Bachelor Degree Project

UNIVERSITY OF SKÖVDE

EMULATION OF A MANUFACTURING PROCESS
Focus on maintenance and operator training

Bachelor Degree Project in Automation Engineering
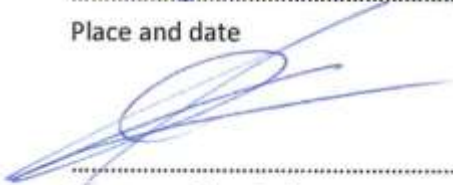30 ECTS
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Certify of Authenticity

Submitted by Aitor Tudero Lorenzo and Julen Azkue Oria to the University of Skövde as a Bachelor degree thesis at the School of Technology and Society. We certify that all material in this thesis project which is not our own work has been identified.

Högskolan I Skövde   02/06/2017

Place and date

Signature **Aitor Tudero**

Signature **Julen Azkue**

Preface

There are so many people to thank for helping us during last semester while this thesis has been developed. So many of them have also made our one-year long stay in Skövde a lot easier than we thought it was going to be. In this preface, we will try to cover all the bases without being too long.

First of all, we would like to sincerely thank Volvo Group Trucks Operations for the great opportunity of working on this project.

Then, we would like to appreciate our company supervisors work. Anna Sandberg has answered all the doubt we had during the project, as well as provided us with all the necessary elements to accomplish this thesis work.

To Mikel Ayani, our supervisor at the University of Skövde, your help in every aspect has been imperative to the completion of this thesis. Your support and guidance have been vital to us keeping developing and performing this project. If you were not here we might be still be trying to disable the security of the PLC program…

We would also like to acknowledge our project partners for the assistance and cooperation. They had been really helpful for the completion of the field work, as well as the literature research.

Last but not least, an even more heartfelt message of thanks is offered to our parents. Thank you! You have made this whole year experience possible. All the knowledge we have gained, the good and not so good experiences, and the completion of this project it is all thanks to you.

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Abstract

Having well-trained operators is a crucial need for Volvo Group Truck Operations (GTO). Mistakes from the factory staff may cause the production line to stop, and lead to economic losses. For this reason, Volvo GTO has decided to investigate the possibility of creating an emulation model from the production line and using it to train operators and maintenance personnel. The aim of this thesis is to develop an Operator Training Station (OTS) for the OP035 of the Volvo GTO Production Line 6. In the first part, a literature research was conducted, from which the authors gained insight into related fields such as emulation, virtual environments, and operator training. After that, an emulation model of the OP035 was created using some hardware from the factory. The real PLC program was analyzed and then modified in order to implement it to the emulation model. Then, communications were established between the different parts; emulation model and PLC program. Finally, a research of the common failures and problems of the production line was carried out, with the aim of being able to reproduce them in the Operator Training Station. Once the OTS was implemented, several tests had undergone to validate its behavior. These experiments verified that the emulation model was an accurate representation of the real system and validated its appropriateness for the operator training application.

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Abbreviations and terminology

Continuously a point will be made regarding the abbreviations and technical terminology used in this report:

Bit   Binary Digit; Is the basic information unit in a computer. A bit can only have two values: 1 or 0.

Byte   Consists of 8 bits.

Double Word Variable type that contains 32 Bits

FPS   Frames Per Second; the main unit to measure device display performance.

HMI   Human Machine Interface; Touchscreen that is used by the operators to introduce data and read information from the different machines.

I/O   Inputs and Outputs; Different peripherals connected to the controller.

Node   In communications, each of the devices connected to the network.

OPCUA   OLE for Process Control Unified Architecture

PLC   Programable Logic Controller; A controller used in industrial environments to control different elements in the factory.

RFID   Radio Frequency Identification; Device that uses electromagnetic fields to identify tags written in the pallets.

Word   Variable type that contains 16 bits

1   Introduction

The introduction is a summary of the background, purpose, and significance of the study. This first chapter will also explain the methodology that has been followed giving some information about sustainability.

1.1   Brief introduction about Volvo GTO

Volvo Group Truck Operations (GTO) is the truck industrial entity within the Volvo Group, one of the world's leading manufacturers of trucks, buses, construction equipment and marine and industrial engines. A powertrain production factory is located in Skövde, which is one of the biggest automotive foundries in the world. Powertrain production in Skövde manufactures diesel engines and engines components for different motors. The engines with the biggest popularity are the HDE13 and HDE16, which are heavy duty engines of 13 and 16 liters. The factory is divided into three processes; casting, machining and assembly. With a surface are of 265 000 m^2, employs around 2800 people.

1.2   Background

Volvo Group Truck Operations is a growing company, and the new foundry built in Skövde's powertrain production factory gives abundant proof of this. It was inaugurated in 2010 and produces cylinder heads using a casting method patented and developed by AB Volvo. From the cylinder head core production to the final inspection, each process must be absolutely perfect for producing a good engine. In this aspect, the operator training tasks are of critical importance. The continuous formation and training of operators will allow Volvo GTO to have a skillful and highly trained staff, leading to a high-quality production and progressive development of the brand. Furthermore, it will increase the security at the workplace and reduce the costs derived from human errors.

The current advantages in automation and virtual technologies might have a high impact in workers' education and skills. Volvo GTO Skövde wants to study the new trends in virtual manufacturing, and the value they could add for maintenance and operator training. By starting up a new project in emulation, Volvo wants to implement a training station in which operators can practice with a virtual copy of the real system in a risk-free environment.

1.3   Aim and Objective

The main objective of the project is to create a virtual twin of the production equipment, where operators will be able to test and train themselves, making sure they are ready enough to handle any situation in the real system. The created emulation model will be just a part of a process in the Volvo´s G2 foundry, specifically, the OP035. This project will bring several benefits to Volvo GTO, such as having efficient operators with less training, improving the productivity of the production line, and increasing the competitiveness of the brand in the market.

The operator training station must resemble as much as possible the real process. Thus, the operator trained with it will feel comfortable and prepared when set on to operate the real machine. Being immersive and realistic is another important fact of the project. Using the same PLC and HMI panel as

in the real production line will guarantee those facts, as well as making the emulation model more complete.

Another important point of the project is to be able to reproduce the real system's alarms and failures in the operator training station. While training in the station, operators will handle the usual and uncommon scenarios that could occur in the factory. This way, the operators can develop and test their skills to work under a situation of stress and considerable responsibility. It is important to integrate the same situations that trainees will have to face in the future. For a proper integration of the faults, a research will be carried out (interview operators from the factory and check the historical alarms of the operation) to determine which faults to include.

In order to make the optimal virtual twin of the system, some points must be considered:

- The functionality of the manufacturing process to be simulated.
- The optimal inclusion of the faults and alarms of the process.
- The integration of an HMI panel in order to make this simulator more realistic.
- The PLC program has to be properly managed and integrated into the model.

In summary, there are three main objectives or for this project:

1. Present an emulation model as similar as possible to the real process, including the HMI panel and the PLC from the real process.
2. Recreate the different failure scenarios and alarms of the real process in the model.
3. Create an operator training station that can be easily used to train staff.

1.1.1 Delimitations

When creating the virtual twin of the operation, some delimitations must be considered:

- Only a specific part of the manufacturing process will be simulated.
- The virtual twin created will be limited to the OP035 from the Volvo G2 foundry.
- The safety task of the control program of Volvo´s foundry will not be considered.
- The PLC and HMI programs used are provided by Volvo, as well as the licenses for the programs RSLogix5000 and Factory Talk.

1.1.2 Manufacturing process and material handling system

The virtual twin created will be a representation of the OP035, which is located at the new foundry of Volvo GTO in Skövde. The factory from Skövde produces cylinder blocks in its 44% of production, cylinder heads in 34%, break discs in 17% and flywheels in the rest 5%.

In the G2 foundry, cylinder heads for the engines are manufactured using an innovative casting method patented by Volvo AB. This method consists on a quick and controlled cooling of the cylinder head with a stable two parts mold (base and cover). First, the cores for the cylinder heads are created using 12 different sand cores. These parts are assembled automatically by robots and checked in a manual inspection. Then, the cores are coated in order to get nice surfaces on the casting. Before the molds are closed, there is a final inspection. Once the cores are ready, the raw material is melted using crucible furnaces and poured into the cores. After the sand and cylinder heads are separated, they are loaded into a pallet and given a heat treatment to reduce the residual stress. Finally, after the heat treatment, shaking, grinding and shot blasting, the cylinder heads are carefully inspected and ready to go.

OP035 is responsible for handling the cores that go out from the core shooting machines to the storage. It is composed of a double conveying line (two levels, one for each direction) and two ABB robots. Industrial robots, pick the cores that go out from the machines and place them onto the pallets in the conveying line. The upper-level conveyors, carry the full pallets to the storage, whereas the lower-level conveyors return the empty pallets to the indexing place. Different type of conveyors (lift tables, turntables, indexing tables…) and sensor are implemented in the system to ensure the proper functionality. There is also an ice cleaning system for the core's mold, vacuum cleaning system for the pallets and a core supervision station connected to this operation. Despite not having the same naming, these extra features (including the ABB robots) are considered as a part of the OP035 conveying zone.

1.4   Sustainable development

Sustainability is a widely used word that can have different meanings. The idea of sustainability has provoked diverse responses, however, all of them can be described as "attempts to combine growing concerns about a range of environmental issues with socioeconomics issues". (Hopwood, et al., 2005)

The first steps concerning sustainability were taken some years ago when in 1987 the U.N. General Assembly created the World Commission on Environment and Development (WCED). The aim of this commission was to examine global environment and development over the years to come, however they are seeking some problems to propose realistic solutions to the problem. Despite their inaccuracy, the WCED definition of sustainability has turned useful for having a global view of our planet's future (Mebratu, 1998):

"*Sustainable development is a development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*" (WCED, 1987)

Two key concepts were taking into account when formulating this quote:

- The concept of **needs.** Meaning that the essential needs of the world's poverty must be prioritized and given.
- The concept of the **limitations.** Based on the environment's ability to meet present and future needs, some limitations and restrictions must be imposed.

As stated by Hopwood, et al. (2005) the WCED report "stresses that humanity, whether in an industrialized or a rural subsistence society, depends for security and basic existence on the environment; the economy and our well-being now and in the future, need the environment".

