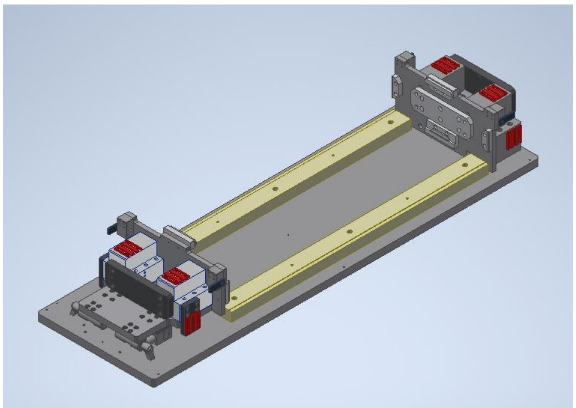


Figure 13: Pallet

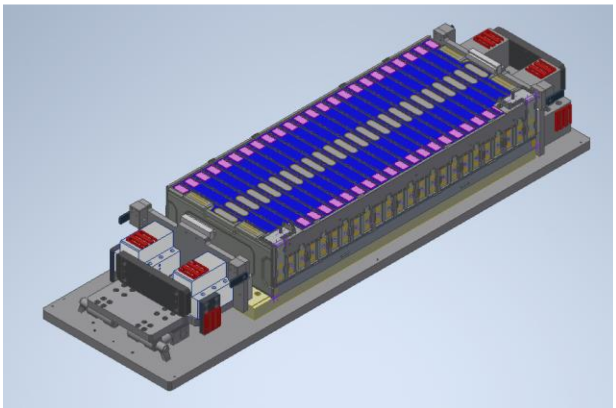


Figure 14: Pallet with battery pack

The recirculation of pallets takes place on a motorized belt conveyor with two linear sections, about 3600 mm long and 335 mm wide, and two lifters to close the movement path, which operate at heights of about 950 mm and 375 mm from the ground. The models are provided by the company and the parts derived from them are modified and remodelled to meet the layout needs.

A 1000 mm length of conveyor is added outside the closed loop of the pallet transport and is intended for emergency management: it moves the potentially dangerous battery pack away to a dedicated safe area in the plant.

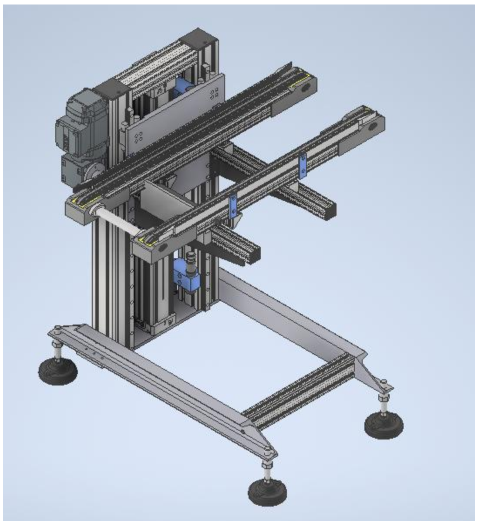


Figure 15: Lifter conveyor

Figure 16: Linear conveyor

The clamping systems are also adapted from models already present in Bonetto Automation's database and consist of components in which the pushing tools are moved on an axis perpendicular to the battery, and everything translates on a slide moved by an electric axis in the longitudinal direction of the pack.

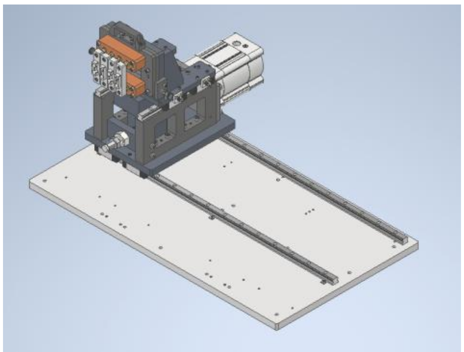


Figure 17: Clamping system

The entire system is supported by a bench which is entirely modelled for this thesis work with dimensions of 2300x2000x700 mm (width x length x height). The structure is also equipped with guards to ensure operational safety conditions, modelled entirely in this work project; there are windows for maintenance and repair operations after faults and there are also passage compartments with automatic safety opening and closing doors for the transit of pallets in the welding area. The robot area is covered with dark panels to improve welding performance and for protection purposes. The cell is covered by a roof from which the hood pipes exit since the laser welding process requires a fume extraction system.

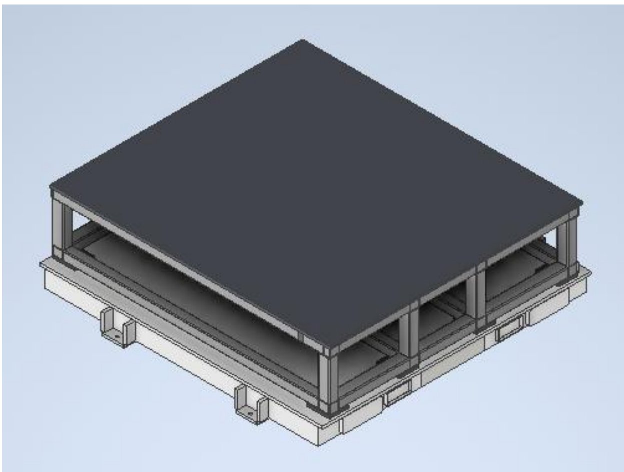


Figure 18: Station bench

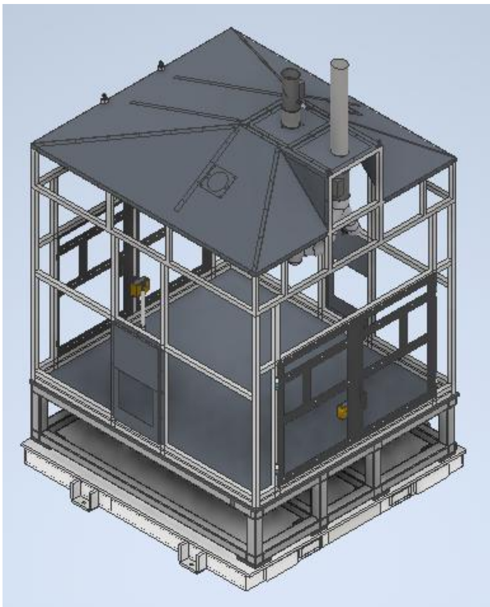


Figure 19: Station bench with guards

The assembly is also equipped with an electrical panel for the management of the electrical and PLC systems.

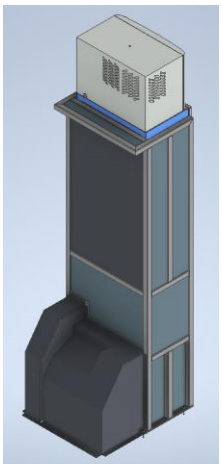


Figure 20: Electric panel

The first assembly created as the first proposal of the cell, visible in the image below *Figure 21*, includes old elements that have been optimized and updated during the study; the second robot with the laser head is fixed on a base designed to be the optional additional module of the version 2 cell.

The proposal with hanging robots is carried forward to this stage of study, then it is decided to continue with the floor-mounted version.

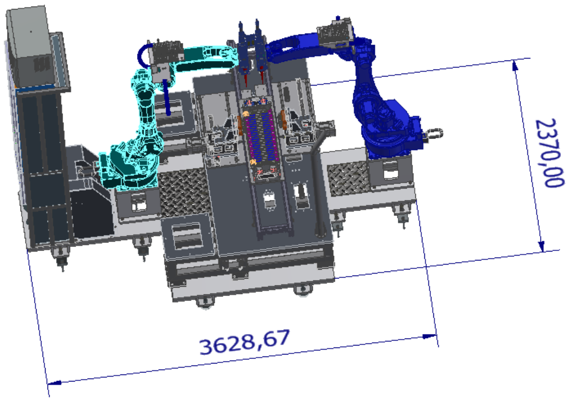


Figure 21: First cell proposal

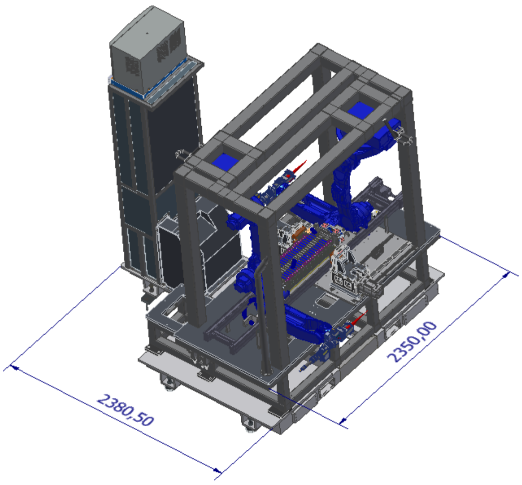


Figure 22: Hanging robots cell proposal

The three-dimensional modelling of the cell undergoes changes and optimizations, as well as revisions, throughout the study of the project, since, during the simulation phase, design problems or different solutions to be implemented came to light.

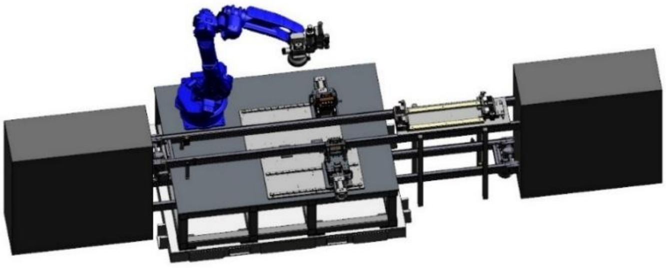


Figure 23: Intermediate stage of cell proposal

At the end of the thesis study the final models of the system for both versions are defined:

- V1 single robot;
- V2 with double robot.

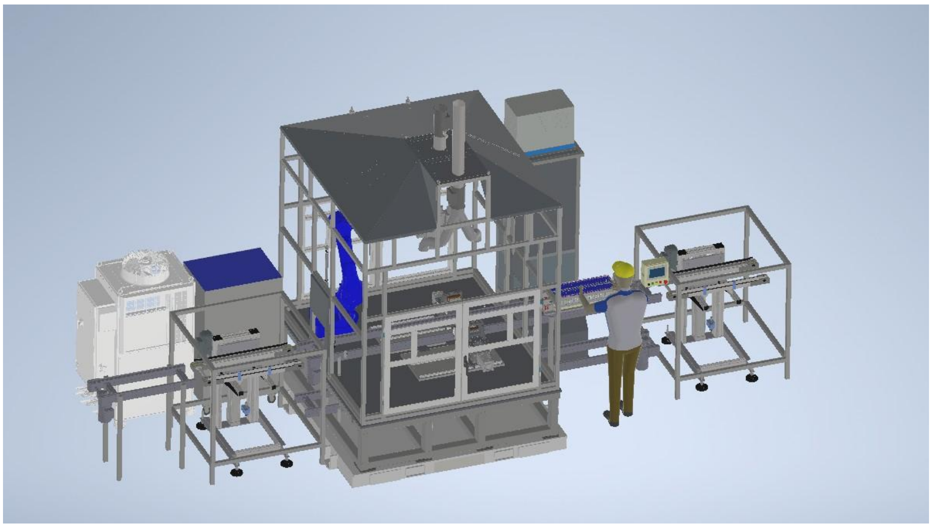


Figure 24: Laser welding cell V1

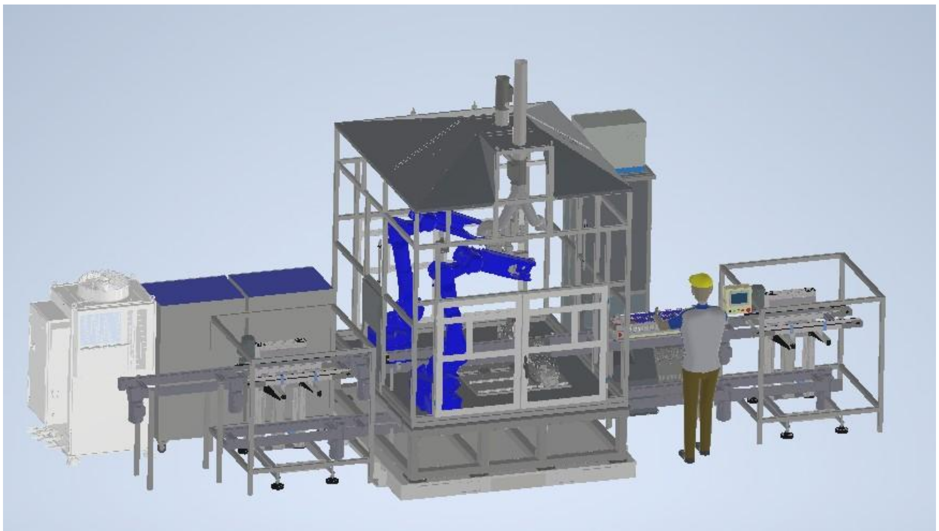


Figure 25: Laser welding cell V2

The overall dimensions of the line are 7000 x 2450 x 3300 mm (length x width x height), as shown in the image below.

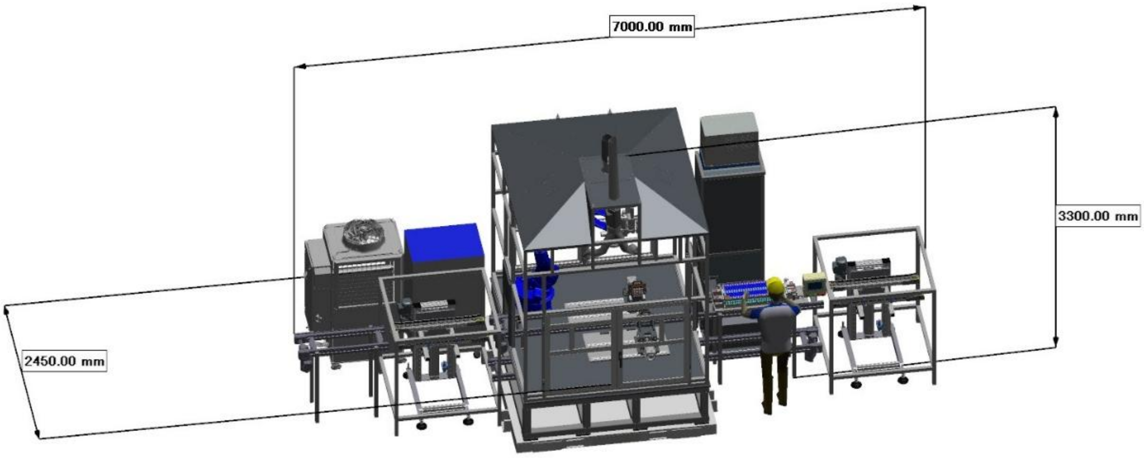


Figure 26: Laser welding cell dimensions

7. VIRTUAL SIMULATION

Once the initial cell assembly proposal is completed, the project proceeds to the use of Siemens Tecnomatix Process Simulate 2502, industrial process and systems simulation software, with the aim of reproducing the station's future work cycle with a view to pre-validating the system, but also to explore the field of digital models and test their use in an application case. [22]

7.1. Resources and parts

To implement the 3D models in .iam format created in Inventor into Process Simulate, each .ipt part is converted to the .jt format as required by the software.

Each component in .jt is added to the virtual environment to recreate the cell assembly.

During the insertion phase, all the objects are classified into specific categories that enable functionalities, special tools and operations based on their intended purpose.

A first division of the components is between resources and parts: the resources are the active elements of the system, i.e. what performs the operations or allows them to happen, the parts, on the other hand, are the physical objects that are manipulated or transformed during the simulation. Resources can be robots, grippers, tools, conveyors, equipment, or even human operators, and in general, a resource is equipped with kinematics, can be programmed, and performs movements or actions on the product. Parts are the components or products, intermediate or finished, that represent the result of the process and do not have active behaviour, i.e. they do not perform autonomous movements, but are moved, assembled, or machined by resources. [22]

The main resource of this work is the YASKAWA GP25 robot which is classified in the *robot* type, in fact it allows functions such as mounting and unmounting tool, following trajectories with the tool center point frame (TCPF), admitting welding processes, painting, pick and place operations. There are controls on the dimensions related to the movements of the joints such as accelerations and speeds, it admits different configurations and poses.

The laser head is classified in the *tool* category and in this study represents the end-effector of the robot. The reference system that reaches the points during the operation, which by default is the TCPF of the robot, is in this case associated with the laser welding head.

The laser source, chiller and robot controller are generic *tools* in the simulation environment, static elements.

An object representing the laser beam generated by the laser head is also created for simulation in the *device* category: it is a long and thin cylinder attached to the tool that can take different orientations depending on the welding point to be imprinted.

The battery pack is the *part* of the simulation: it is moved and processed during the cycle.

The pallet is classified as a *device*, i.e. a group that allows different functions including assuming poses, such as open and closed, by moving its joints.

The linear sections of the pallet recirculation system are converted into *conveyor* resources: they are equipped with paths along which the parts or pallets are transported and it is possible to set their length, direction and travel speed. The conveyor for emergency management is also a *conveyor* resource while the lifters for lifting and lowering pallets are *device* resources.

Clamping systems are classified in this study as *grippers*, but they could also be part of the *device* group. The necessary function is to assume different poses at the right signals. Finally, other static resources that complete the cell are the bench, the guards, the electrical panel, the HMI and the operator.

Figure 27: Project resources

7.2. Kinematics

Once the virtual environment is recreated in Process Simulate, i.e. all parts and resources are inserted and placed in the right position, the assembly is static; the sizes of the objects and of the line are visible, as they were already in Inventor.

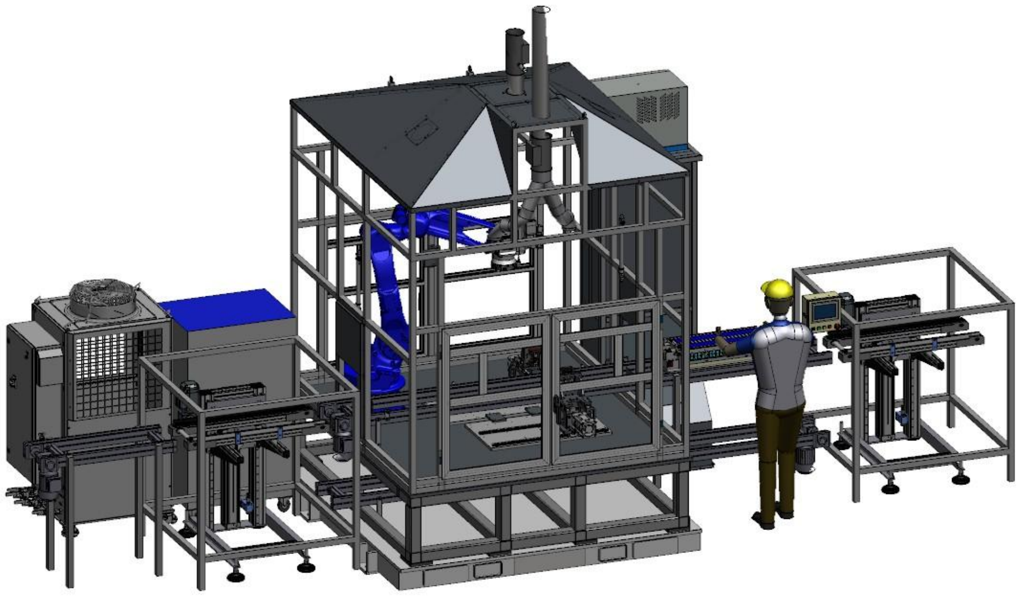


Figure 28: Laser welding cell in SIEMENS Process Simulate environment

For each object it is possible to activate the *"Modelling Scope",* i.e. a working mode that is used to modify the geometric and structural definition of a resource or component within the simulation environment; when the *Modelling Scope* is active, the user enters a sort of "modelling mode" of the single object where a deeper level of the model can be accessed, useful when it is needed to, for example, add a local reference, update a link, change an end effector or set the initial position of a resource. All these operations are performed within the context of the *Modelling Scope*, which temporarily isolates the resource from the rest of the simulation, allowing changes without altering the overall behaviour. When this mode is turned off, the changes are saved as the final part of the model, and from then on, the object retains that configuration in the normal simulation.

To imprint actions and allow the various components to move, the fundamental step is to define the kinematics of each resource that needs it.

The *"Kinematics Editor"* feature allows establishing links and defining resource joints. The joints are prismatic or revolute and the limits of movement can also be specified in this phase. [22]

The first object whose kinematics is analysed is the robot. In the following image it is possible to see the division of the manipulator into the 7 links and the hierarchy of the 6 revolute joints.

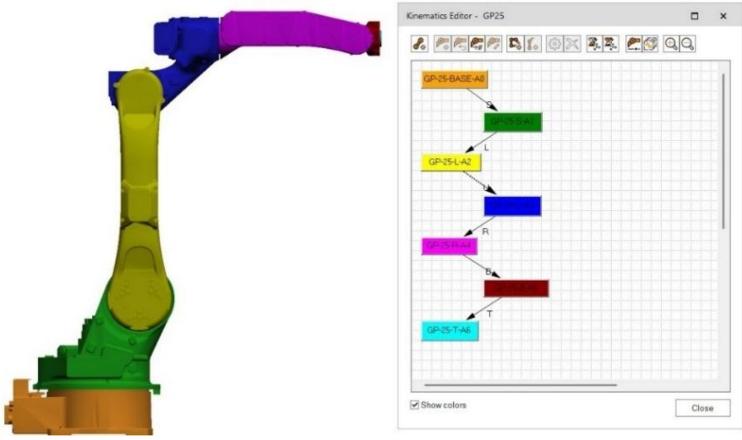


Figure 29: YASKAWA GP25 Kinematics Editor

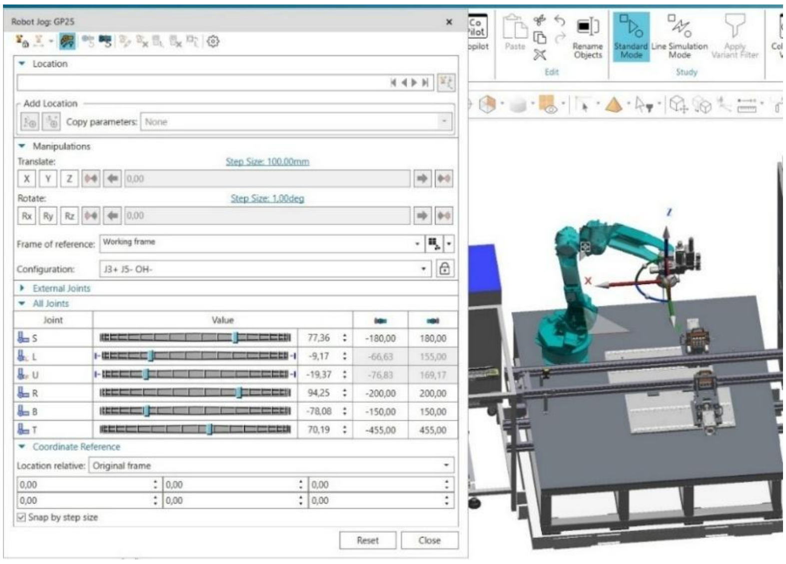


Figure 30: GP25 Robot Jog

The "*Robot Jog*" is a function that allows visualizing the kinematic structure and manually moving, through joint sliders, the joints of a resource within the set limits, between the lower limit and the upper limit.

Each slider graphically represents the position of the joint with respect to its range of motion: moving it, the angular or linear value of the joint is modified, while the asset updates itself in real time in the scene.

For *robot* resources it is also possible to modify the configuration of the robot by directly moving the TCPF with the axes in the scene or rotate it through the appropriate sliders. [22]

Other objects for which the kinematic definition is necessary are clamping systems: they consist of 3 links and 2 prismatic joints with specified movement limits.

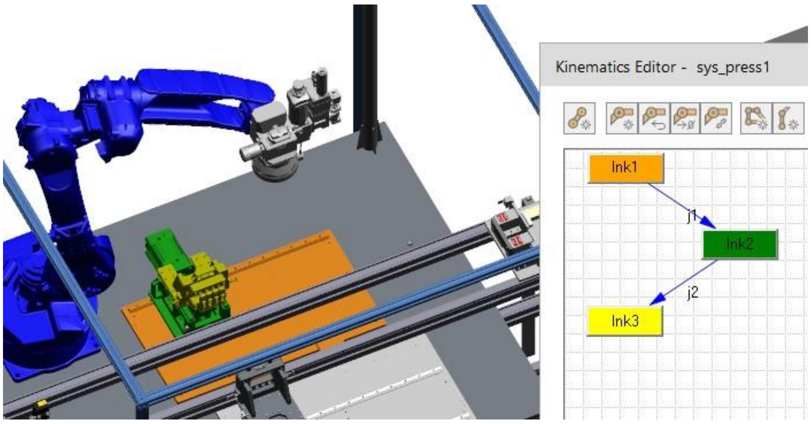


Figure 31: Clamping system 1 Kinematics Editor

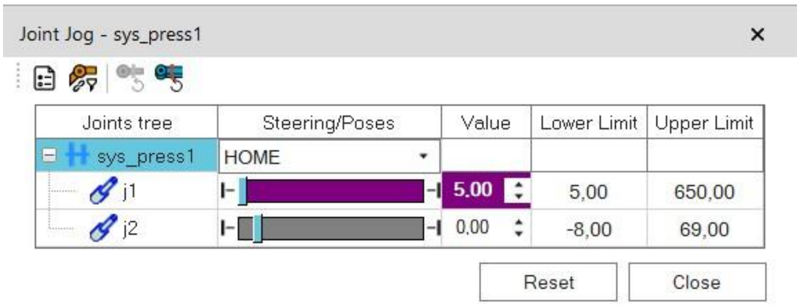


Figure 32: Clamping system 1 Joint Jog

The base visible in orange in *Figure 31* is the first link, fixed to the workbench which is composed of the interface plate and the guides on which the slide moves; the green link is the slide that makes the movement in the longitudinal direction of the battery while the yellow link is the pressure tool, which has the task of pressing the busbars against the cells to be welded.

The *"Joint Jog"* is the analogous function to the *"Robot Jog"* but for kinematic resources that are not *robots*.

The kinematics of the second clamping system is the same as the kinematics of the clamping system already described.

The pallet, having the battery blocking system, is a component that requires kinematic definition: the first link is formed by the pallet itself and the fixed reference of the battery and, connected via a prismatic joint, there is the mobile reference for fixing and centering the object to be welded.

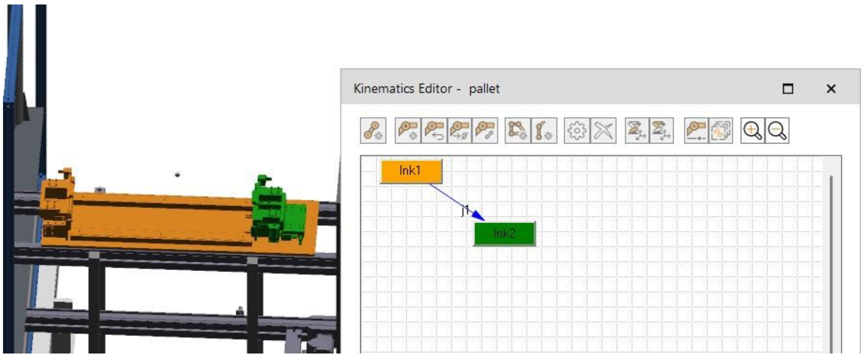


Figure 33: Pallet Kinematics Editor

Other components that move and therefore need kinematics are the transport lifters: they consist of the fixed parts, that are the structures anchored to the ground, and of sections of conveyors, that move up and down, allow the pallets to recirculate.

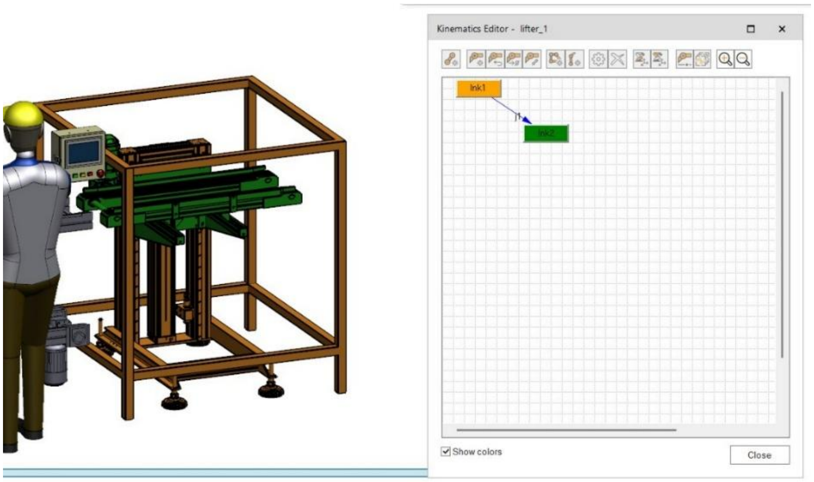


Figure 34: Lifter 1 Kinematics Editor

The kinematics of the *lifter_2* is the same as the kinematics of the *lifter_1*.

Device and *gripper* resources are moved by functions that work by imposing certain poses on objects that must be achieved and must be preset. This is defined in the *"Pose Editor"* of each resource in which, by entering the values of the joints corresponding to a given pose and marking it, it is possible to save it and to reach it directly during the actions in the work cycle.

The clamping system allows the welding of four points to be imprinted on two cells; in the case study, the battery has twelve prismatic cells so the pusher tool must move in six positions longitudinally along the pack and, in each of these positions, it assumes the contact configuration, i.e. by pressing the busbars, and the out configuration. For this reason, for each clamping system, the "*out*" and *"C"* (clamping) *poses* are defined for each of the six positions to be achieved. Other poses are also marked to optimize the work cycle.