An important outcome is that since WCED, many initiatives have been taken at local, national and global levels, with the purpose of facing different environmental challenges. In addition, some ideas have arisen concerning the economic model that affect directly the industrial organization. These ideas contrast with the "make, use, dispose" model of production that is currently being used, and propose a model based on cycles:
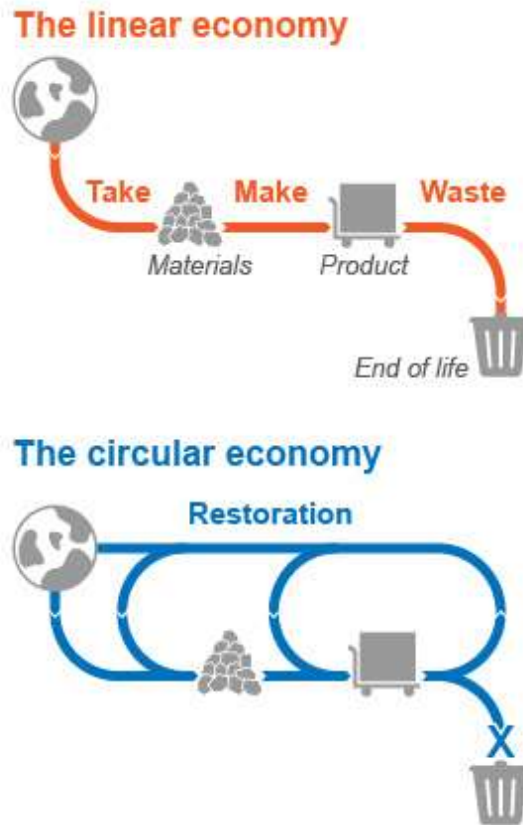
Figure 1. Closing loops of a circular economy model vs linear economy (Lupi, 2014)

As can be seen in *Figure 1* the circular economy is based on turning goods at the end of their service life into resources for others. This way, resource consumption and waste are considerably reduced, while the reprocessing of goods and materials saves energy and creates new jobs. "It would change economic logic because it replaces production with sufficiency: reuse what you can, recycle what cannot be reused, repair what is broken, and remanufacture what cannot be repaired" (Stahel, 2016). Recent studies of some European nations conclude that the implementation of a circular economy would have huge benefits such as reducing green-house-gas emissions by up to 70% and growing the workforce around 4% (Stahel, 2016).

In the automotive industry, taken steps towards remanufacturing or alternative business models based on the circular economy would be advantageous as well as beneficial. The dependence upon raw materials is a well-known fact of the automotive industry, and it is a considerable percentage of the annual budget (Claude, 2013). The company of Volvo is aware of this fact, and it is currently remanufacturing the gearboxes of some of their vehicles. Despite being cheaper than new parts, this process reduces the waste generated, the raw materials, energy and water used.
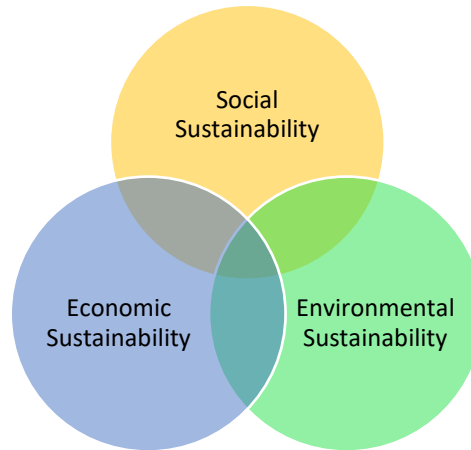
Figure 2. The three pilars of sustainability

As can be seen in *Figure* 2, sustainability is based on three main pillars; social, economic and environmental. For a system to be sustainable, each of the three pillars must be enforced. In this project, the relation and the possible outcomes it will have regarding sustainability have been studied and approached.

The implementation of an operator training station has no direct effect on the environment, however, it is directly connected with the economic and social fields. The main outcome from this system would be to have trained and skillful operators, ready to work efficiently in the factory and capable of doing their job in less time and with fewer errors.

Operators and maintenance people are key factors in the production line. Failures and critical situations in the process derive in stopped production and stressful situations for the personal. Every time the process is stopped, the company loses production which is translated into profits. A well-trained operator won't avoid machines from failing, but it will reduce the time needed to bring them back to operation. This fact will have a positive effect on the economy of the company, as the production will increase and the losses derived from machine failures will be reduced. In contrast, the increase in the production will not affect positively the environment, as it can increase the waste generated and the energy consumption.

The personal wellbeing of the operators will also be improved with the training station. As the operators will be better trained and prepared for their work, they will be able to relive their stress under critic scenarios. They will be comfortable at the workplace and feel confident about the solution for the different issues arising. Furthermore, as they are better prepared and have a broad knowledge, they might be better paid too, improving their economic wealth.

Finally, it must be considered that the simulation model implemented in the operator training station might have other utilities. The company could use this virtual twin of the manufacturing process to make some research with a focus on reduction of the energy consumption in the factory or the better usage of wastes generated. This application will enforce the environmental aspect of the company sustainability to a large extent.

1.5 Methodology

1.1.3 Principles

According to Bryman (2008), the methodology is the study of the methods that are to be employed. This is used to determine the progress that the project or work that is going to be developed will have. Thanks to the methodology, it is easier to follow a systematic architecture during the project. The methodology is vital when doing any work for any field, so as an unpredicted methodology will result in unpredicted results making possible wrong assumptions when finishing the project. The used method must be appropriate to its type of work and must fulfill the main objectives of the study ensuring a well-structured plan of work allowing enough and the correct amount of time for each part.

The paper "Selecting a Project´s Methodology" (Cockburn, 2000) defines 4 different principles that involve a methodology used in a project.

1. The first one refers to the size of the group of people involved in the project. The larger the group is, the larger will be the number of objects in the methodology. Although more than the number of people working depends on the number of roles which are distinguished in it.
2. The second one is related to complexity. It claims that the more complex the project is, the more complex will be the methodology involved and having a higher density of parts.
3. The third principle says that a minimum optimization of the methodology can make a big difference in the cost of the project. Updating of documents, designs and planning can be time and budget consuming, so a big importance is given to the first or base methodology. The critical point is that there is no way to determine what the problems will be, and is not possible to know how many people will be involved in it.
4. The fourth and the last principle, argues that face to face is by far the best method of communication. This way of communication makes the work much faster and easier, being able to reduce the costs and increasing the effectiveness of the project.

1.1.4 Research Method

Regarding the type of research to follow in the project, three different methods can be distinguished according to Bryman (2008):

1. Qualitative research: analyses a particular object not making any prediction. These methodologies use interviews and observations to collect information, providing contextual explorations of the subject that may be personal or culturally significant.
2. Quantitative Methods: this type of research is much more objective than the previous one. The researcher can make a hypothesis and validate it making several assumptions. This type of research is commonly used in science so as it deals directly with statistics.
3. Mixed methods: this researching method combines elements of both above mentioned. This method includes some interviews as contextual understanding, also including its results and facts. This type of research helps to gain different views and compare them statistically.

After analyzing the different research types, it can be clearly seen that this project follows a mixed research methodology. Regarding data involved in the project, it has been collected both quantitative and qualitative data. On the one hand, measurements taken in the factory, dimensions of the components in the drawings and position of each part in the layout are examples of the quantitative data. On the other hand, the interviews held with the operators and the observations made during the visits to the factory, have provided significant qualitative data.

1.1.5   Process

This project follows a sequential process, which is based on a waterfall model. According to Bassil (2012), "the Waterfall model defines several consecutive phases that must be completed one after the other and moving to the next phase only when its preceding phase is completely done".

Five different phases can be distinguished in this project (see *Figure 3*):
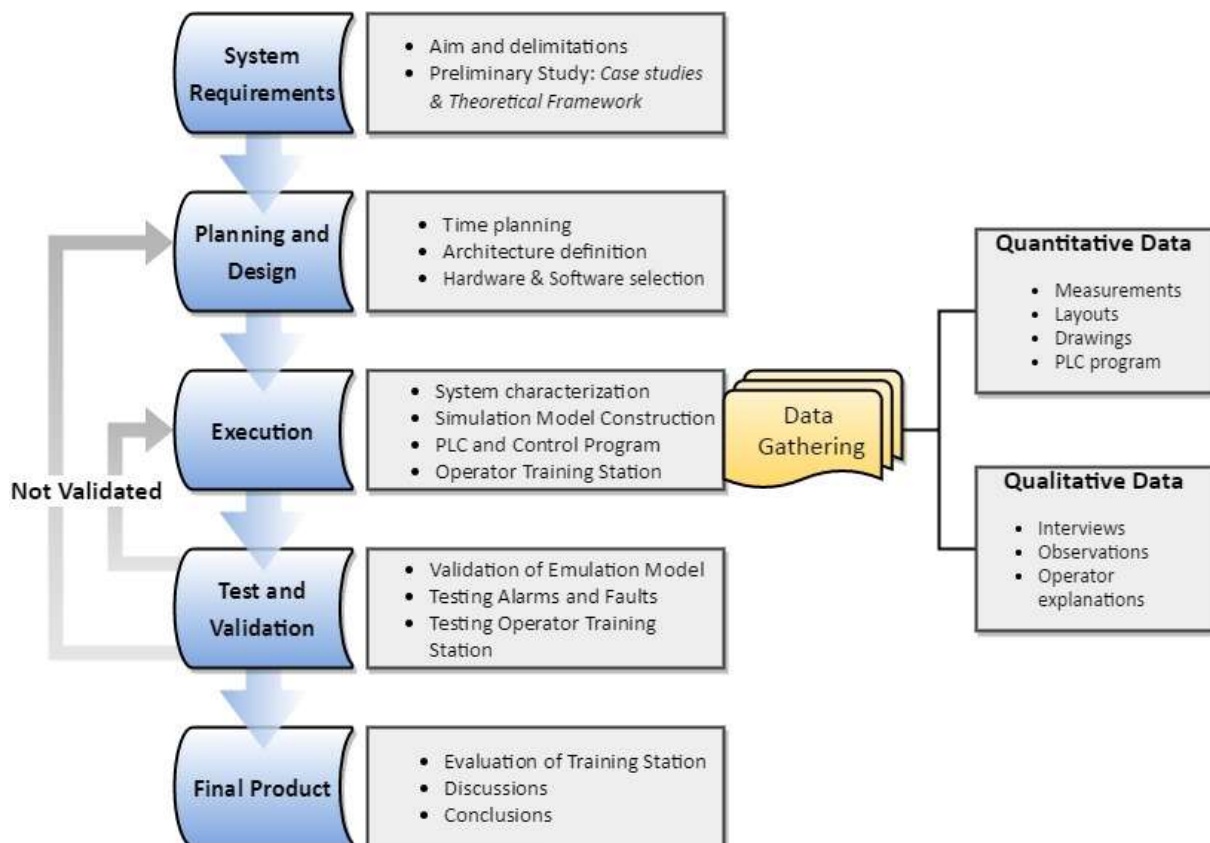
Figure 3. Methodology scheme

1. System requirements are the first step and involve the preliminary study of related projects and the definition of the requirements. Here is where all the understanding of the system must be done, asking for the needed material (layouts, 3D models…)
2. In the Planning and design phase, the overall system architecture is defined, the time planning is done and the hardware and software to be used are selected. In this project, it is decided to use Simumatik3D software to build the emulation model and the RSLogix and Factory Talk View from Rockwell Automation for running the control program on the PLC and HMI panel respectively.
3. At the Execution part, each part of the project is developed. In this case, it evolves to build the emulation model, then communicate it with the PLC program, and finally implement both parts into an operator training station. As mentioned before, this project has a mixed research method, which involves having both data to analyze; qualitative and quantitative. At this phase of the project, the data is gathered and studied.