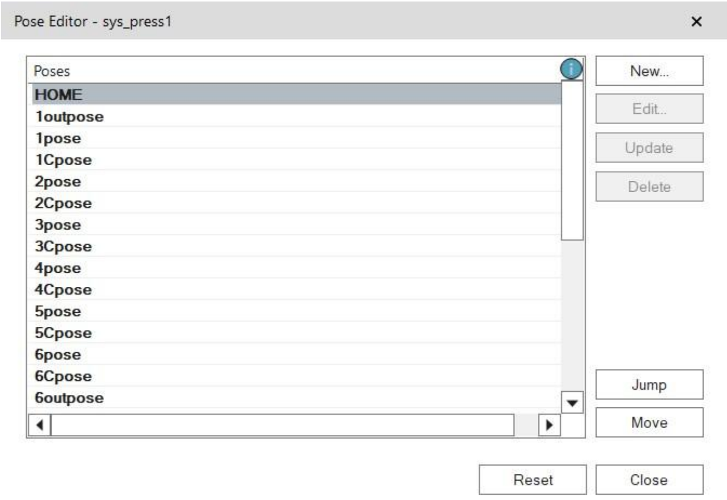


Figure 35: Clamping system 1 Pose Editor

The *Pose Editor* of clamping system 2 is the same as the one of clamping system 1, but with the opposite pose numbering.

The poses set for the other resource are *open*, *blocked* and *closed* for the pallet, where *open* represents the references completely open, *closed*, completely closed and *blocked* represents the right configuration for tightening the battery.

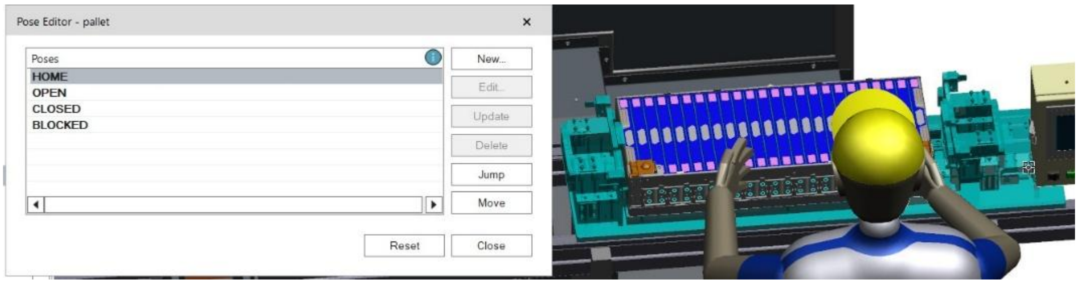


Figure 36: Pallet Pose Editor

The poses assumed by both lifters are *up* and *down*.

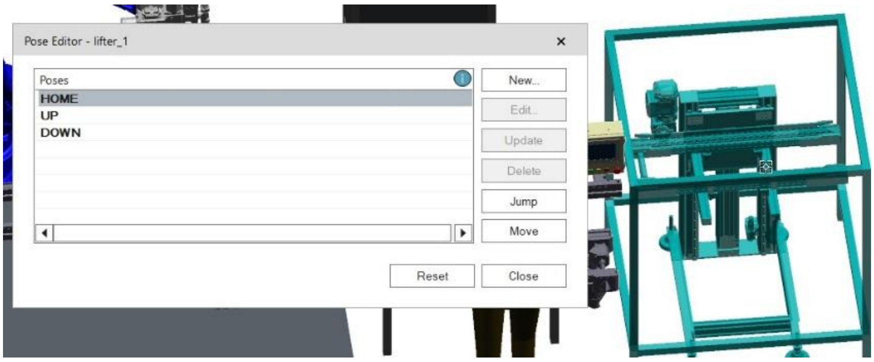


Figure 37: Lifter 1 Pose Editor

The poses are also defined for the positions of the welding points assumed by the robot, but not because they are necessary for the movement of the manipulator, since it is conducted through path planning, but for the recognition of the configuration in which it is located, simulating sensors on the joints for sending status signals.

There are the twelve welding positions of one face (*w1, w2, w3, w4, w5, w6, w7, w8, w9, w10, w11 and w12*) and the other twelve on the opposite face (*w1o, w2o, w3o, w4o, w5o, w6o, w7o, w8o, w9o, w10o, w11o and w12o*).

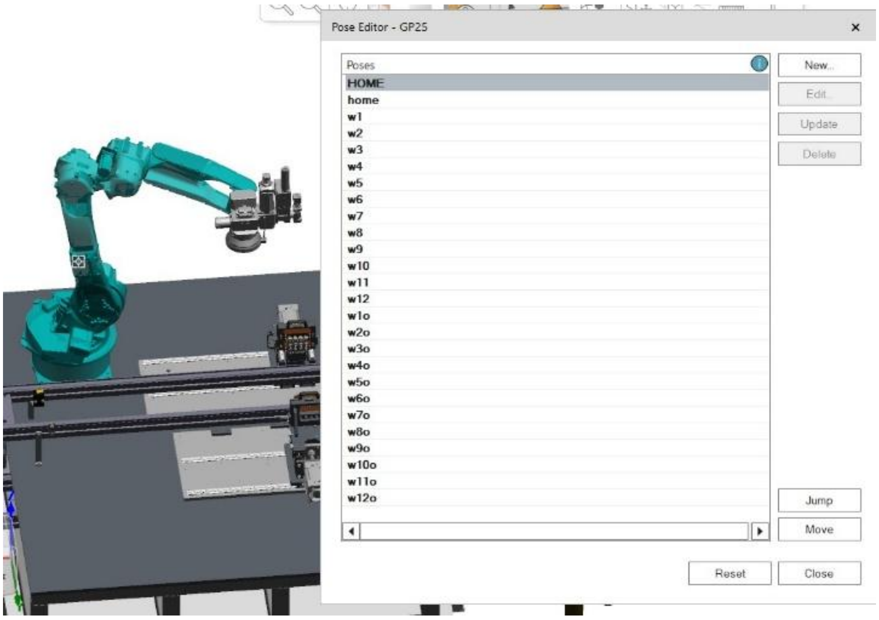


Figure 38: Robot GP25 Pose Editor

In Process Simulate, there is a distinction between resources and instances: a resource represents the basic model, i.e. the general definition of an object with its geometric structure and kinematics, while an instance is a copy of that resource used within the simulation scene. When a pose is created or modified within the *Modelling Scope*, it is saved in the resource definition and thus becomes available to all its instances; on the contrary, if the pose is defined outside the *Modelling Scope*, it remains linked only to the instance on which it is created, without affecting the others. In this way, the *Modelling Scope* controls the level of generality of the poses: global, if belonging to the resource, or local, if associated with a single instance. [22]

7.3. Operations and path-planning

As already mentioned, the work cycle is divided into operations; this division is the basis in the definition of the different operations in Process Simulate.

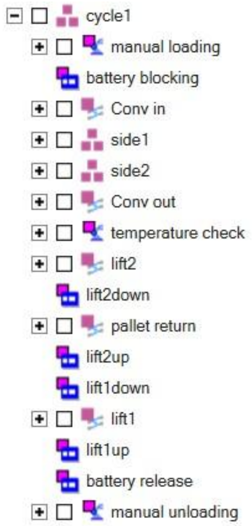


Figure 39: Work cycle operations

Manual loading and unloading operations are simulated in this work by imposing delays in the operating flow of 4 seconds.

The locking of the battery pack in the pallet takes place through the use of a "*device operation*" in which the selected *device* resource is moved from an initial pose to a final pose (poses previously set in the kinematic definition) in a given time interval: in this case the pallet device is moved from the *open* configuration to the *blocked* one in one second.

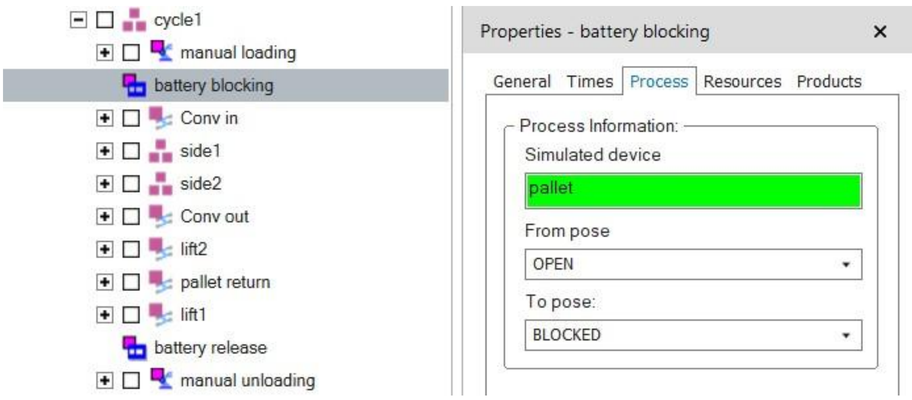


Figure 40: Device operation battery_blocking

Once the battery is fixed, the pallet moves on the conveyor thanks to a *flow operation*: the selected objects, bound together with the *attach* function, move from a starting frame and reach, one after the other, the frames defined in the *Path Editor*.

The pallet exchange takes 5 seconds since the supposed speed for the conveyor is 18m/min = 300mm/s (typical speed of industrial conveyor) and the distance between the manual station and the welding station is about 1500mm.

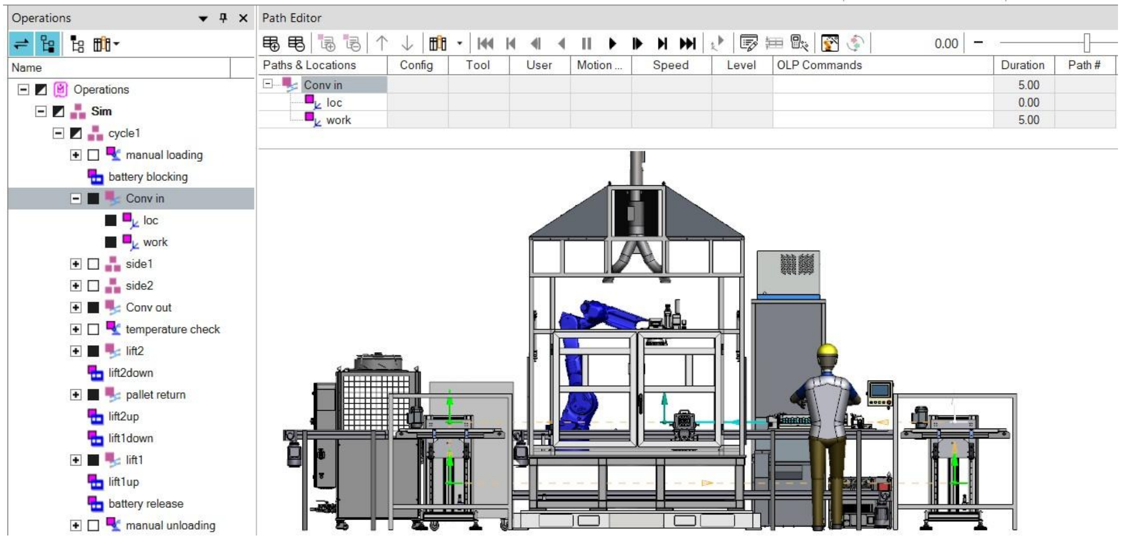


Figure 41: Path Editor of "conv in" flow operation

When the pallet is in the welding position, the *compound operation "side1"* begins for the first face to be processed, i.e. a group of operations dedicated to the welding of one side of the battery pack: the *sys_press1* device (the clamping system) is moved from the detachment configuration with the battery, *1out*, to pose *1C*, i.e. the first compression of the busbars against the cells is carried out.

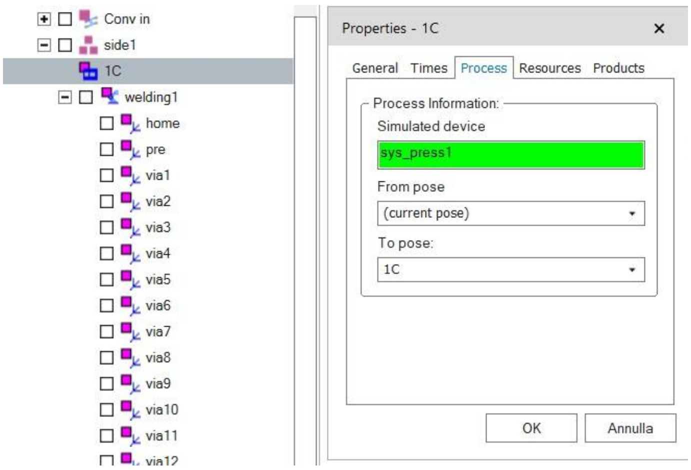


Figure 42: Device operation 1C

While clamping takes place, the robot begins to move from its home configuration to the position of the first welding point to be imprinted.

Once clamped, the robot can start its welding cycle defined in the operation *"welding1"*. The robot's work cycle is defined through a *generic robot operation* in which all the frames that the robot must reach with the TCPF (the center of the welding head) are set in the *Path Editor*.

The frames of the robot path are created beforehand, placing each reference at the correct focal distance with respect to the welding points to be applied, 400 mm as laser head datasheet.

For each stop of the manipulator, two welds are carried out, so the frames generated for the path planning, taking this specific battery as an example, are twelve plus two additional for the pre-welding and post-welding positions.

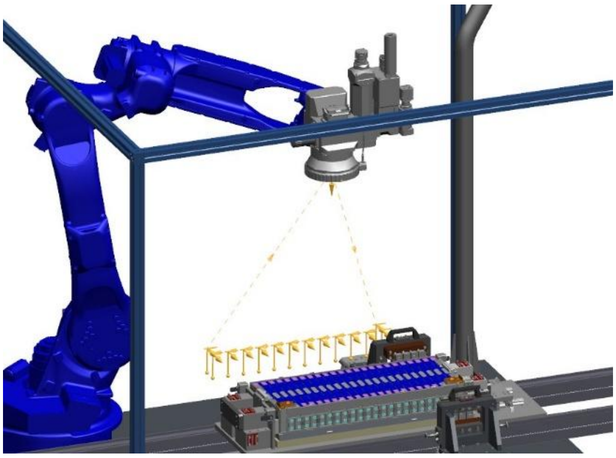


Figure 43: Laser welding path of battery pack's first side

In each welding location, through the *OLP Commands*, the direction of the laser beam (which is managed as a *device* resource) and the movements of the clamping systems are commanded.

Figure 44: Laser beam control

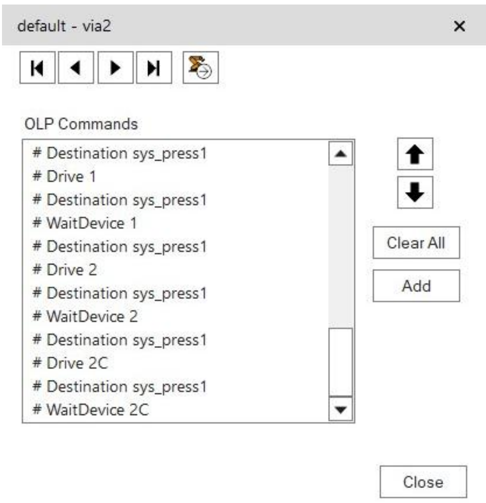


Figure 45: Clamping system control

By designing the cell conservatively, a welding time of about 0.25 seconds is estimated for each point. For each segment of the robot path, it is possible to specify the type of movement and the speed, in percentage or linear in mm/s, referred to the TCPF, or the specified frame.

Clarifications about the different motion parameters are described in the table below, extracted from Siemens' Manual of Process Simulate.

Table 1: Motion parameters for robotic operations in SIEMENS Process Simulate [22]

Parameter	Description
Motion Type	Determines the exact path of the robot's TCPF from its current position to the defined location. The following values are available: • **PTP** - Moves the joints in the most efficient way and disregards the path of the robot's TCPF. All the robot joints begin each movement together and finish together. The duration of a movement cannot be shorter than that allowed by the joint which, when operating at its maximum allowable speed, requires the longest time to complete the movement. The other joints operate accordingly at speeds lower than their maximum. If the speed specified for the TCPF or final frame is less than the allowed maximum speed, the speed of each joint is reduced proportionately. • **Lin** - Causes the origin of the TCPF to move in a straight line between locations. • **Circ** - Moves the robot's TCPF along an arc. This motion is used primarily in arc-welding or sealing processes.
Speed	Specifies either the Cartesian speed (if Motion Type is set to Lin or Circ) or percentage of the maximum speed (if Motion Type is set to PTP) .

The welding operation for the first side of the battery takes about 25 seconds.

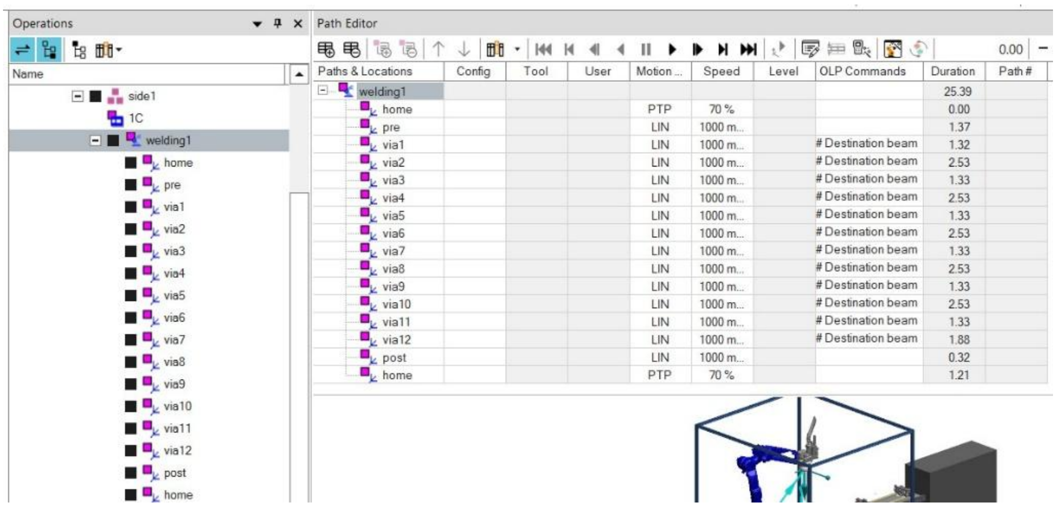


Figure 46: Robotic operation welding1

The clamping system then returns to the *1out* position, ready for a new cycle, while the robot reaches the other side of the battery for *compound operation "side2"* and "*welding2"*. These operations are similar to what is described for *side1* and *welding1*.

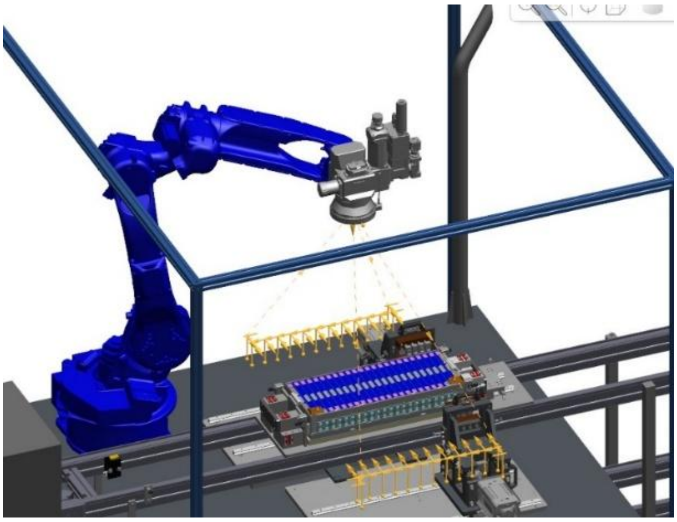


Figure 47: Laser welding robot path

At the end of the welding cycle, another *flow operation* (v=300mm/s) moves the pallet to the lifter, where, through a temperature sensor, the battery is controlled (delay of 1 second).

The lifter is lowered to allow the recirculation of the pallet through a *device operation* that moves the resource from the *up* pose to the *down* pose. A *flow operation* allows the pallet (v=300mm/s) to slide to the other lifter which goes from *down* to *up* and the pallet reaches the manual station again.

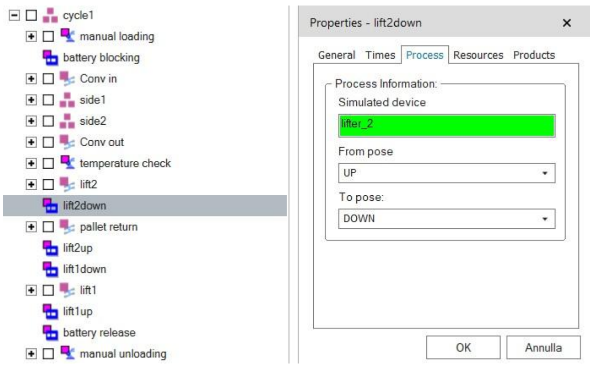


Figure 48: Lifter 2 device operation

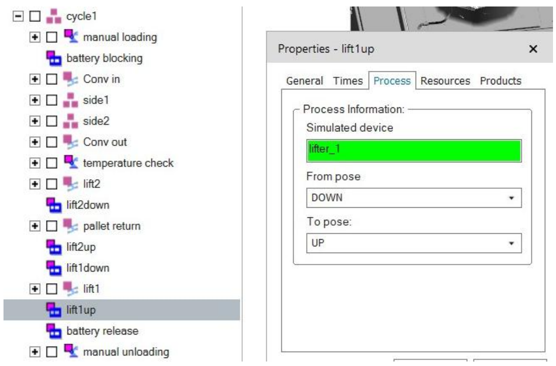


Figure 49: Lifter 1 device operation

The image below shows the path of the pallet recirculation.

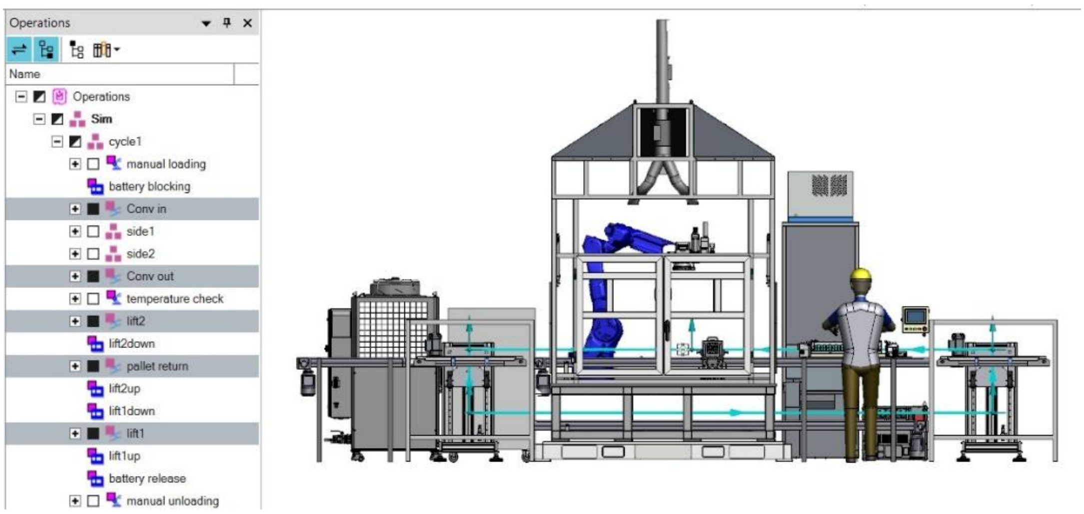


Figure 50: Pallet recirculation path

The pallet is unlocked to allow the welded battery to be unloaded: device from *blocked* pose to *open* pose.

The cycle repeats.

The sequence of operations is managed in a Gantt diagram by defining the conditions of the transitions, having the possibility to clearly visualize the workflow and the timing of the different actions.

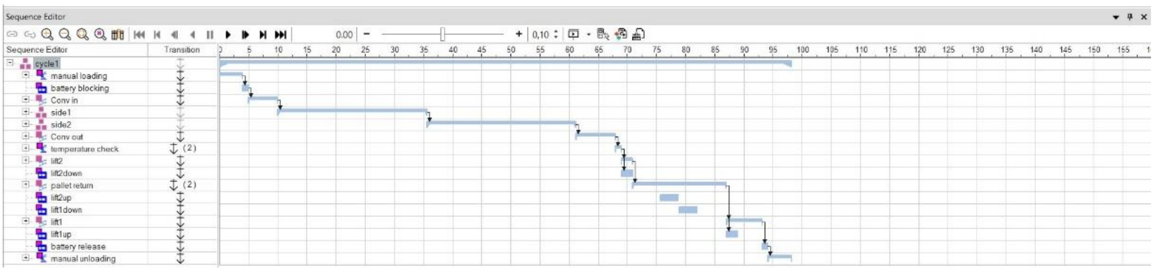


Figure 51: Operations Gantt diagram

7.4. Reach test

A very useful and powerful feature of Process Simulate is the possibility, by selecting the robot operation, to test the reachability of all the locations included in the path planning: the *reach test*.

Moreover, the reach indications are updated while moving the robot or the locations in the path.

The table below, from Siemens Tecnomatix Process Simulate 2502 manual, describe the possible reach test results.

Table 2: Reach test results in SIEMENS Process Simulate software [22]

Symbol	Description
	The robot can reach the location. The location is colored blue in the Graphic Viewer.
	The robot has partial reachability to the location. The robot reaches the location, but must rotate its TCPF to match the TCPF of the target location.
	The robot has reachability to the location outside its working limits (but within its physical limits).
	The robot has partial reachability to the location outside its working limits (but within its physical limits). The robot reaches the location, but must rotate its TCPF to match the TCPF of the target location.
	The robot has full reachability to the location outside its physical limits.
	The robot has partial reachability to the location outside its physical limits. The robot reaches the location, but must rotate its TCPF to match the TCPF of the target location.
	The robot cannot reach the location at all. The location is colored red in the Graphic Viewer.

The TCPF, tool center point frame, is the reference system associated with TCP, which not only defines the position of the TCP, but also the orientation of the tool in space (i.e. the angle at which it appears in relation to the workpiece).

Working limits are the recommended operating limits for robots: in this area, movement is stable, safe and kinematics and dynamics are optimal. It is the volume of work in which the robot should operate during a normal production process.

Physical limits, on the other hand, are the maximum mechanical limits of the robot's joints: they represent the absolute boundaries of its movement, beyond which the robot cannot go because it would exceed the maximum travel of the axes.

Staying within working limits means operating in optimal conditions; arriving within physical limits but outside working limits means that the robot can still reach the position, but in an extreme condition, close to joint limits, which can compromise precision, speed or safety.

During the design phase of the robotic cell in Inventor, one challenge is to verify whether all the locations that the robot needs to reach are actually accessible; the CAD environment allows precisely defining geometries, dimensions and theoretical trajectories, but does not offer native tools to evaluate the real ability of the robot to perform those movements in compliance with its kinematic limits.

With the first proposal of layout configuration, the robot could not reach some locations at all.

The integration with Process Simulate makes it possible to overcome this limitation thanks to the reach test function and it allows identifying unfeasible configurations to correct the cell layout, thus optimizing the feasibility of the process. In this way, the project is moved from a purely geometric definition to a kinematic and functional validation. [22]

Figure 52: Reach test laser welding operations results

7.5. Collisions check

After obtaining complete reachability for the locations of the robot operations, collision checking is carried out through *collision check* functionality. It allows observing impacts between objects in the work cycle of the system.

Two sets are configured for collision checking:

- the first controls the movements of the robot and the laser head with respect to all other relevant elements in the system.

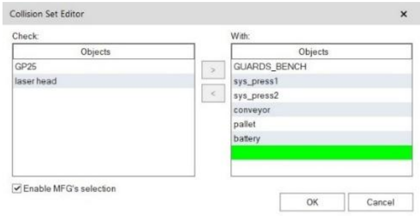


Figure 53: First collision set

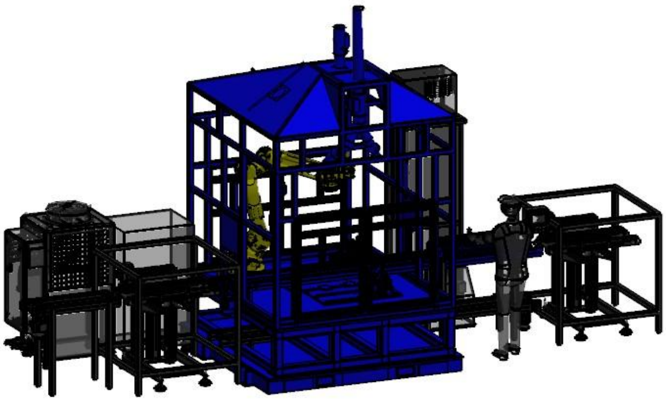


Figure 54: Collision check between robot with laser head and all other elements in the system

At this stage, a collision happens between the welding head and the clamping system and therefore the path of the robot is slightly corrected (carrying out the reach test again and obtaining a configuration that avoids collisions and guarantees accessibility to all locations).

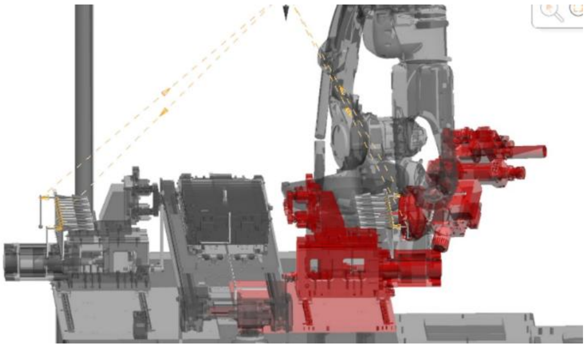


Figure 55: Collision happening

- The second control set monitors the collisions that may exist between the robot and the welding head during the operations. Collisions are avoided.

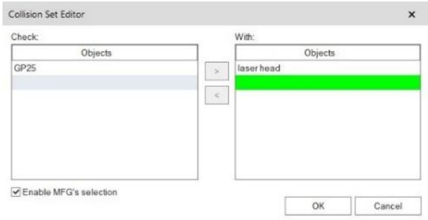


Figure 56: Second collision set

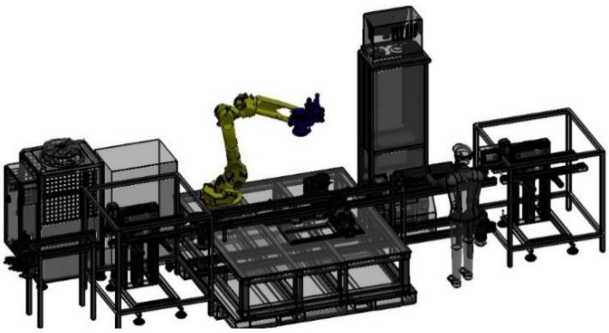


Figure 57: Collision check between robot and laser head

Process Simulate also provides a very useful feature, called *Swept Volume*, which creates a three-dimensional object representing the footprint occupied by a selected group of resources during one or more operations. This tool is used for the sizing of the station bench and guards, which, at an early stage of the work, they were very approximated and not very optimized compared to the space actually needed for welding.