4. Test and validation part consist of making sure that all the parts are working properly. This phase is where software or hardware errors that may happen are corrected, and the project requirements set on previous phases must be fulfilled. In case that some functionality is not properly validated, it might be necessary to come back to a previous phase, such as execution or design parts.

5. The final and fifth part finished when the product is validated and fully operative. Here must be evaluated if the model is representative of the real production system and if the project can be taken as concluded.

1.6   Disposition

Table 1 shows the document disposition. Distinct parts of the project are enlisted and a brief description is given. The type of reader who might be interested in each of the parts is also addressed.

Table 1. Recommended reader for each part

Chapter	Description	Reader recommendation
1. Introduction	It is shown the overall description of this project together with the objectives and delimitations.	All readers.
2. Frame of reference	It is useful to the reader put into context.	All readers.
3. Literature review	It is done a theoretical framework of related projects.	All readers.
4. System description	It describes the system needed to simulate with all its elements.	Readers who are interested in the different element of the system.
5. Simulation model construction	It describes the model created in Simutatik3D and all its single elements.	Readers who are interested in the emulation model.
6. Control program and communication interface	How the virtual PLC program works and how is the connection between different software done.	Readers with an interest in using the communications and the PLC program of the station.
7. Operator Training Station	It is listed the faults and alarms of the station, the software and hardware used, the user manual and the market survey	Readers interested in the hardware and the software, and the ones who need to learn how to use it.

8. Testing and validation of the emulation model	Four tests and experiments have been conducted both in the emulation model and PLC program.	All readers with interest in the testing of the station.
9. Evaluation of the Training Station	Evaluating the correct appearance and sequence of the virtual model.	Readers with an interest in the results.
10. Discussions	Discussions and future work.	All readers.
11. Conclusions	Conclusions achieved in this project.	All readers interested in the results obtained in this thesis.

Table 1 explains all the different parts of this report. In the first chapter, the reader is introduced to the project and the objectives and limitations are explained. In the following two chapters, it is immersed into related projects and the subject itself. Chapters four and five describes the system which is simulated together with the emulation model. In the sixth chapter, the Operator Training Station is defined with the implemented faults and alarms, the used software and hardware, the user manual and the possible integration in the actual market. In the seventh chapter, the simulator is tested and the last chapters conclude with the overall results, discussions, and conclusions of this thesis.

2   Frame of reference

The frame of reference gives a theoretical background to support the main subjects covered in this project

2.1   Production Systems

As defined by Groover (2001), a production system is the collection of people, equipment, and procedures of a company, organized in a determined way in order to accomplish the manufacturing operations. The production systems can be divided into facilities and manufacturing support systems. The factory, the equipment in there, and the way the equipment is organized conform the facilities of the production system. The procedures used by the company to manage the production and solve technical and logistical problems are known as the manufacturing support systems.

Shell & Hall (2000) mentions the fact that the Industrial Revolution spawned organized small manufacturing companies. In such situation, the key for manufacturing excellence was to be able and willing to communicate with every entity (people and equipment) from the company. However, as companies grew in size, it became more difficult to operate in such a manner. The invention of the digital computer had a huge impact on it and changed the situation completely. Out of this invention grew a wholly new concept, the computer integrated manufacturing system. It gave the possibility to automate and optimize the manufacturing. Despite the struggle to implement digital computer technology and significantly improve manufacturing's productivity, over the years the knowledge was developed and very substantial benefits were obtained:

- Improvement in product quality.
- Decreased lead times.
- Increased worker and customer satisfaction.
- Cost reduction.
- Increased productivity and production capacity.

2.2   Robots

An industrial robot is defined by Rembold, et al. (1993), as follows:

"An industrial robot is a general purpose programmable, multi-functional manipulator designed to move material, parts, or tools through specialized variable programmed motions for the performance of a variety of tasks."

The typical industrial robot has its base fixed in a pedestal and connected to other links. Usually, industrial robots are programmable in three or more axis. Despite the success of industrial robots in manufacturing applications, they are limited in sensory capabilities, flexibility, adaptability, learning, and creativity. (Shell & Hall, 2000)

Industrial robots most common applications are traditionally spot and arc welding and spray coating. However, the use of industrial robots for other applications is increasingly growing:

- In welding process, various metals are joined together by fusing them. Commonly used in fabrication industries.

- Material Handling applications consist on grasping and movements of work parts from one point to another (machine loading/unloading, palletizing…).
- In the spray coating process, paint or a coating thin layer is applied to an object, in order to have a smooth finish.
- Assembly means placing automatically two or more parts together. Some of the human assembly products cannot be assembled automatically by robots.
- In order to have a good product quality is necessary to have a reliable system to check the products. For that reason, automatic inspection and measurement processes are done. Human inspection systems have failed to reach "zero defects" goal.

2.3   PLC

Programmable Logic Controllers (PLC) are the improved substitutes of the electromechanical relay controllers. Introduced around 1970, they have brought lots of capabilities that the relay controllers lack. This evolution has been possible by advances in computer technology. (Groover, 2001)

Bolton (2015) defines a PLC as "a special form of a microprocessor-based controller that uses programmable memory to store instructions and to implement functions such as logic, sequencing, timing, counting, and arithmetic in order to control machines and processes." PLCs can be found in both process industries and discrete manufacturing; however, it is commonly associated with the machine, transfer lines, and material handling equipment control. The main advantages that using a PLC rather than conventional relays controllers offers are enlisted below (Groover, 2001):

- PLCs ease the programming process. It is simpler than wiring the relay control panel.
- PLCs can be reprogrammed. Notable advantage comparing to conventional controls that must be rewired to change its functionality.
- PLCs are more space efficient (take less floor space).
- Easier maintenance and greater reliability in PLCs.
- PLCs can do control functions that relay controllers cannot.

PLCs are composed of six main parts: processor unit, memory unit, power supply unit, I/O interface section, communications interface and the programming device. Programmable logic controllers have their basic components housed in a suitable cabinet, which is designed for industrial environments. (Bolton, 2015)

- Processor unit or central processing unit (CPU): It has the PLC program (instructions) stored in its memory. This unit interprets the input signals, carries out the control actions and sends the response signal to the outputs.
- The power supply unit: Converts the main AC voltage to low DC voltages levels for operating the PLC circuits.
- The programming device: Is used to enter the required program to the CPU memory.
- The memory unit: Is where the program containing instructions to be executed and the data from the input and output is stored.
- Input and Output modules: Information from external devices is acquired (inputs) and send to the processor. The processor communicates information to external devices through outputs

module. The inputs are usually sensors, whereas the output devices are commonly motor starter coils or similar devices.

- Communications interface: It usually has an Ethernet port, which is used to transfer and receive data in the PLC network.

2.4   Sensors

Having a good feedback from the system and being aware of the external changes that occur is a key factor when controlling an industrial process. For that purpose, there is a variety of measuring devices. "In general, a measuring device is composed of two components: sensors and transducers". (Groover, 2001)

Sensors respond to a specified physical input, providing a usable output (e.g. transducer are devices that convert a signal from one form to another different physical form. This way, all the sensors are transducers, but there are also other devices that can be transducers (e.g. motors converting the electrical input into rotational force). (Bolton, 2015)

For the proper function of the manufacturing process, changes occurring detect any changes and control the product flow in it. The following are some of the commonly used sensor types according to Bolton (2015):

- Mechanical switches: Detects the presence of pieces in a process. The piece presses against the switch and closes it.
- Proximity sensors: When an object is close enough to the sensor, it detects the object and sends an electrical signal.There is a wide range of technologies for this detectors, some of them only suitable for metallic parts.
- Photoelectric sensors: Use light-emitting diode and photodetectors. Can operate as transmissive type (the detected object breaks a beam of light) or reflective type (the object being detected reflects a beam of light).
- Encoders: Provides a digital output depending on the angular or linear displacement. There are two types of encoders; incremental encoders (track the cyclical signals when the encoder is rotated, loses position when power is removed) and the absolute encoders (reads the current position from code rings assembled in the device, maintains position information when turned off).
- Pressure sensors: Gives a proportional output to the difference pressure between two input ports. This type of sensors has many applications to fluids control, e.g. measuring the fluid flow.

2.5   Simulation

Banks (1998) defines simulation as the imitation of a real-world process or system over time. The main goal of the simulation is to describe and analyze the behavior of a real system. Due to its capabilities to solve many real-world issues, simulation has become an indispensable problem-solving methodology.

Underlying simulation there are several concepts that have to be addressed. The simulated process is usually called *system*. "A system is defined as the collection of entities (e.g. people or machines) that act and interact together toward the accomplishment of some logical end" (Law, 2007). The model is a representation of the actual system, where some assumptions about how it works are made. "This assumption […] constitute a model, that is used to try to gain some understanding of how the corresponding system behaves" (Law, 2007). Limits or boundaries of the model are important facts to take into account. The model should be complex enough to answer the questions raised about the system, but not too complex so that the simulation process is slowed (Banks, 1998).

Systems can be categorized into two types, discrete and continuous. In discrete systems, variables change instantaneously in determine points in time, whereas in continuous systems variables change continuously with respect to time (Law, 2007).

In the same way, simulation models can be classified into discrete-event and continuous simulation models. In the discrete-event simulation models, "the goal is to portray the activities in which the entities (e.g. people, equipment, orders, raw materials…) engage and thereby learn something about the system's dynamic behavior" (Banks, 1998). In the continuous simulation model, variables that change continuously over time are used to represent the state of the system. (Banks, 1998)

Manufacturing is one of the primary applications areas of the simulation. It is very useful when improving and validating design models of different manufacturing systems. This type of applications includes both facility design and supply chain simulations. When modeling different facilities of the manufacturing system (e.g. equipment selection, control strategy, buffer sizing, material handling design…), the goal is to improve or even optimize the part under study. Modeling of supply chains has its focus on enterprise-wide process study (Miller & Pegden, 2000). In this project, the main focus will be on a material handling system, which is one of the most important elements of manufacturing. As mentioned by Banks (1998), material handling systems can be as much as 85% of total manufacturing time. For this reason, simulation turns critical in order to have insurance that the material handling solution will work on the desired application.

2.6   Emulation

Emulation represents one of the major advances in the study of complex mathematical models. Despite the great increase in the computing power over the last years, computational limitations remain as the major barrier when studying simulation models. (Ratto, et al., 2012)

McGregor (2002) defines the concept of emulation comparing it to a "pure" simulation model. "As distinct from a simulation model, emulation is that one where some functional part of the model is carried out by a part of the real system". Names the differences between real systems and their respective models as the "credibility gap". Emulation models are known for attempting to reduce these differences. They often use a part of the real system in order to bring the model closer to the "reality". (McGregor, 2002)

Emulation is not limited to the case before, a part of the real system can also be replaced by a simulated one. Using emulation to test simulation models in turns to be of a big interest for the installation, commissioning and other aspects of automated systems. (McGregor, 2002)

Complex simulation models can provide clear advantages when trying to understand the natural processes, however, due to over-parameterization, introduce problems of model identifiability and suffer from high computational burden when used in management and planning problems. (Ratto, et al., 2012)

McGregor (2002) explains how simulation and emulation are related to the use of models in order to give a continuous feedback to manufacturing systems and test their functionality on commissioning.

There are different fields where Emulation is useful under economically justifiable circumstances. The first one is when the testing is needed to be carried out in a critical path. The second one is when the available time does not give the opportunity of a full testing. The third, when the system cannot be enough loaded yet to be fully tested and the last one is when the budget of real testing is greater than that of emulated testing. (McGregor, 2002)

2.7   Virtual Commissioning

Virtual Commissioning (VC) is defined by Hoffmann (2010) as the process of "testing manufacturing systems and associated control programs through simulation before the real system is realized". The VC methodology provides a more effective validation than the digital simulation. VC is a solution that considers the mechatronic behavior of the resources, implementing PLC in loops with a virtual environment (Makris, et al., 2012). The expected outcomes from this practice are the reduction in the debugging and correction efforts expended during real commissioning of the system.

These benefits mentioned before will only be achieved if sufficiently detailed manufacturing system models are built (Hoffmann, et al., 2010). Oppelt et al. (2014) explain that when the automation system believes it is communicating with the real production system, the model is detailed enough. Apart from the extended 3D model, there are also another data requirements to realize a VC project. As stated by Makris, et al. (2012), it is necessary to have a detailed layout of the production cell (to show exact placement of the resources) as well as material flow in shop floor (sequence of operations in the production process). Having real hardware control systems (e.g. current PLC programs working on the production line) and detailed description of I/O signals of the system, will ease the VC process and make the obtained results more reliable.

2.8   Virtual reality

Virtual reality technology uses software to generate a realistic situation (images, sounds, and sensations) by introducing the user to a virtual environment.

As said by Seidel & Chatelier (1997), Virtual Reality is "a multi-dimensional human experience which is totally or partially computer generated and can be accepted by those experiencing the environment as consistent". This turns to be a human immersion for the process or activity in which should be evolved.

The paper "Some effects of using Virtual Reality technology" (Seidel & Chatelier, 1997) discussed some of the effects that virtual reality has to the user. The first one causes a conflict of the senses which

results to be confusable sometimes, whereas in the second one shows that some symptoms are dependent on the technological factors screen resolutions, the speed of simulation, etc. In addition, the paper "Use of Virtual Reality in Training" (Seidel & Chatelier, 1997) tells that the impact Virtual Reality has on the operator´s mind must be considered seriously. This technology might have both positive and negative effects on the cognitive and emotional part of the user. The main reason for these secondary effects is that perception of the boundary between reality and Virtual Reality fantasy is too close.

The major advantage of virtual reality is that can be simulated the presence of the user in the required environment. This computer interface is developing by its potential benefits providing a much more intuitive link between the computer and the user. It can be applied in many different situations or scenarios. The paper "Virtual reality applications in manufacturing process simulation" describes the different parts that a virtual environment should include (Mujber, et al., 2004):

- Functionality: the simulator should be as realistic as possible in order to become functional and have a dynamic behavior for the operator.
- Human interaction: the simulation needs to consider that the operator must be an important part of it, so should be designed for the best utilization.
- Environment: a single or a combination of computers can be used to create a real-time simulation.

2.9   Operator training simulator

Chang, et al. (2008) describes an Operator Training Simulator as an advanced computer-based training tool which helps the user or operator to gain skills to run an operation or process. This system uses a dynamic simulation of an industrial process integrated together with an emulator of the system. This operator training method gives the operator some advantages comparing with real-time training, such as safety, shut-down avoidance, production increasing and the avoidance of a possible breakdown of complicated and expensive equipment. All these advantages make the operator to have a higher regularity and better process flow making a realistic training in a safe environment. An effective operator training system ensures a realistic and correct behavior identical to the automation system (Stawarz & Sowerby, 1995).

The paper "Effects of learning support in simulation-based physics learning" (Chang, et al., 2008) describes 5 benefits of simulation-based learning:

1. Provides background knowledge. In this environment, learners can use online to learn about the definitions of certain concepts.
2. Helps learners to make hypotheses; which is one of the major challenges.
3. Helps learners to conduct experiments; they often show inefficient behaviors under pressure.
4. Helps learners to interpret data.
5. Helps learners to be in control of their own learning progress.

3 Literature review

In this chapter, previous works about the field under study such as dissertations, conference papers, and case studies have been analyzed.

3.1 Robot and PLC emulation

In the recent years, modeling and simulation (M&S) have gained popularity due to their usefulness in the testing and development of industrial systems. Engineers use M&S methodologies to test, in a free risk environment, different systems in a cost-effective manner. "Using a simulated environment, it is possible to verify the correctness of the system under different circumstances". (Glinsky & Wainer, 2004)

In industrial applications, a 3D model of the system is created and then connected to the real PLC controller. OLE Process Control facilitates the communications between PCs and PLCs, allowing the testing of control systems with an emulation model. A 3D model of the system controlled by the real-world control system is a powerful visualization tool that can be used for different purposes: real-time monitoring, analysis and validation of the design, etc. (Johnstone, et al., 2007)

Successful emulation implementations have been achieved in different fields, for example, baggage handling systems. Rengelink & Saanen (2002) modeled a baggage handling system using a PLC as the control system. An extension to an existing baggage handling system was going to be built. For that project, a proper emulation was needed, to reduce on-site costs and improve the quality of the installed system. A 2D model was created (see *Figure 4*), with up to 70 conveyors. Each PLC in the systems controlled the information flow of the baggage and a specific group of conveyors. Only one PLC was tested, without connecting it to upstream and downstream PLCs. The emulator and PLC were linked using a Profibus net. The authors state that emulation could also be used to improve the layout of the system (defining capacity and traveling time of the section). Finally, the emulation environment has been properly developed, enabling the project to be finished on time and with limited on-site adjustments.
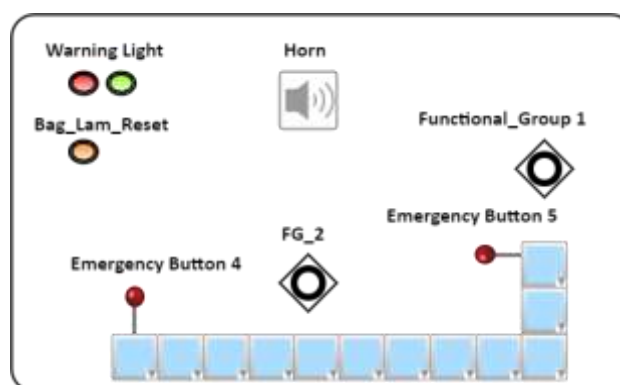
Figure 4. Visualization of the baggage handling system emulation

Another field where emulation plays a distinguished role is in robot manipulator design. Martin & Emami (2011) developed a generic Hardware-In-The-Loop platform to simulate N-DOF (Degree of Freedom) serial-link manipulators and its controllers. The concept of Hardware In the Loop Simulation (HILS) is to use physical hardware for system components that are difficult to model linked with a

virtual model with other aspects of the system. This study covered two main issues; simulation of the manipulator in real time and whether the platform could be used as a design tool in some process of the design cycle. As can be seen in *Figure 5*, two different motors and torque sensors were mounted on the platform and connected to the Computer Simulation, where the generic model of an industrial robot was running. Then three industrial applications tests were carried out:

- Basic functionality and real-time monitoring of joints position, velocity and acceleration.
- Validation against the physical prototype, comparison of performance in different scenarios (different working loads and speeds).
- Design capabilities or platform usefulness as a design tool for various aspects of the manipulator and control unit.
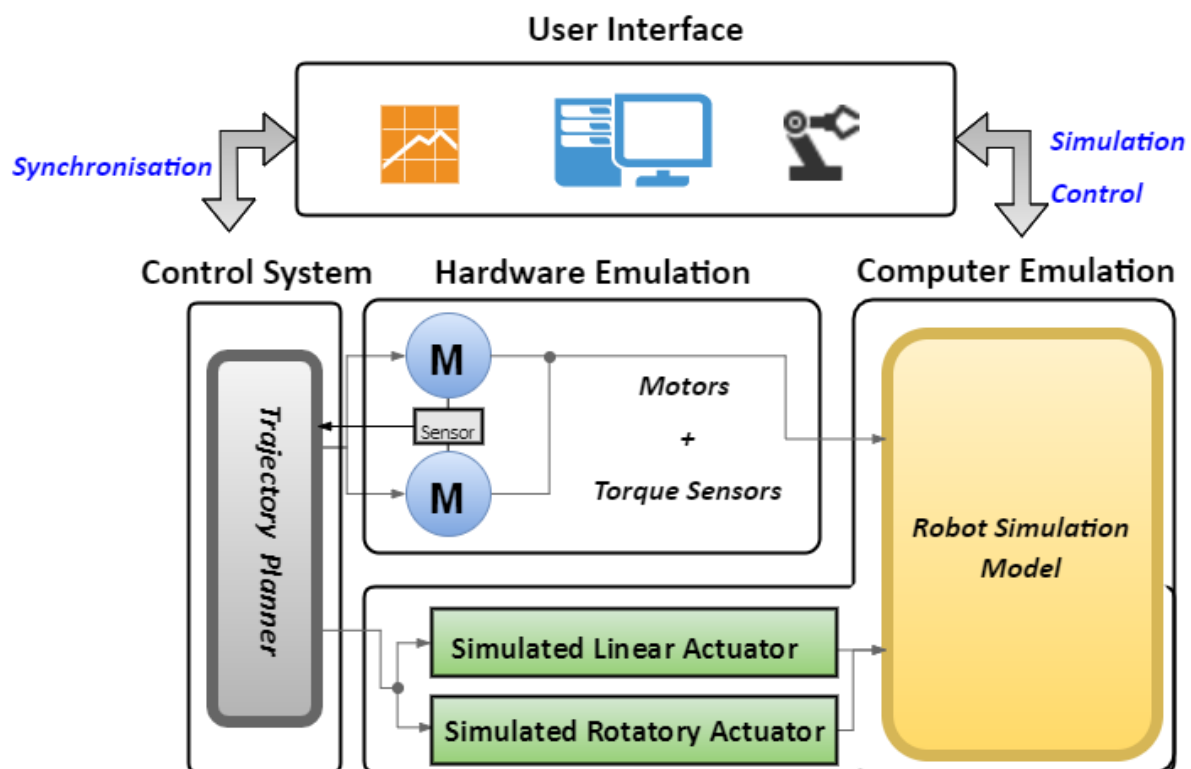
Figure 5. Freely interpreted architecture for Hardware in the Loop Emulation (Martin & Emami, 2011)

The authors concluded that HIL architecture combined with suitable hardware configuration was a coherent strategy for simulation and design of robot manipulators.