They are modelled ad hoc, knowing the 3D object of the swept volume of the welding operations on both sides of the battery pack. [22]

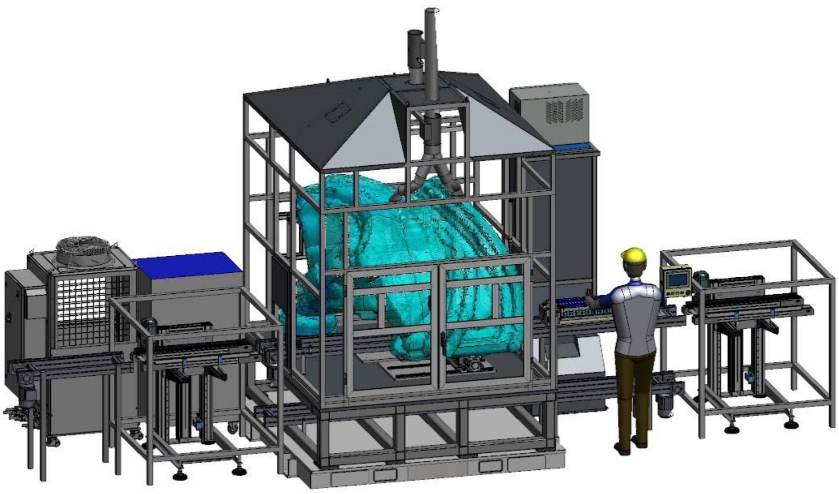


Figure 58: Swept volume of welding operations

7.6. Cycle time and version 2

A key parameter to evaluate during the virtual simulation of the laser welding cell is the overall cycle time of the system, as it is one of the main indicators of production efficiency. In the preliminary design phases, accurately estimating this value can be challenging, especially in the presence of articulated systems.

For the welding station with a single robot, an approximate cycle time of 55 seconds per battery pack is obtained, considering all loading, unloading, welding and pallet handling operations.

With a view of a modular and scalable design, a second cell configuration (V2) is then developed and analysed, characterized by the presence of two robots and two laser heads, each associated with a dedicated controller and a source. In this version, the welding operations of the *side1* and *side2* are performed in parallel by the two manipulators, resulting in an improved operating efficiency and in a significant reduction in cycle time, which drops to approximately 30 seconds per battery.

With this reduction in processing times, however, it is necessary to introduce a buffer position along the return conveyor, in order to properly manage the flow of pallets and ensure process continuity without creating bottlenecks.

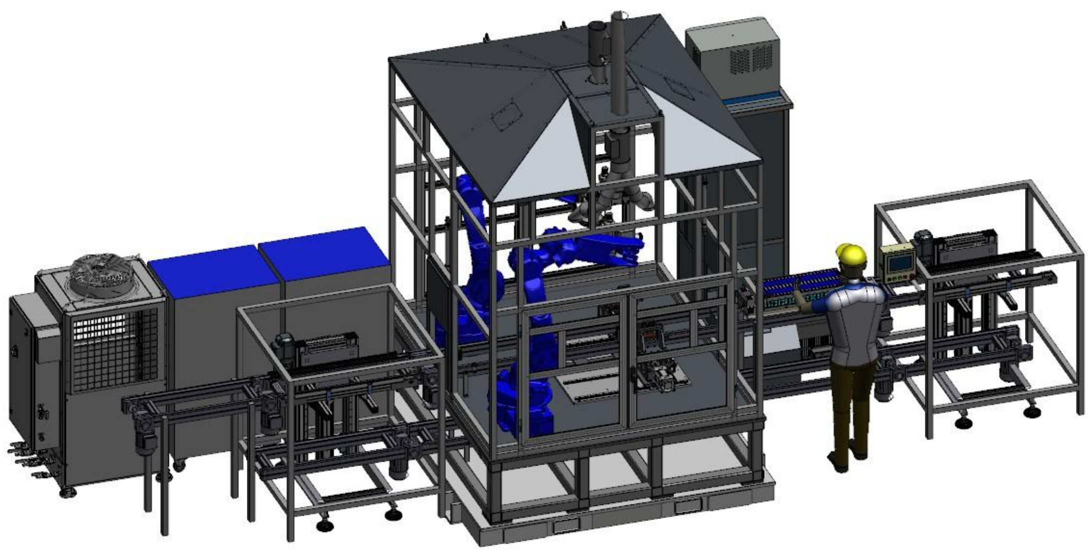


Figure 59: Laser welding cell V2 in SIEMENS Process Simulate environment

7.7. Sensors and connections

In the project, both a time-based simulation and a line simulation are performed within the Process Simulate environment, in order to analyse the dynamic behaviour of the welding cell.

Time-based simulation allows reproducing a single complete production cycle, following a predefined sequence of operations (Gantt diagram). This approach makes it possible to accurately assess the overall duration of the cycle, the progress of the individual phases and the temporal consistency between the various activities. However, it is a deterministic simulation, based on a fixed order of operations, which does not take into account the dynamic interactions between the different components of the system.

To obtain a more realistic representation of the plant's operation, line simulation, or CEE (Cyclic Event Evaluator), is also used, which is based on event-driven logic. In this mode, the execution of operations does not depend on a fixed timeline, but on events and transition signals during the simulation; every time an operation ends, an *operation_end* signal is produced by default and that activates the conditions necessary for the start of subsequent operations, thus allowing the behaviour of the system to be simulated more faithfully, also adding logics deriving from other elements.

In general, the use of CEE simulation makes it possible to validate the coordination logic between the resources and to verify the correct management of waiting times, operational priorities and interdependencies between the different components of the cell. In this way, it is possible not only to analyse the kinematic feasibility of the operations, but also to optimize the synchronization between the components, bringing the virtual model closer to the behaviour of the real plant.

Photoelectric sensors are created to test the signal logic and the operation of the CEE simulation.

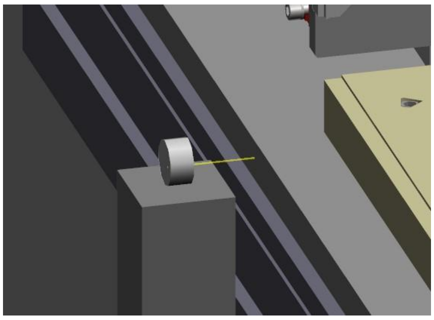


Figure 60: Photoelectric sensor

manual_pos1 and *manual_pos2* are the two photoelectric sensors to control the presence of the pallet in the manual loading/unloading station; *battery_presence* is the sensor that checks the presence of the battery on the pallet, while *work_pos1* and *work_pos2* check the presence of the pallet in the welding position.

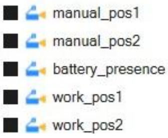


Figure 61: Presence sensors in manual and welding stations

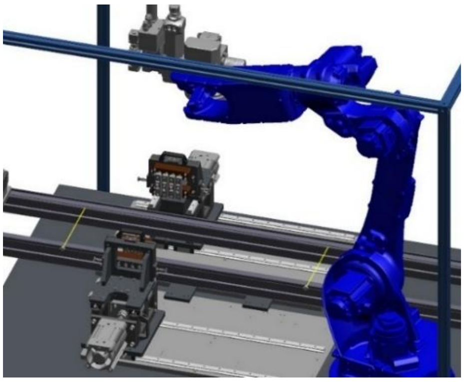


Figure 62: Pallet not detected by sensors

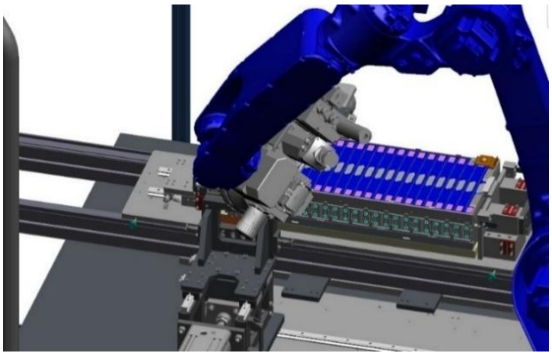


Figure 63: Pallet detected by sensors

By adding sensors to the study, the program automatically generates the Boolean signals associated with them; the outputs are green or red during simulation.

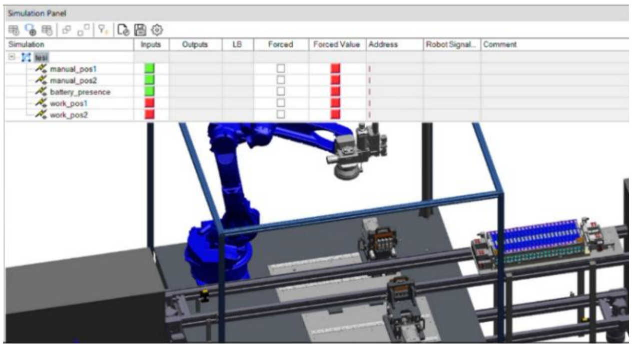


Figure 64: Pallet in manual station (Boolean signals)

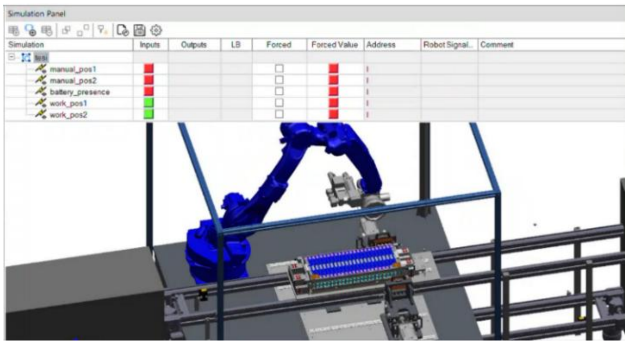


Figure 65: Pallet in welding station (Boolean signals)

For a simulation closer to reality, sensors are added to the robot, clamping systems and the locking system of the pallet, which could provide information on the poses and on the status of the assets.

This is done through the *"Resource Logic Behaviour Editor"* of each resource in which there are defined the input and output variables of the given object. The signals that communicate the state of being in a certain pose are called *resourceName_at_poseName*, while the signals that command the actions to perform are called *resourceName_mtp_poseName*, where *"mtp"* stands for "move to pose".

Images of the robot's and clamping_system 1's *Resource Logic Behaviour Editor* are inserted below as examples.