3.2   Virtual Commissioning of manufacturing process/systems

Modern processes and manufacturing plants are increasingly becoming more complex. In order to meet the requirements of quality, minimal costs and fast delivery, the automated process test becomes a critical part (Oppelt, et al., 2014). The testing of the engineered automation solution usually takes place during the on-site commissioning, once the equipment is being located in the actual plant. Problems happening in this part of the process could lead not to meet the start-up schedule or even worst to the destruction of the equipment. Despite the many benefits of the virtual commissioning, it is not widely used in automation engineer. The reason for this is the modeling effort and knowledge

needed to develop usable simulation models. Thus, if the modeling process is simplified, it will make virtual commissioning an interesting and smart choice for industrial applications.

This problem is addressed by Oppelt, et al. (2014), with the aim of automatizing the process of creating simulation models, using the plant engineering data. The concept described in this article was checked by a prototype implementation. All the simulation-relevant components and information are collected into an XML file and then imported to create the simulation model. This way, automatic generation of the simulation model was successful. Furthermore, the information was only introduced once, easing the generation of simulation models.

Another study mentioned at Hoffmann, et al. (2010) shows an application of VC for offline validation and verification of control logic. This project was carried out by Thapa, et al. (2006). Authors proposed a three phase validation method (see Figure 6): manual testing, model checking, and virtual commissioning.
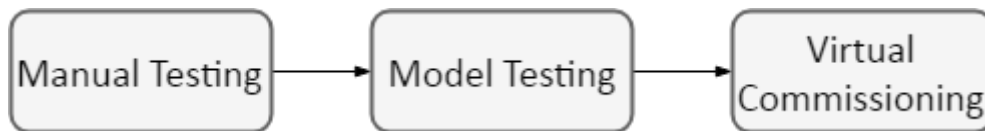
Figure 6. Freely interpreted III-phase Verification and Validation process

Manual testing phase is based on checking PLC code on a softPLC (simulated PLC) by user inputs. This method is limited to small programs or part of programs. For the model checking, the formalized language of the automata (according to IEC 61131-3 code), is converted to an intermediate language to check the timing behavior of the model. Finally, for the virtual commissioning, the virtual plant model and the softPLC are connected together and the standard code is run. According to the conclusions drawn by the authors, this method turned to be costly and time-consuming, requiring a considerable effort and expertise to conduct.

Makris, et al. (2012) conducted a case study of an assembly cell with cooperating robots, with some interesting outcomes. As shown in *Figure 7*, the assembly cell consists of a robot equipped with a gripper and another robot with a spot welding tool. In this case, the system was completely modeled (mechatronic model of the robots, working station and I/O signals definition), and tested using two computers, one for the simulation model and the other one for the simulation of control signals and communications between the devices.

Figure 7. Real assembly cell (left) vs virtual assembly cell (left) (Makris, et al., 2012)

The authors managed to reduce the total installation time about 15-25%, as having validated all the programs through VC, errors during installation are unlikely to appear. In addition, they reduced the investments costs, by reducing the time of deployment for the line (plant can be in full production faster and less investment in human resources for troubleshooting). Makris, et al. (2012) sums up with an interesting quote about the path towards VC: "To promote the adoption of VC, manufacturers and their suppliers need to create and provide forward mechatronic simulation models with structured data".

3.3   Test and validation of a simulation model

Modern manufacturing industries are mainly composed of automated process stations. Besides its great benefits, such as improved product quality, reduced production times and efficient use of materials, they are a major challenge to maintain and control. (Erlandsson & Rahaman, 2013)

Simulation models are increasingly being used in the problem solving and in the decision making of automated workstations. This means that information obtained from the simulation model is usually used and applied to the real system. For that purpose, the model and its results must be verified and validated. As defined by Sargent (2000), model verification consists of "ensuring that the computer program of the simulation model and its implementation are correct". In the same papers, model validation is defined as "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consisted with the intended application of the model". The following are some of the techniques and tests used in model verification and validation (Sargent, 2000):

- Animation: Model's operational behavior is displayed graphically as the model moves through time.
- Event Validity: The "events" of the simulation model are compared with the ones of the real system to determine how close they are.
- Extreme Conditions Test: The model structure and output should be reasonable for any combination of variables in the system.

In the conference paper "PLCStudio: Simulation Based PLC Code Verification" (Park, et al., 2008) a visual or animation verification technique is applied for the validation of a PLC program in a 3D virtual environment. The author's proposed architecture (see *Figure 8*) integrates a PLC program (running in soft PLC) and a simulation model of the plant with all the manufacturing devices. PLC program and plant model are communicated using an I/O mapping model. "The 'PLC simulator' performs the simulation of the control program, and the 'plant model visualizer' shows the corresponding plant model (3D graphic models) reflecting the changing status of the production system during the PLC simulation" (Park, et al., 2008). Both, control logic and production system must be synchronized and show the same process stage in order to be validated.
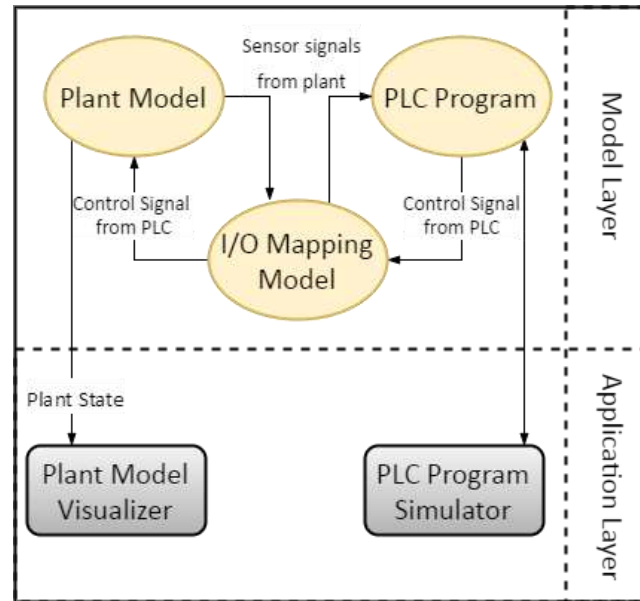
Figure 8. Freely interpreted architecture for the PLC code verification (Park, et al., 2008)

Despite Park, et al.(2008) do not test their simulation model against the real plant, it would have been interesting to perform an Event validity test to determine if its behavior is similar to the real systems.

Erlandsson & Rahaman (2013) also carried out a verification of PLC code using a virtual model. A tetra-pack filling machine has been modeled and communicated with the PLC. In this case, a Hardware In the Loop configuration is used, whit a real PLC running the program. The communication is established between the Allen Bradley PLC and the PC with a virtual model using Ethernet/IP-CIP protocol.

Due to the complexity, the real PLC code has not been run in this. Instead, a simple PLC program for basic functionality of the process has been implemented. According to the authors, the servo motor was difficult to model and control and lacked a robust communication with PLC and model. However, they aim to implement this part in a future work and be able to run the real PLC code. Furthermore, the authors mention the fact that it would be possible to reduce the differences between the virtual model and real system by facing them.

Both papers conclude that facing the simulation model against the real system could minimize the differences, leading to a proper validation of the model and a enhance of the applications range of it.

Binnberg & Johansson (2016) have carried out a virtual commissioning of an assembly operation which includes an ABB robot and was controlled by a Siemens PLC. They have created a virtual twin of the real system, including all the different equipment, involve in the production line. The robot basically substitutes the main caps from the motor with piston cooling nozzles. The remarkable of this project is that the simulation model has been tested in the real production line. They manage to connect their digital twin to the real production cell and see how the emulation model reacted to changes in the real production cell. After doing some experiments, the authors concluded that the emulation model they have created behaved exactly the same as the real process in the different scenarios tested.

3.4   Simulation-based learning

Simulation is a tool that can be used for many different purposes. One area of application is being increasingly developed due to the interest that is generating in the current society and the advantages it offers. This is undoubtedly the use of simulation for educational purposes. Three-dimensional (3D) technologies have become a fundamental element of almost all modern video games. Furthermore, it can be used in many different areas, replacing the real environment where the user of learning would have to submerge with a virtual reality environment. "Internationally, educators and educational institutions envisage great potential in the use of 3-D simulations, games and virtual environments (VEs) for teaching and learning, as they provide the possibility of rich learner engagement, together with the ability to explore, construct and manipulate virtual objects, structures and metaphorical representations of ideas". (Dalgarno & Lee, 2010)

Many professionals from different sectors use simulation combined with 3D environments as a training technique. Its main benefit is the ability to support the learners with a risk-free environment to train. This type of learning avoids the trainee suffering from any stress that does not have to do with the implanted learning process. Group learning is also an option for this learning technique. Making apprentices and operators work together, coordination between team members is improved, as well as communication. This group methodology has some extra benefits comparing it to individual learning methods.

The quality of the simulator has a close relationship with the domain that the user can obtain in the matter since this is involved in the degree of reality that he encounters with the real situation. Therefore, this technique is continuously being developed, and more research is being done in the field of simulation-based training.

Lateef (2010) gives a suitable example of simulation-based learning in the article "Simulation-based learning: Just like the real thing". Here, a computerized mannequin has been implemented to be used by medical students and doctors in order to acquire necessary skills and train. Thus, they will perform perfectly in a real situation, when the time is crucial and somebody's life depends on them. The full-body simulator used is connected to a computerized simulation model, which approximates the behavior of it to the physiology of a human body. This simulation training center offers unique opportunities to the user, being involved in unanticipated, complex, stressful situation where can practice without the stress of a real situation. The author believes that this learning method enhances the efficiency of the learning process in three different skills:

- Technical and functional expertise training.
- Problem-solving and decision-making skills.
- Interpersonal and communications skills or team-based competencies.