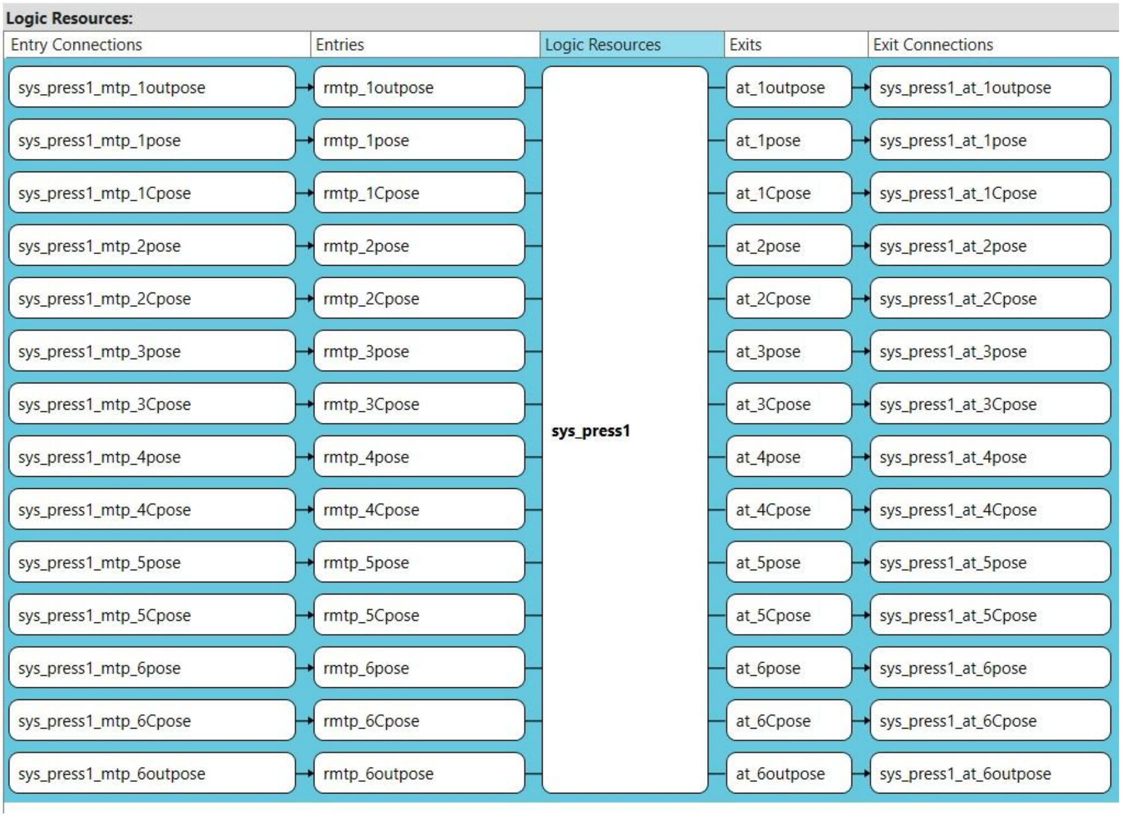


Figure 66: Clamping system 1 Logic Behaviour Editor

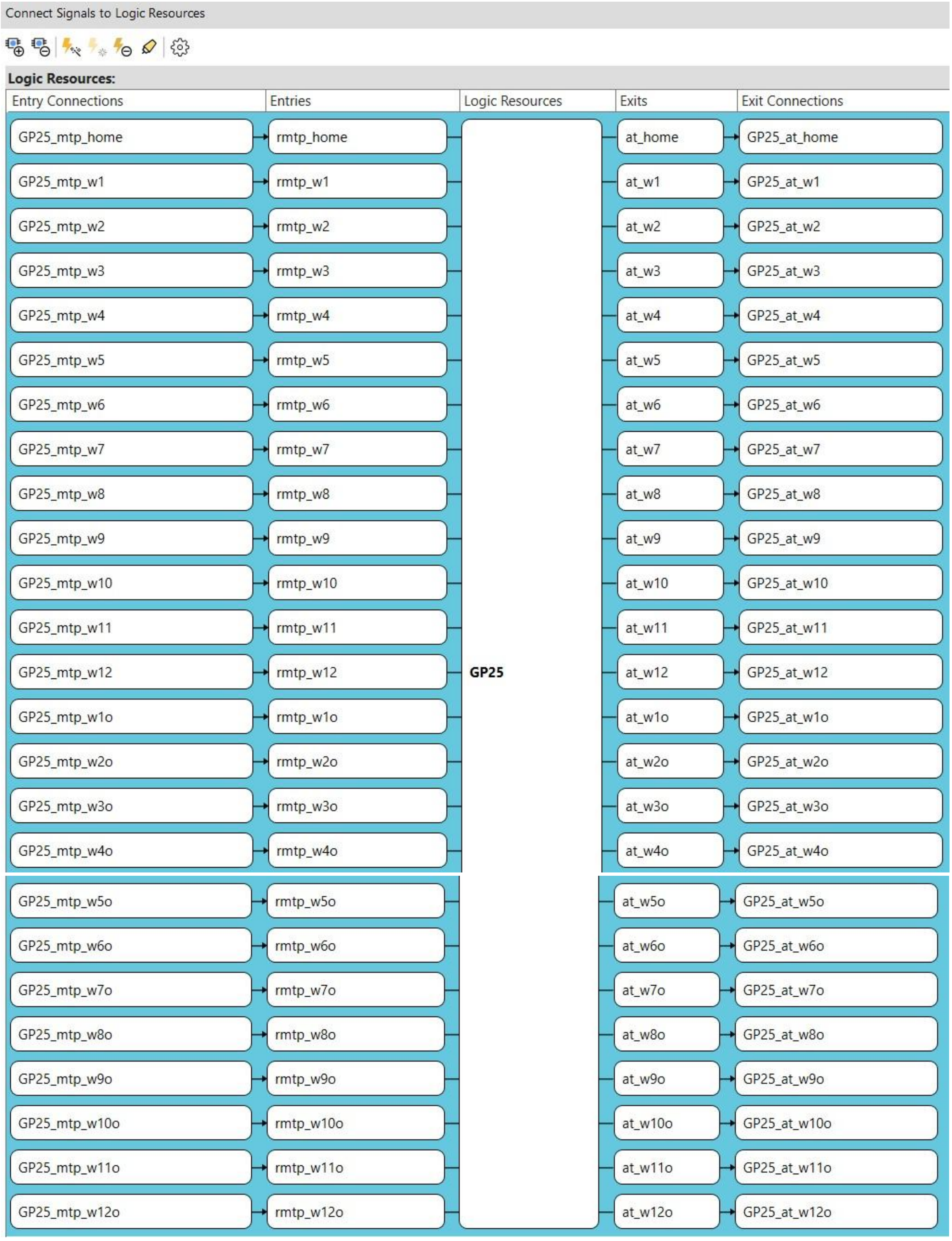


Figure 67: Robot GP25 Logic Behaviour Editor

The Boolean signals of the variables just discussed are functional and tested during the simulation, they change True/False (Green/Red) state consistently with the poses assumed by the robot and the configurations assumed by the clamping systems.

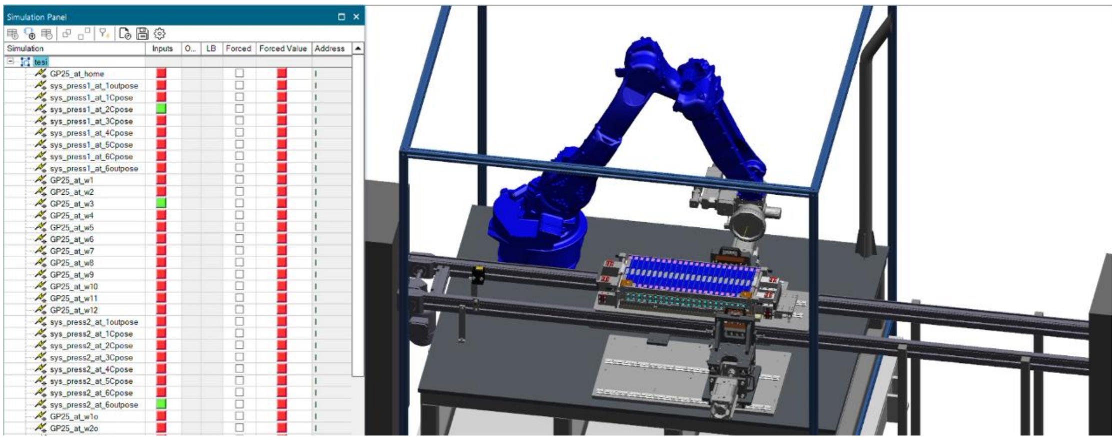


Figure 68: Boolean signals during cell simulation

In Process Simulate, the input and output logic signals associated with the assets are not limited to representing exchanges within the virtual model, but can also be connected to an external control system, such as a real or virtual PLC.

In the restricted virtual simulation setup, signals are generated and managed exclusively within the software environment: in this case, they represent the operating conditions of different entities, such as reaching a location, ending an operation, or the availability of a resource. This approach allows validating the logic of cell operation and the correct sequence of events.

In other cases, Process Simulate can be connected directly to a programmable logic controller through communication protocols such as OPC or PLCSIM Advanced and the logic signals defined in the simulation are mapped to the PLC tags, allowing a bidirectional interaction between the virtual model and the control system. In this way, it is possible to verify in real time the consistency between the logic of the PLC program and the operating behavior of the cell, simulating the same conditions that will arise in the plant.

This integration makes it possible to move from a simple analysis of sequences and movements to a virtual commissioning phase, in which the automation logics are validated.

The activity carried out in Process Simulate ends with the definition and verification of the correct functioning of the logical signals associated with the different resources of the cell. The entire system is tested in a virtual environment, simulating the management of the input and output signals and verifying the logical consistency of the transitions between the various operational phases.

However, it is not possible to proceed with the direct connection between Process Simulate and a programmable logic controller (PLC) due to performance limitations of the available hardware, which doesn't allow for stable simulation execution.

As a result, the next step of integration with the PLC is left as the future phase of completion of virtual commissioning.

At the same time, the corresponding PLC logic is developed and tested to ensure compatibility between the signal structure in Process Simulate and the control program.

[22]

8. PLC LOGIC DESIGN

The PLC code is developed using CODESYS V3.5 SP16 Patch 3 and represents the operating logic of the welding station, laying the foundations for future virtual commissioning activities.

A central aspect of the project is the use of the same variables used in simulation in Process Simulate, in order to simplify the integration between the two software environments and ensure greater clarity in understanding the system.

The focus is mainly on the management of the robotic station, with particular reference to the operations carried out and the I/O signals necessary for the correct functioning of the system. On the other hand, the management logic of transport, lifters and the manual station, nor the control of the related sensors, are not developed.

The project is organized in different functional diagrams, which allow the various parts of the system to be clearly structured and modulated, promoting better readability and maintenance of the code.

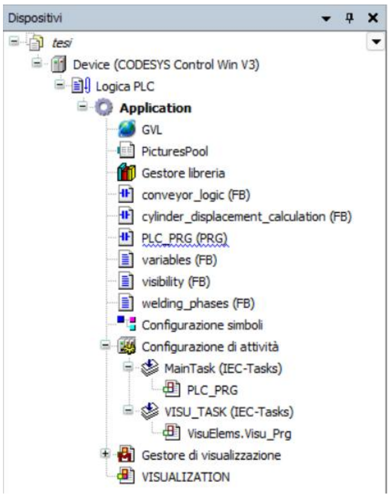


Figure 69: CODESYS project

The first diagram to be analysed is the one defined as an interface for the simulation software; it contains the global variable list (*GVL*) of the program, such as I/O signals, and specifies their type. In this work, the variables are Boolean.

The following image shows the key variables of the logic that deal with the start and stop of the system and the management of emergencies.

```
START: BOOL;      // start
STOP: BOOL;       // stop
EMERGENCY: BOOL;  // emergency
RESTART: BOOL;    // re-start
```

The interface signals between the programs for connecting the logic to the digital model of the system are now listed.

```
// Robot
GP25_at_home: BOOL;
GP25_at_w1, GP25_at_w2, GP25_at_w3, GP25_at_w4, GP25_at_w5, GP25_at_w6,
GP25_at_w7, GP25_at_w8, GP25_at_w9, GP25_at_w10, GP25_at_w11, GP25_at_w12 : BOOL;
GP25_at_w1o, GP25_at_w2o, GP25_at_w3o, GP25_at_w4o, GP25_at_w5o, GP25_at_w6o,
GP25_at_w7o, GP25_at_w8o, GP25_at_w9o, GP25_at_w10o, GP25_at_w11o, GP25_at_w12o : BOOL;

GP25_mtp_home: BOOL;
GP25_mtp_w1, GP25_mtp_w2, GP25_mtp_w3, GP25_mtp_w4, GP25_mtp_w5, GP25_mtp_w6,
GP25_mtp_w7, GP25_mtp_w8, GP25_mtp_w9, GP25_mtp_w10, GP25_mtp_w11, GP25_mtp_w12 : BOOL;
GP25_mtp_w1o, GP25_mtp_w2o, GP25_mtp_w3o, GP25_mtp_w4o, GP25_mtp_w5o, GP25_mtp_w6o,
GP25_mtp_w7o, GP25_mtp_w8o, GP25_mtp_w9o, GP25_mtp_w10o, GP25_mtp_w11o, GP25_mtp_w12o : BOOL;

GP25_ext: BOOL;
GP25_ret: BOOL;

GP25_mtp_extend: BOOL;
GP25_mtp_retract: BOOL;

// Clamping system 1
sys_press1_at_1outpose, sys_press1_at_1pose, sys_press1_at_1Cpose,
sys_press1_at_2pose, sys_press1_at_2Cpose,
sys_press1_at_3pose, sys_press1_at_3Cpose,
sys_press1_at_4pose, sys_press1_at_4Cpose,
sys_press1_at_5pose, sys_press1_at_5Cpose,
sys_press1_at_6pose, sys_press1_at_6Cpose, sys_press1_at_6outpose : BOOL;

sys_press1_mtp_1outpose, sys_press1_mtp_1pose, sys_press1_mtp_1Cpose,
sys_press1_mtp_2pose, sys_press1_mtp_2Cpose,
sys_press1_mtp_3pose, sys_press1_mtp_3Cpose,
sys_press1_mtp_4pose, sys_press1_mtp_4Cpose,
sys_press1_mtp_5pose, sys_press1_mtp_5Cpose,
sys_press1_mtp_6pose, sys_press1_mtp_6Cpose, sys_press1_mtp_6outpose : BOOL;

// Clamping system 2
sys_press2_at_1outpose, sys_press2_at_1pose, sys_press2_at_1Cpose,
sys_press2_at_2pose, sys_press2_at_2Cpose,
sys_press2_at_3pose, sys_press2_at_3Cpose,
sys_press2_at_4pose, sys_press2_at_4Cpose,
sys_press2_at_5pose, sys_press2_at_5Cpose,
sys_press2_at_6pose, sys_press2_at_6Cpose, sys_press2_at_6outpose : BOOL;

sys_press2_mtp_1outpose, sys_press2_mtp_1pose, sys_press2_mtp_1Cpose,
sys_press2_mtp_2pose, sys_press2_mtp_2Cpose,
sys_press2_mtp_3pose, sys_press2_mtp_3Cpose,
sys_press2_mtp_4pose, sys_press2_mtp_4Cpose,
sys_press2_mtp_5pose, sys_press2_mtp_5Cpose,
sys_press2_mtp_6pose, sys_press2_mtp_6Cpose, sys_press2_mtp_6outpose : BOOL;

sys_press_ext: BOOL;
sys_press_ret: BOOL;

sys_press_mtp_extend: BOOL;
sys_press_mtp_retract: BOOL;

// Sensors
manual_pos1: BOOL;
manual_pos2: BOOL;
battery_presence: BOOL;
work_pos1: BOOL;
work_pos2: BOOL;

conveyor_ON: BOOL;
conveyor_BACK: BOOL;
conv_ext: BOOL;
conv_ret: BOOL;
```

There are variables that will not be necessary to connect the PLC code directly with Process Simulate but used in this project in which the plant is simulated by a simpler system, which only serves to correctly manage input/output signals and test the written logic, created in FluiSIM 6.

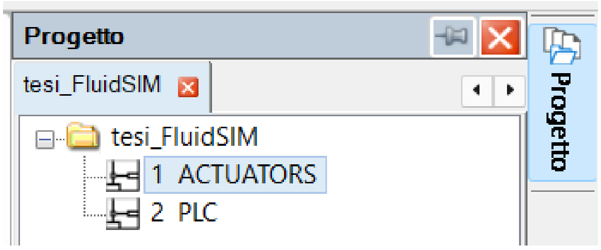


Figure 70: FluidSIM project

The entire system is schematized with the movements of three pneumatic cylinders inserted in the *ACTUATORS* sheet of the FluidSIM project.

In this diagram are inserted three double-acting cylinders:

- *conveyor-cylinder* schematizes the movement of the conveyor transport system. Its limit switches are *c0* and *c1* and the encoder, that gets precisely the position's value, is the *encoder_conv;*
- *robot-cylinder* schematizes the movement of the welding robot in the cell. Its limit switches are *r0* and *r1* and the encoder that gets precisely the position's value is the *encoder_robot*;
- *pusher-cylinder* schematizes the movement of the clamping_systems. Its limit switches are *p0* and *p1* and the encoder that gets precisely the position's value is the *encoder_pusher*.

The cylinders are managed by 5-2 valves that are switched by solenoids *c+, c-, R+, R-, P+* and *P-*.

The flow of the compressed air is governed by 2-2 NC valves that are opened by pneumatic signals and close automatically by spring repositioning.

These valves open the channels according to the *open_channels* solenoid signal through a 3-2 NC valve.

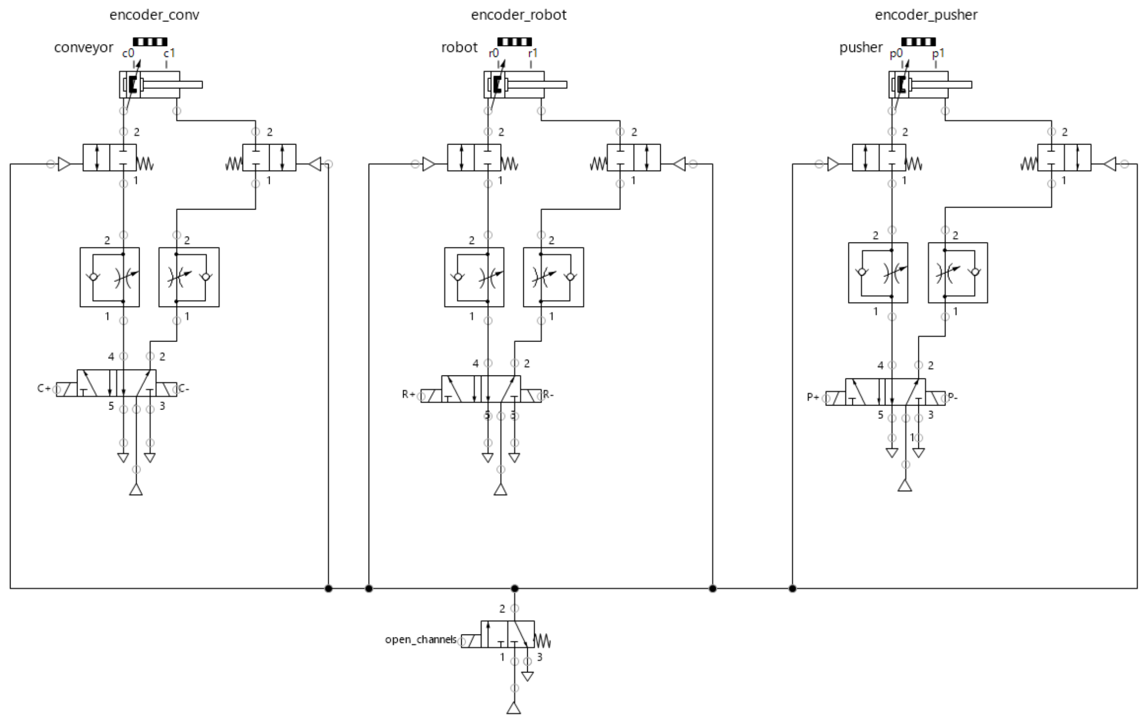


Figure 71: Actuators diagram in FluidSIM project

The simplification of the entire complex cell designed in Process Simulate with the use of three pneumatic cylinders is based on this basic concept: each movement (outstroke or instroke) of the cylinder in FluidSIM corresponds to a corresponding movement of the resource in Process Simulate (conveyor, robot or clamping systems).