In conclusion, for this educational application in medicine, the optimal decision would be to integrate the simulation model into the traditional program of training. Virtual reality would offer a potential benefit to the traditional didactic method, enhancing the performance and reducing errors. (Lateef, 2010)

In the next paper "Computer simulations in physics teaching and learning: a case study on students' understanding of trajectory motion" (Jimoyiannis & Komis, 2001) a research in the educational field

has been carried out. The research has focused on the physics education and has used computer simulation as the main tool. *Figure 9* shows the created simulator display, in which some graphs and an interactive free fall demonstrator can be seen.
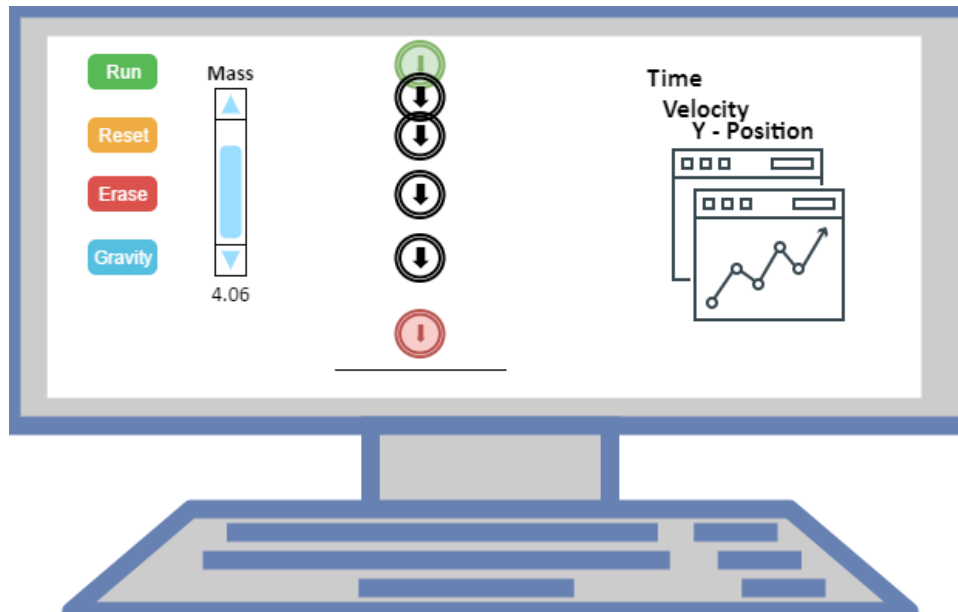
Figure 9. Freely interpreted interactive physics view on the simulator (Jimoyiannis & Komis, 2001)

Physics is one of the first areas where a big research in educational software has been done and a variety of computer applications have been developed. The new educational environment that simulation offers simulation, enhance the instructional potential helping students to develop scientific understanding using active learning methods. "Simulation-based learning offers to develop their understanding of physical laws by hypothesis making and testing, isolating/manipulating parameters to understand physical variables, using different animations or graphs, expressing their mental models and the last and most important one: investigating phenomena which are technically difficult, dangerous, money or time consuming". (Jimoyiannis & Komis, 2001)

The author provides evidence that students of the experimental group reached to a more improved learning of physics concepts of velocity and acceleration (7 out of 10 students in the experiment group have understood the meaning correctly). These results confirmed the author's hypothesis: "It seems that educational environments based on simulations assist students to overcome their cognitive constraints and refine their alternative conceptions about the trajectory motion up to a significant point". (Jimoyiannis & Komis, 2001)

Both articles mentioned in this section show that simulation-based learning helps the user to achieve a conceptual and purposeful understanding of what is being taught. So, the results present that simulations are beneficial as a complementary or alternative tool for the students´ and operators to develop a better understanding.

Simulation seems to be here to stay, there will be a day when it will be used frequently as a tool in evaluating users; including a portion of time dedicated to learning through gaming. More studies and research are also made in order to determine that simulation improves learning processes, so

developers will continue improving the technology of virtual reality in order to make experiences greater and better.

3.5   Operator training simulation

The correct training of the operators in a company has a great importance if the optimal productivity wants to be reached. Competent station operators are vital when high-quality and uninterrupted service is required for the production line. For that reason, the personnel training is an unneglectable activity in today´s industry. Not only to reach the desired goal of production but also to increase the productivity and have a smoother fluidity of the products, regular training must be done. Apart from productivity improvement, this training also allows heightening the security of the workforce and equipment. (Vehl, et al., 1996)

In the paper "Design and Operation of a Virtual Reality Operator-Training System" (Vehl, et al., 1996) it is studied and proved the benefits of a correct staff instruction. Power system operators have usually to deal with situations where their capacity of memory, ability to put into practice their theoretical learnings and the capacity to overcome with continuous stress situations is continuously tested. The author, shows the practicability of virtual reality in an operator training station in different fields, describing a design and operation of a virtual reality prototype. The platform, known as Esope-VR, includes 3D viewing equipment and a realistic control room with the required control panels equipped with switches and buttons (See *Figure 10*).
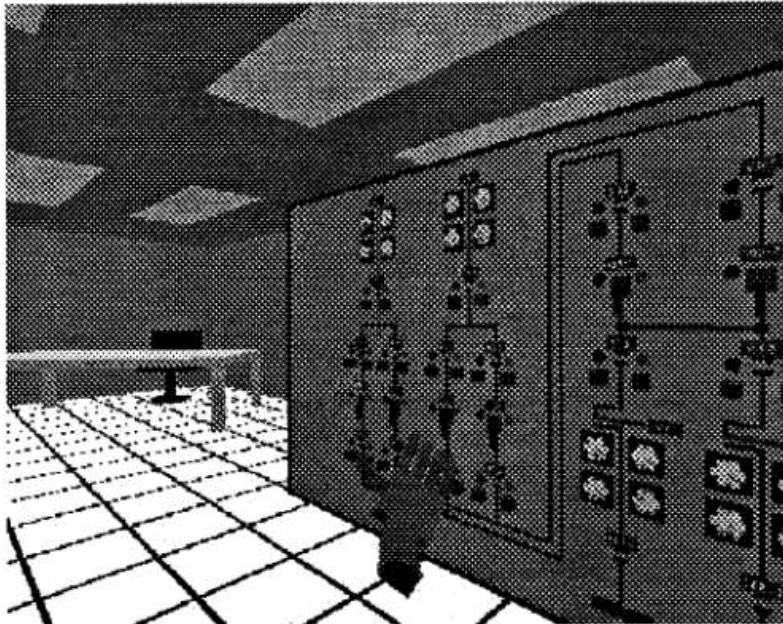
Figure 10. View of the virtual control room (Vehl, et al., 1996)

The objective of Esope-VR is to provide a training environment that prepares the operators for the real world. The main communication between the environment and operator is done by speech recognition, permitting the user having its hands free for the task he is doing. In addition, the operator will be able to ask the simulator for help in any moment of the process. The simulator will also give

oral feedback of the performed task. The successful integration of a dynamic 3D visual interface, the animation of switchyard equipment, speech recognition and oral feedback have two main conclusions:

- A complete training station can be built with existing technology.
- It is possible to immerse the operator into a virtual environment for a correct safe training.

Yang & Qiao (2010) explains the development of an intelligent environment for CNC machine operator training application. Due to complex dynamic systems of CNC machines, a wide range of knowledge is required to operate them. Operators knowledge and skills update has become a problem for the manufacturing industry in the last years. "An operator must comprehend the physical operation of machine tools and must be skilled in handling a number of decision-making problems of process". The authors, build an Intelligent Environment for CNC machining knowledge acquisition through VR. The virtual scenario contains virtual machine tools, a Control Panel Interface (where the user can manually operate the machine tool), Cutter&Parameter Selection Expert System (for the user to choose between a known set of candidate cutters) and a Web-Based Tutor (presents operator the learning and technology materials in a convenient way). The developed station was tested with operators against OJT (On-Job-Training methodology). This study showed positive benefits of the virtual training, both in task completion time and in the mistakes made by the operators (see Figure 11 and Figure 12). (Yang & Qiao, 2010)
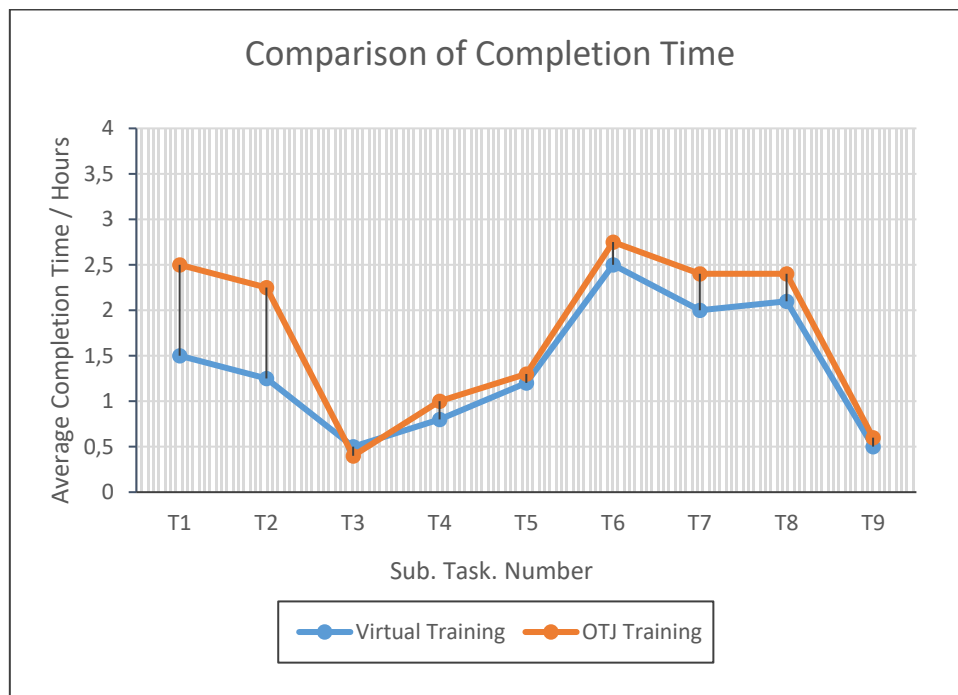
Figure 11. Freely interpreted graph of the completion time test results (Yang & Qiao, 2010)
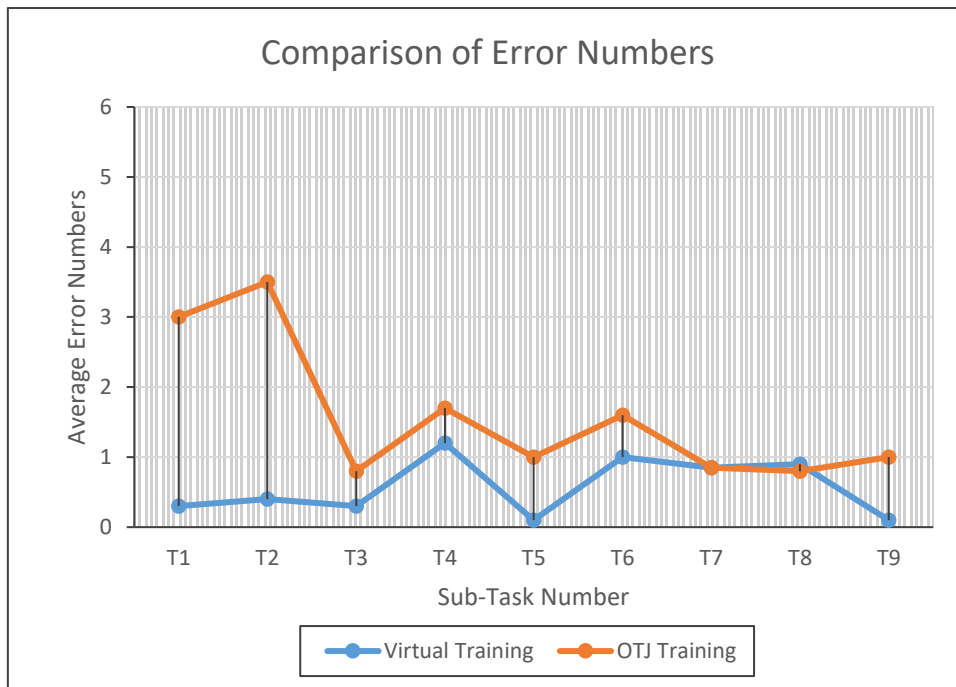
Figure 12. Freely interpreted graph of the error number test results (Yang & Qiao, 2010)