For example:

1) *robot-cylinder* moves outstroke = GP25 goes to first welding point
2) *r1* signal = GP25 at first welding point
3) *robot-cylinder* moves instroke = GP25 goes to second welding point
4) *r0* signal = GP25 at second welding point
5) *robot-cylinder* moves outstroke = GP25 goes to third welding point
6) *r1* signal = GP25 at third welding point
7) *robot-cylinder* moves instroke = GP25 goes to fourth welding point
8) *r0* signal = GP25 at fourth welding point
9) and so on …

The reasoning is similar for the conveyor system, which is schematized with the *conveyor-cylinder*, and for the clamping systems, both of which are simplified with the *pusher-cylinder*.

The other diagram defined in FluidSIM is *PLC* where there are the PLC cards.

The inputs of the PLC are the limit switches signals *c0, c1, r0, r1, p0* and *p1*. The outputs of the PLC are the solenoids that switches the valves on the *ACTUATORS* diagram: *c+, c-, R+, R-, P+, P-* and *open_channels*.

There is also the encoder of the *conveyor-cylinder* connected to the 'Analog OUT' blocks of FluidSIM, used to transmit data to CODESYS.

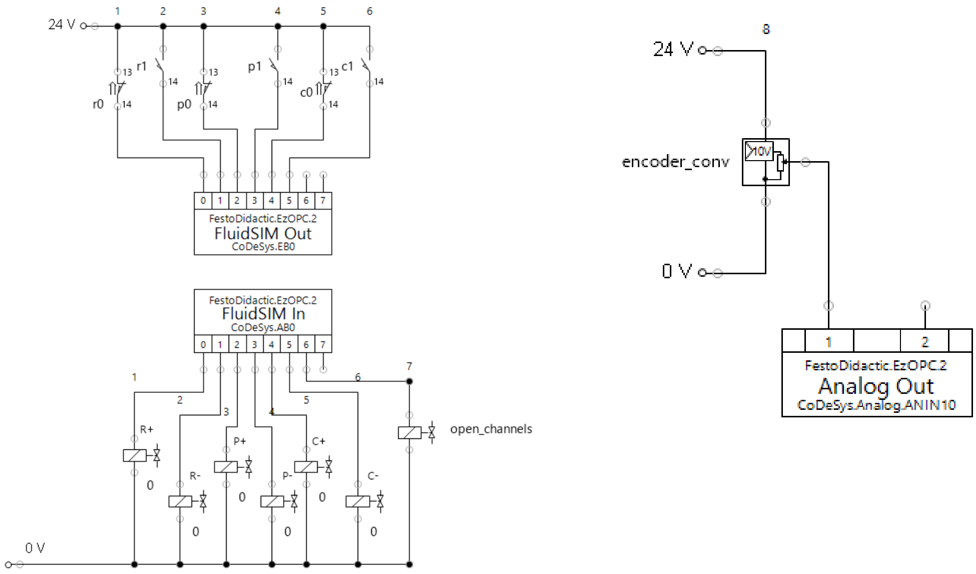


Figure 72: PLC diagram in FluidSIM project

It is inserted also the block that, in simulations, plots the positions on time of the pistons.

It is an important instrument to monitor and visualize development.

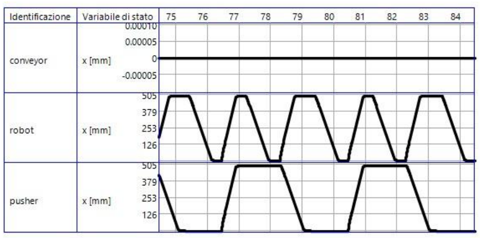


Figure 73: Cylinders positions plot

Once the system built in FluidSIM is explained, the PLC logic written in CODESYS can be analysed, starting by describing the lines of code that deal with the variables just mentioned and the management of the I/O signals between CODESYS and FluidSIM.

```
VAR
    EB0 AT%IB0 :BYTE;
    AB0 AT%QB0 :BYTE;
END_VAR
```

With these lines of code, the variables on CODESYS are connected with the input and output bytes signals of the PLC, in particular, *EB0* represents the signals that come from the limit switches of the cylinders to the input of PLC, while the output signals that are sent by the controller, such as the variable *open_channels* or the solenoids signals for the valve switching, are managed by the byte *AB0*.

The "*variables*" diagram of the CODESYS project is now described.

In this sheet the global variables of the program are connected to the byte's signals coming from FluidSIM.

When the project is connected to the Process Simulate software, this diagram can be deleted with due care.

The robot logic is inserted as an example of structure, but the same pattern is used for the other resources as well.

```
// -- ROBOT GP25 -- //
// Limit switches

GVL.GP25_ext := EB0.1;
GVL.GP25_ret := EB0.0;

GVL.GP25_at_w1:= GVL.GP25_ext;
GVL.GP25_at_w2:= GVL.GP25_ret;
GVL.GP25_at_w3:= GVL.GP25_ext;
GVL.GP25_at_w4:= GVL.GP25_ret;
GVL.GP25_at_w5:= GVL.GP25_ext;
GVL.GP25_at_w6:= GVL.GP25_ret;
GVL.GP25_at_w7:= GVL.GP25_ext;
GVL.GP25_at_w8:= GVL.GP25_ret;
GVL.GP25_at_w9:= GVL.GP25_ext;
GVL.GP25_at_w10:= GVL.GP25_ret;
GVL.GP25_at_w11:= GVL.GP25_ext;
GVL.GP25_at_w12:= GVL.GP25_ret;

GVL.GP25_at_w1o:= GVL.GP25_ext;
GVL.GP25_at_w2o:= GVL.GP25_ret;
GVL.GP25_at_w3o:= GVL.GP25_ext;
GVL.GP25_at_w4o:= GVL.GP25_ret;
GVL.GP25_at_w5o:= GVL.GP25_ext;
GVL.GP25_at_w6o:= GVL.GP25_ret;
GVL.GP25_at_w7o:= GVL.GP25_ext;
GVL.GP25_at_w8o:= GVL.GP25_ret;
GVL.GP25_at_w9o:= GVL.GP25_ext;
GVL.GP25_at_w10o:= GVL.GP25_ret;
GVL.GP25_at_w11o:= GVL.GP25_ext;
GVL.GP25_at_w12o:= GVL.GP25_ret;

// Actions

IF GVL.GP25_mtp_w1 OR GVL.GP25_mtp_w3 OR GVL.GP25_mtp_w5 OR GVL.GP25_mtp_w7 OR GVL.GP25_mtp_w9 OR GVL.GP25_mtp_w11 OR
GVL.GP25_mtp_w1o OR GVL.GP25_mtp_w3o OR GVL.GP25_mtp_w5o OR GVL.GP25_mtp_w7o OR GVL.GP25_mtp_w9o OR GVL.GP25_mtp_w11o THEN
    GVL.GP25_mtp_extend := TRUE;
    GVL.GP25_mtp_retract := FALSE;
END_IF;

IF GVL.GP25_mtp_w2 OR GVL.GP25_mtp_w4 OR GVL.GP25_mtp_w6 OR GVL.GP25_mtp_w8 OR GVL.GP25_mtp_w10 OR GVL.GP25_mtp_w12 OR
GVL.GP25_mtp_w2o OR GVL.GP25_mtp_w4o OR GVL.GP25_mtp_w6o OR GVL.GP25_mtp_w8o OR GVL.GP25_mtp_w10o OR GVL.GP25_mtp_w12o THEN
    GVL.GP25_mtp_extend := FALSE;
    GVL.GP25_mtp_retract := TRUE;
END_IF;

AB0.0 := GVL.GP25_mtp_extend;
AB0.1 := GVL.GP25_mtp_retract;
```

The *EB0.0* signal, which represents the limit switch *r0* (i.e. *robot-cylinder* instroke), is assigned the global variable *GVL.GP25_ret*, i.e. retracted, while the *EB0.1* signal, which represents the limit switch *r1* (outstroke), is assigned the global variable *GVL.GP25_ext*, i.e. extended.

Having to simulate with these two variables all the different positions assumed by the robot during welding, the variables representing the 24 positions of robot are associated with *GVL.GP25_ret* and *GVL.GP25_ext*. This is done because, by eliminating these matches, the code is already written according to the 24 different variables coming from Process Simulate.

A very similar reasoning is also applied to the output signals: *AB0.0* which is the node connected to *R+*, the solenoid that manages the outstroke of the *robot-cylinder*, is associated with the global variable of the system *GVL.GP25_mtp_extend*, while *AB0.1*, which corresponds to *R-*, binds to *GVL.GP25_mtp_retract*.

To keep the code general with the Process Simulate's variables already present, *GVL.GP25_mtp_extend* and *GVL.GP25_mtp_retract* are associated with the signals of all the different movements that are needed to perform in the virtual cell with IF conditions constructed through chains of OR logic.

Particular attention can be dedicated to the *AB0.6* signal which corresponds to the *open_channels* solenoid; it allows the flow of compressed air to the entire FluidSIM system. It is connected to the *run* variable of the project that will be described later.

```
AB0.6 := PLC_PRG.run;
```

The main part of the program is written in *PLC_PRG* diagram where the general structure of the code is managed, in Ladder Diagram language.

In addition to recalling the various function blocks present in the project, activated by the right signals, the fundamental variables for the operation of the system are defined, such as *run, stop, emergency*.

The cell is designed to start with a *START* signal, coming from the operator panel (HMI), only if it is not in emergency conditions, while, in a resolved emergency situation, the cell can restart by pressing the *RESTART* button. This logic defines the states of the *run* and *emergency* variables. The emergency condition is simulated in this work by means of an HMI button, which, when pressed, alarms the system, stopping it instantly.

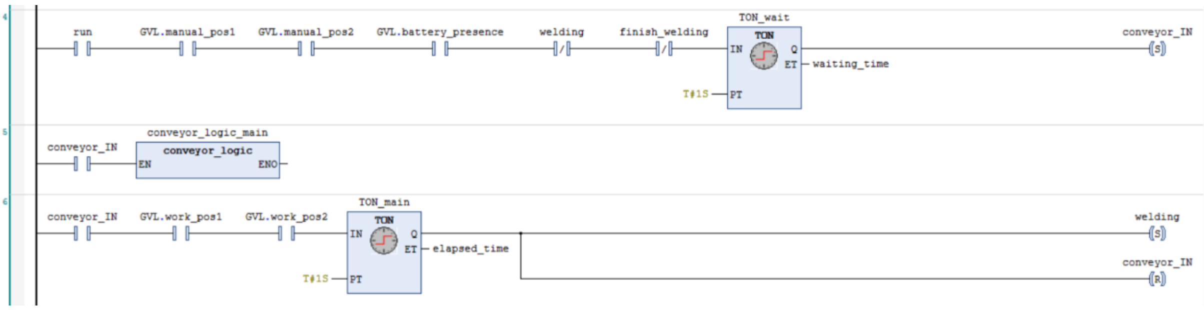
In the HMI there are lights that inform the operator about the status of the machine, whether it is in *run, emergency* or *stop*.

The stop condition is designed to force the system to finish the battery it is welding and then stop, i.e., by pressing the *STOP* button, the machine will finish machining the piece in the station which will be the last of that cycle; this is done thanks to the set of the Boolean variable *last_cycle*.

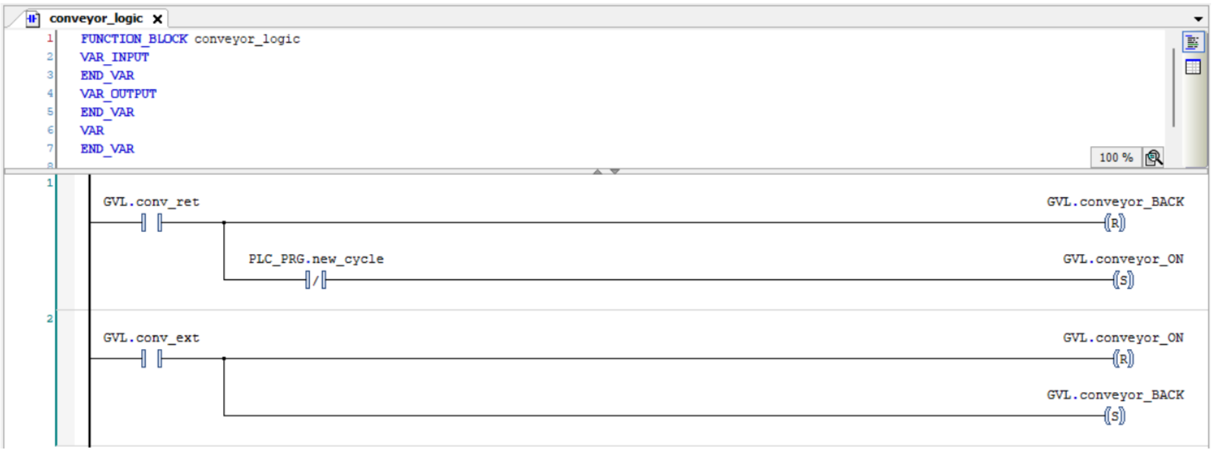
The HMI also includes a display that shows the number of welded battery packs since the first start of the machine and a button for counter resetting, which is pressed at the operator's discretion.

Figure 74: HMI

Once the machine is started, by pressing *START*, and after the positive outcome of the pallet and battery presence check, the *conveyor_IN* variable is set. In this way, the transport system brings the pallet to the welding position and, upon recognition of the presence signals, the *welding* variable is activated. It enables the process of the robot and the laser head.



The *conveyor_logic* functional block is very simple: it enables global variables that connect to FluidSIM's *C+* and *C-* solenoids for piston outstroke and instroke.



The *welding* variable enables entry to the *welding_phases* function block where the robot operations are handled, which means that the conditions for the GP25 and clamping systems movements are written.

In the code, the sequential management of the automatic welding cycle, divided into several phases, is implemented in Structured Text language. The operation is based on a step-by-step logic and the progress of the process is function of position signals and control variables.

When a new cycle is started, detected by the variable *new_cycle*, the program resets the step counter and the end-of-cycle variable (*finish_welding* := FALSE). Once initialized, the process management takes place within a CASE structure, in which each value of the step variable represents a specific phase of the welding cycle.