Summarizing, all the papers presented above draw positive conclusions from the use of simulation in the operator training. However, "the biggest positive effect that the use of emulation models will provide is the hazard-free environment for testing code, training operators and testing scenarios that would not have been possible in real life due to a different type of hazards". (Binnberg & Johansson, 2016)

4 System Description

In this chapter, the functionality and structure of the real system are described, as well as the different components of it.

4.1 Sequence and operations

The OP035 is an operation of the G2 foundry's production line. Concretely, it is the conveying line which takes the cores coming out from the core shooting machines to the storage. A study of the functionality and sequence is required to gain insight into how this process works.

There are two levels of conveyors in this operation: the upper level, which takes the full pallets to the storage, and the lower level, which brings the empty pallets to the indexing places. There are also two core shooting machines, one of them produces inner parts of the sand cores, while the other makes the base and cover. Both machines produce one part per minute and change their mold every 40 cycles. In the case of inner parts, one in ten parts is taken to supervision, whereas for base and cover, one in twenty parts is supervised. Each pallet contains information regarding the pallet itself and the content. This information is transmitted along the conveying line together with the pallet. At specific points of the line, Radio Frequency Identification (RFID) system checks that information flow matches the pallets movement.

An empty pallet comes from the lower level to one of the machines' indexing place, and it is lifted to the upper level by a lifting conveyor. Both indexing places work the same way. Once the pallet is in position, the indexing table raises the pallet from the conveyor and it is ready to be loaded. A robot picks the cores coming out from the machine and places it on the pallet. The sensors in the indexing table detect that the pallet is loaded, then the pallet is placed on the conveyor and starts moving. The full pallet can be either taken to the storage directly or to the supervision station. If taken to supervision, the production does not stop. The pallet is diverted from the main flow, checked that is okay by an operator, and then redirected to the main flow. For this operations turning and transfer conveyors are needed. The pallets enter filled to the storage from the upper level and come back empty from the lower level. The empty pallet coming from the storage pass through a vacuum cleaner operation to remove any dust left in it, and then it is taken to one of the indexing positions of the two machines, starting the sequence again.

4.2 System components

4.2.1 PLC

The programmable logic controller is the main element used in the automatization and control of this production line. The production process is written in PLC's internal control program. The programming language used is RSLogix5000 from Rockwell Automation, and the PLC model is Allen Bradley 1756-L62 ControlLogix5562s.

4.2.2   Robot

For the OP035 operation, two ABB robots are used in order to place the cores coming out from the machine onto the pallets. The robotic operations in this part of the production line, are known with the name OP030 and OP050. The model of the robots is ABB IRB 6640, which is specially designed to work in foundry environments. This type of robots can reach a height of more than 3 meters and have a payload up to 235 kg.

4.2.3   Conveyors

The conveyors involved in the OP035, have been manufactured by ULMA Handling Systems, and are based on chains. For the handling of the pallets, various movements (e.g. lifting, turning or transferring) are needed. In this material handling system, different types of conveyors have been used, which are going to be explained in the Conveyors and moving elements section from the fifth chapter.

4.2.4   Sensors

Different types of sensors are used in OP035. Most of them are inductive sensors used to detect the position of conveyors and pallets. Photoelectric sensors, both through the beam and with reflector, are used to detect the presence of cores on the pallets. A light barrier is also used to protect the operator in the supervision operation. In the hydraulic systems, different pressure sensors and temperature sensors are located. This way, the different parameters can be monitored throughout the equipment function, and in case any of the parameters exceeds a set range, the machine is stopped.

4.2.5   Armorstart

Armorstart is a distributed motor controller that integrates I/O and network capabilities. In this application, the armorstart is used to drive the AC motors of the conveyors and turning tables, as well as to connect the sensors required for those operations. It communicates with the main control unit via DeviceNet, from which it sends the information regarding its sensors and motors, and receives the commands for actuators.

4.2.6   HMI Panel

In the OP035 conveying zone there are two HMI panels. One main HMI is located in the principal electrical cabinet, whereas the other is located near the inspection operation OP055. The HMI panel is complemented with a button panel. The panel structure is shown in Figure 13:
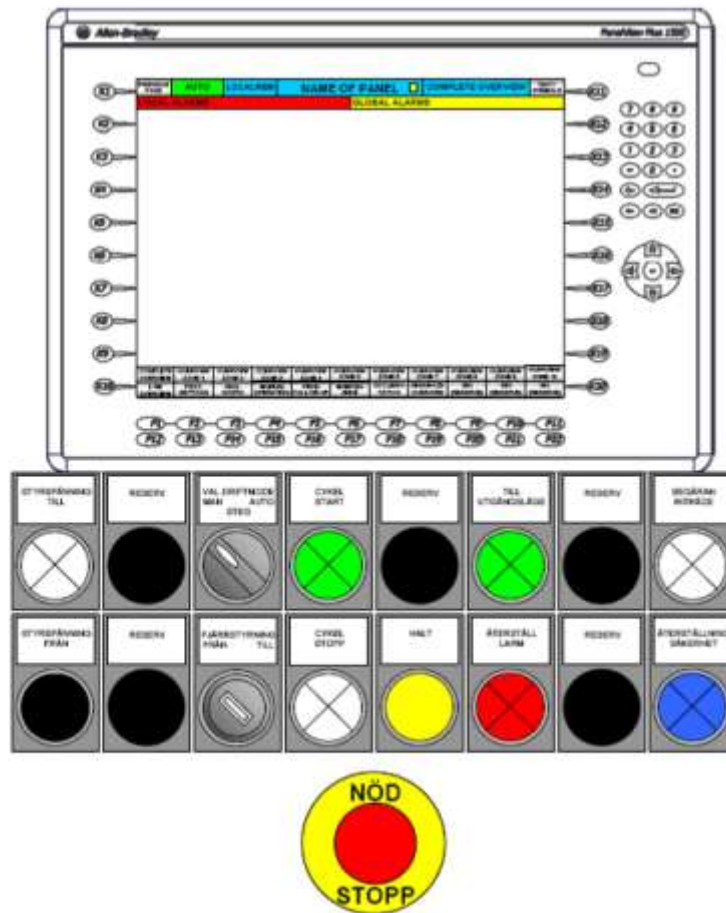
Figure 13. Structure of the main HMI panel in the foundry

As can be seen in *Figure 13*, there are several buttons to control the material handling operation. Control voltage buttons turn on and off the circuits in the machine, pneumatics, and hydraulics. Cycle start and stop buttons are used to manage the automatic cycle in automatic or step-by-step mode. There is also an emergency button (stop all the circuits and power in the line immediately) and a triple mode selector (manual, automatic or step modes).

4.2.7   RFID

RFID are placed in strategic points of the conveying zone. This device identifies the pallet and reads the information in them. Then this information is compared to the one stored in the PLC program and checked if it is correct. If not it will result in an error and the operator will need to take action.

4.2.8   Compactblock and Armorblock

The compactblock and armorblock devices are compact modules of distributed I/O. Instead of wiring the different inputs and outputs of the system to the main cabinet, this device can be used to send the information of the peripheral devices via Ethernet to the control unit.

4.2.9   Pneumatic Modules

In the production line, there are modules to manage the different pneumatical devices. The manufacturer of this modules is *SMC,* and its main function is to connect and control the different pneumatical devices, such as valves and cylinder sensors.