When the welding variable is activated, the sequence begins with the robot moving to the first working position (*w1*). Each time the system reaches the required position, it is verified through signals such as *GVL.GP25_at_wX* and *GVL.sys_press1_at_XCpose*, the clamping systems are activated, the motion variables (*GVL.GP25_mtp_wX*) are updated, and the step value is incremented to move to the next step.

The logic continues in a cyclical way: at each stage, the system verifies that it has arrived in the correct position and, if so, updates the variables that control both the movement of the welding unit and the positions of the pressers. After a series of twelve welding positions on the first side (managed by clamping system 1) and another twelve on the second side (managed by clamping system 2), the program reaches the last step.

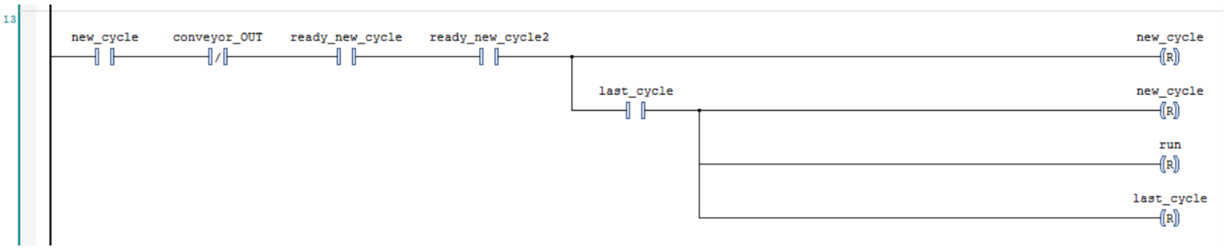
In the last phase, all outputs are deactivated, the pressers are released and the variable *finish_welding* := TRUE is set, which signals the end of the cycle and interfaces with the main program outside the function block.

```
CASE step OF

0:
    IF welding THEN
        GVL.GP25_mtp_w1 := TRUE;
        GVL.sys_press1_mtp_1Cpose := TRUE;

        step := 1;
    END_IF
1:
    IF GVL.GP25_at_w1 AND GVL.sys_press1_at_1Cpose THEN
        w1 := TRUE;
        clamp1_1 := TRUE;

        GVL.GP25_mtp_w1 := FALSE;
        GVL.GP25_mtp_w2 := TRUE;

        step := 2;
    END_IF

2:
    IF GVL.GP25_at_w2 AND GVL.sys_press1_at_1Cpose THEN
        w1 := FALSE; w2 := TRUE;

        GVL.GP25_mtp_w2 := FALSE;
        GVL.GP25_mtp_w3 := TRUE;

        GVL.sys_press1_mtp_1Cpose := FALSE;
        GVL.sys_press1_mtp_2Cpose := TRUE;

        step := 3;
    END_IF
```

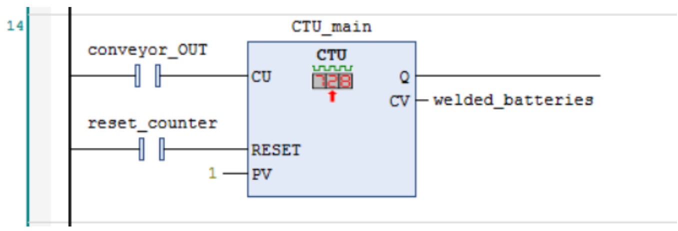
```
23:
    IF GVL.GP25_at_w11o AND GVL.sys_press2_at_1Cpose THEN
        w10o := FALSE; w11o := TRUE;
        clamp2_5 := FALSE; clamp2_6 := TRUE;

        GVL.GP25_mtp_w11o := FALSE;
        GVL.GP25_mtp_w12o := TRUE;

        step := 24;
    END_IF

24:
    IF GVL.GP25_at_w12o AND GVL.sys_press2_at_1Cpose THEN
        w11o := FALSE; w12o := TRUE;

        timer_weld(IN := w12o, PT := T#1S);

        IF timer_weld.Q THEN
            GVL.GP25_mtp_w12o := FALSE;

            GVL.sys_press2_mtp_1Cpose := FALSE;

            step := 25;
        END_IF
    END_IF

25:
    w12o := FALSE;
    clamp2_6 := FALSE;

    finish_welding := TRUE;

END_CASE
```

Once the welding is finished, in *PLC_PRG*, the pallet return logic is managed through the *conveyor_OUT* phase which makes the program enter the functional block already mentioned *conveyor_logic*.

Once the piston is outstroke, representing the movement of the conveyors, the variable *new_cycle* is set, which enables the cyclical repetition of the operation on another battery pack to be welded, if and only if *STOP* was not pressed and therefore that was the last piece to be processed.



In the ladder network 14, a *CTU counter* is implemented that is used to count the number of welded batteries and it is based on the variable *conveyor_OUT*.



In the central program and throughout the CODESYS project, logics are included that manage the correct functioning of the simulation, such as auxiliary set reset variables that define intermediate phases of the operational flow or lines of code dedicated to the reset of the variables and the correct configuration of the system.

In addition, there are functional blocks in which the movements and visibilities of objects are programmed, for a simple and clear visual understanding of the operation: *cylinder_displacement_calculation* and *visibility* function blocks.

In the *VISUALIZATION* diagram of the project, a schematized top view of the welding cell is constructed for the simulation and validation of the logic written in the program.

Figure 75: Visualization diagram in CODESYS project

In the project, a connection is made between the automation program developed in CODESYS and the pneumatic system modelled in FluidSIM, using EzOPC, the proprietary communication system from Festo Didactic. This tool allows FluidSIM to communicate with PLC simulators such as CODESYS and therefore allows verifying the correct functioning of the control logic, testing the program sequences and identifying any logic or synchronization errors, in a completely virtual context, without the need for a PLC or a real system.

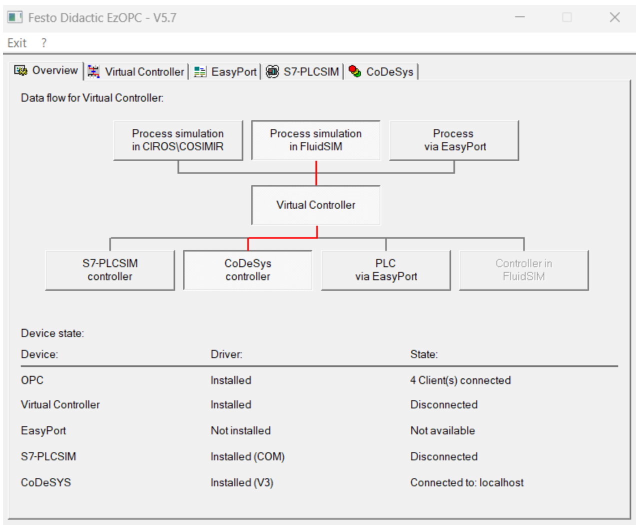


Figure 76: Software connection window

[23]

9. CONCLUSION AND FUTURE WORKS

The work carried out develops the preliminary design of a laser welding cell for busbars intended for battery packs used in electric vehicles.

The activity focuses on the conceptual and functional definition of the station, with the aim of proposing a standard company solution characterized by modularity, flexibility and customizability according to different production needs.

Through three-dimensional modelling and the subsequent implementation of the digital model in Siemens Tecnomatix Process Simulate, it is possible to create a digital model of the welding cell; this makes it possible to analyse the behaviour of the system in a virtual environment, evaluate the feasibility of the proposed solutions and verify critical aspects such as geometric interferences, the reachability of the robot and the operational sequence of the work cycle.

The definition of kinematics and operations makes it possible to realistically simulate the movements of resources and the flow of components, providing a concrete basis for the optimization of cycle times and for future integration with a real control system.

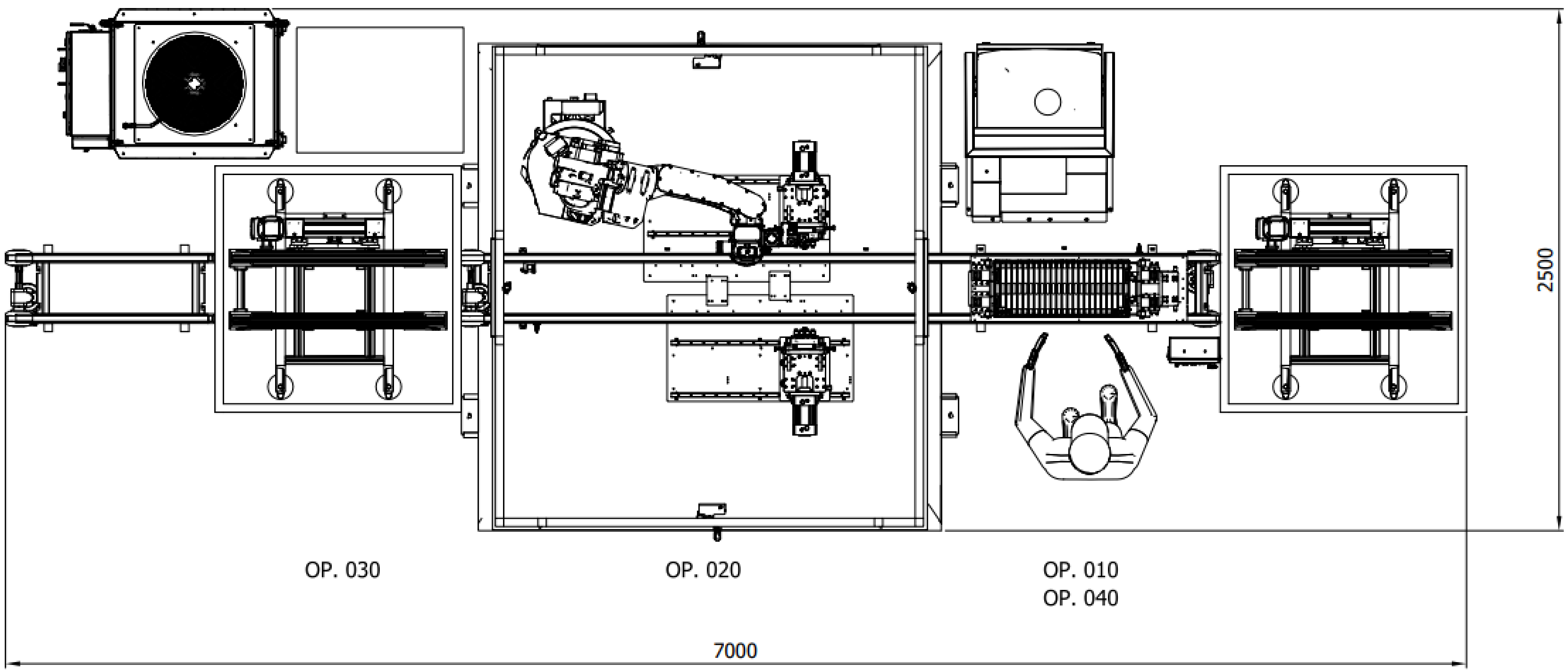
At the same time, the PLC program that manages the control logic, the input/output variables and the sequence of operations is developed in CODESYS, thus preparing the model for a subsequent virtual commissioning phase.

The result obtained is a complete digital model of the laser welding cell, accompanied by a functional layout and a dynamic simulation capable of faithfully representing the behaviour of the system and this demonstrates the effectiveness of methodologies based on the digital twin approach, which anticipates the verification of mechanical, kinematic and control solutions in a virtual environment.

In the future, the work can be further developed by connecting the simulated model to the PLC program in real time, thus completing the virtual commissioning phase and allowing the complete validation of the automation logic before the physical construction of the cell.

This approach represents an important step towards the widespread adoption of advanced digital techniques in the design of production systems, in line with the principles of Industry 4.0.

LASER WELDING CELL



OP.010 = Battery pack loading
OP.020 = Laser welding
OP.030 = Temperature check
OP.040 = Battery pack unloading

FORMATO A3

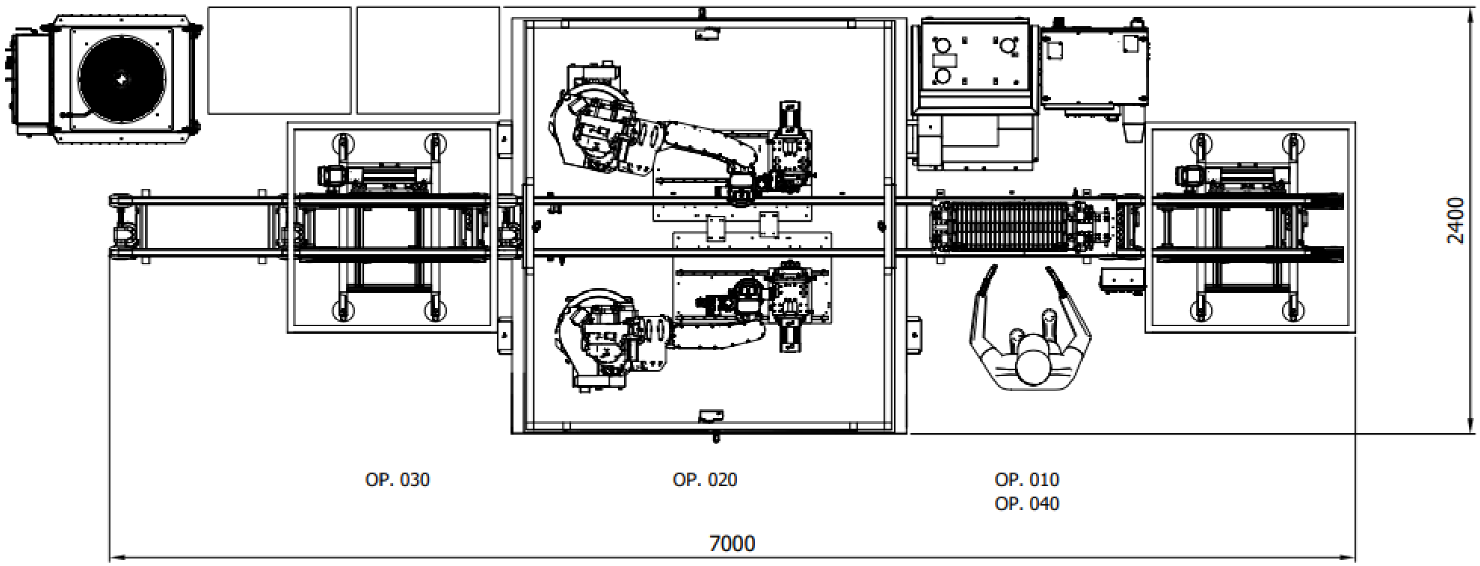
Filename	Laser welding cell V1
Offerta n.ro	-
Descrizione	Standard laser welding cell for busbars in EV battery pack
Data	29/10/2025
Produzione oraria	65 [p/h]
Tempo ciclo	55 [s]
Efficienza	85 [%]
Scala	1:20

BONETTO AUTOMATION

Giorgia Gennero

LASER WELDING CELL

stat. 010



OP.010 = Battery pack loading
OP.020 = Laser welding
OP.030 = Temperature check
OP.040 = Battery pack unloading

FORMATO A3

Filename	Laser welding cell V2
Offerta n.ro	-
Descrizione	Standard laser welding cell for busbars in EV battery pack
Data	29/10/2025
Produzione oraria	120 [p/h]
Tempo ciclo	30 [s]
Efficienza	85 [%]
Scala	1:25

BONETTO AUTOMATION

Giorgia Gennero

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