4.3   Electrical Schemes and Layouts

When studying the system structure, all the information provided by the company is of high importance. Volvo let the electrical schemes and the factory layouts for this project. OP035 is divided into different sub-operations (SOP) ranging from SOP100 to SOP154. The even SOP numbers allude to conveyor systems, whereas the odd numbers allude to other components in the conveying line, such as safety gates, emergency stops, etc. The OP035 is divided into groups of sub-operations, as can be seen in *Figure 14* and *Figure 15*. This way, each area can be controlled individually and avoid the stop of the whole line if a zone has a problem. Each of the conveyor levels has its architecture and it's divided into a different group of sub-operations:
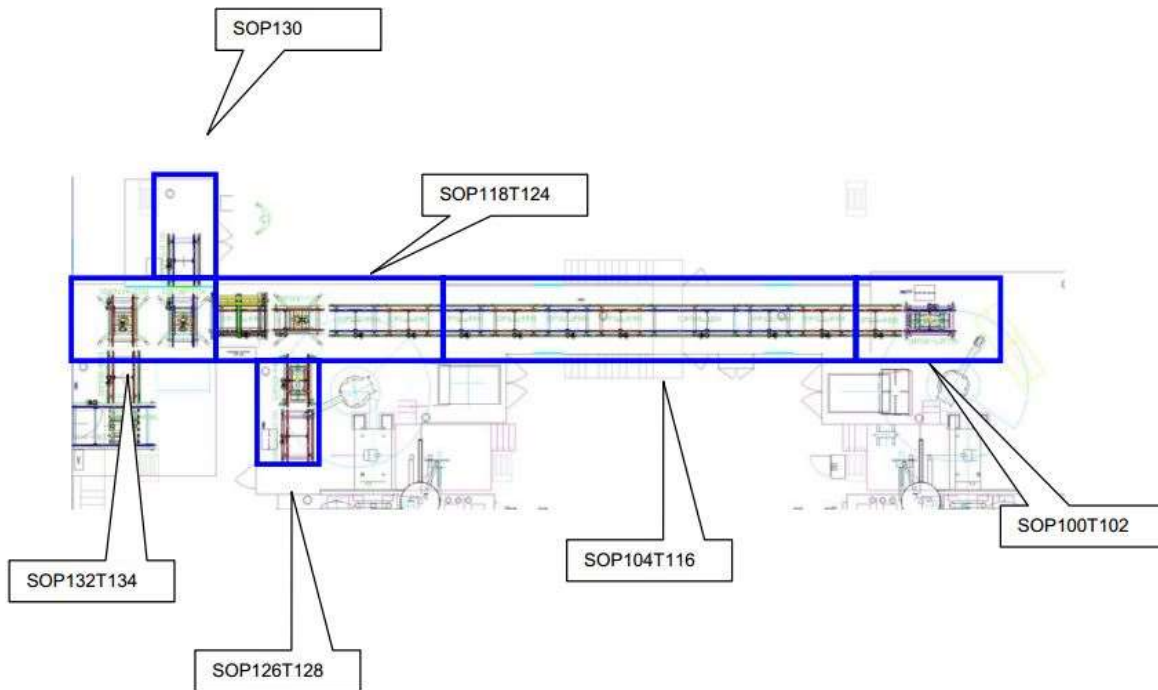
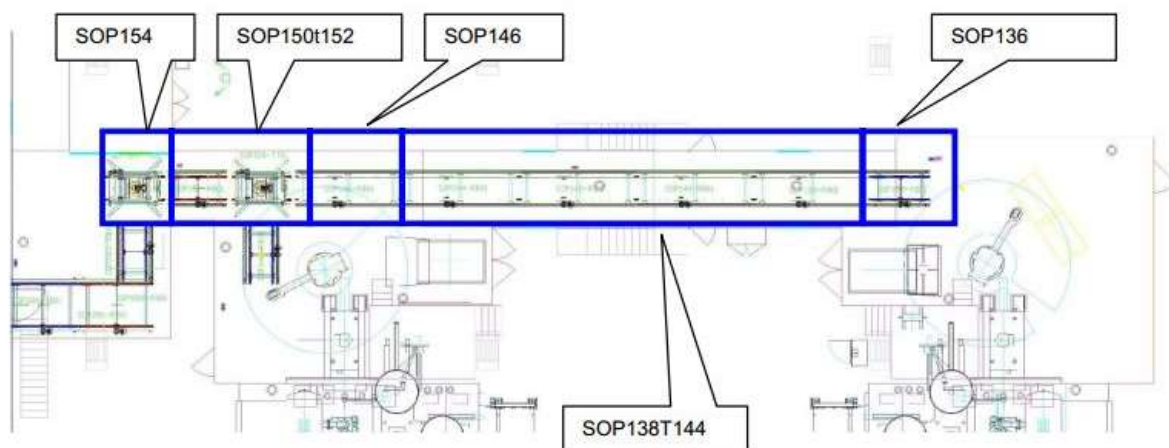*Figure 14. Upper-level layout from the OP035 conveying zone*

Figure 15. Lower level layout from the OP035 conveying zone

Power lines of the OP035 are divided into five zones. Each zone has its magneto-thermal switch to protect the electrical installation, and a circuit breaker in case of the power line needs to be shut down. The power line will only be break under hazardous circumstances; for example, when a safety door is opened without a previous opening request, an emergency button is activated or a short-circuit is detected in the installation. The SOP groups are the followings:

1. The group includes the SOPs 100, 102 and 136, the first core shooting machine indexing zone with the feeding of empty pallets to the upper level and its respective lifter.
2. Group consists of SOPs 104 to 116 from the upper level and SOPs 144 to 138 from the lower level. This part is the main line between the two core shooting machines.
3. Group is formed by SOPs 116 to 128 from the upper level and SOPs 146 to 152 from the lower level. This part has the indexing zone from the second core shooting machine in it, as well as the turning tables and vacuum cleaner close to that part.
4. Group consists of the SOPs 132, 134 and 154, final part of the line which connects the OP035 to the entrance of the storage OP060.
5. The group is the supervision zone. OP030 is the name of this zone and it comprises all the elements related to the cores supervision operation.

4.4   Inputs and Outputs

There are several signals involved in the PLC and control program of the conveying line. Some of the functions of the PLC program require signals in order to execute different tasks, such as operations between variables or saving a value in a specific part of the memory. Those signals, apart from being complex to access, are useless for our project. We will focus on the PLC inputs and outputs (I/O) and on the signals responsible for sending the information between one PLC to another in the production line.

The inputs for the PLC are usually signals coming from the sensors in the conveying line, e.g. positioning inductive sensors in the conveyors or pressure sensors in the hydraulic and pneumatic circuits. Outputs refer to signals acting on the system's equipment, e.g. signals for conveyors' motor starters, lifting tables, cylinders or stoppers of the indexing tables. Priority attention must be given to this type of signals as they are fundamental when building the emulation model of the cell.

The use of Armorstarts for the conveyor's control eases the manipulation of the control signals (inputs and outputs) for the conveyors. This device has four inputs where the required sensors of each conveyor are connected. This way, manipulating the control word from the Armorstart, the sensors can be read and the conveyor can be controlled easily. Armorstarts are also implemented to the turning tables and transfer conveyors. For the other elements of the conveying line, decentralized periphery terminals are used to send the information to the controller. This way, the PLC is not wired to the different terminals, it communicates with the system equipment via Ethernet network. The network scheme from the OP035 line in the factory can be seen in *Figure 16*:
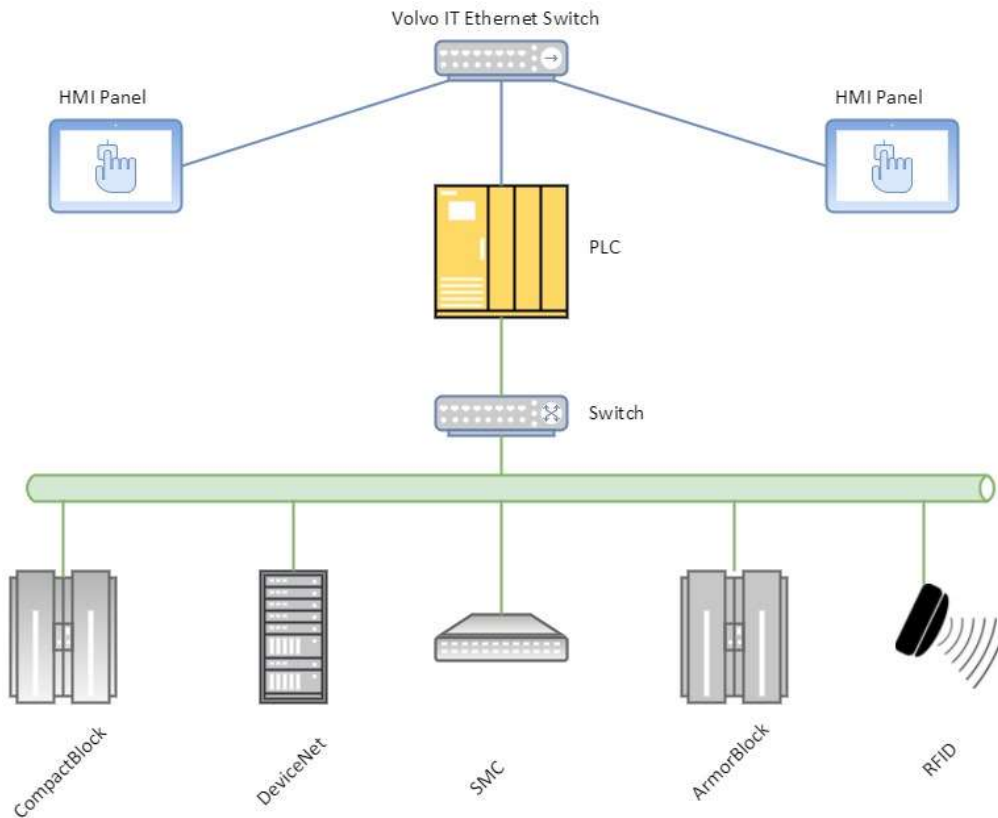
Figure 16. OP035 network schematic

As it can be deduced from the *Figure 16*, the main switch connects the PLC and the HMI panels. Then, the PLC has a device network in order to communicate with the different peripherical devices in the line. The second switch connects the communication modules from elements in the line (sensors, motor starters, pneumatical actuators…) and the RFID devices.

In RSLogix, controller tags can be printed to an Excel file. This fact results useful when managing a considerable number of signals. For our project, different types of signals are read from the PLC. The information blocks transmitted by the PLC are mostly variables of double integer type (32 bits) and integer (16 bits). Despite reading all the blocks completely, all the information containing in those packets might not be useful and only a part of the words (concrete bits from the whole word) is used. For that reason, the signals to be used in the simulation model must be chosen carefully beforehand. The PLC program has up to 1400 variables stored. From those variables, only 185 are I/O signals, and most of them have been used to build the emulation model. 175 I/O signals are used of which 99 are inputs and 73 are outputs from the PLC.

5   Emulation Model construction

In this chapter, the process of creating the emulation model is explained. Each part of the model is analyzed and the integration into the emulation model is addressed.

5.1   Analyzing the model

Before starting to build the emulation model, it is necessary to analyze the design of the different components. These elements are the normal and turning conveyors, stoppers, sensors, elevators, indexing tables, and pallets, as well as the structure of the entire system. In the initial part, the required information to build the model is gathered. For that, all the information has been provided by Volvo in the documentation, drawings, and 3D models. Once the information collected is enough to build the model (layout and position measures, quantity and type of sensors, model sizes…) is time to start building.

5.2   Models conversion and simplification

First of all, it must be highlighted that the emulation model has been constructed in a laptop computer. The hardware specifications are not the ideal for building the model, and that is why is necessary to optimize the memory space used by the program. The final tests and validations have been done with a more powerful desktop computer.

The 3D models provided by the company had such a grade of detail that slowed down the execution of the model. The number of faces for each model could even reach the million. With that quantity of faces, the model needs more space to be loaded and the frames per second (FPS) of the emulator drops down. With a more powerful graphic module, it will not have been a problem. The solution to this problem involved filtering the 3D models and converting them into simpler ones. In some cases, when Simumatik3D did not support specific format files, Robot Studio software turned out to be a useful tool for converting the models into another format.

For the simplification of the 3D models, MeshLab software was used. This is a free license program that can easily convert very detailed models into simplified ones. The models were loaded in the program and a simplification and meshing filters were applied. As a result, the models' complexity was reduced, remaining the geometry unchanged and reducing the number of faces. The option chosen for the simplification process was the quadric edge collapse decimation conserving its texture. In *Figure 17* an example of this simplification can be seen. The model detail was reduced from 750k faces to 10k, reducing also the space in memory used by the files: from 131Mb to 1Mb.
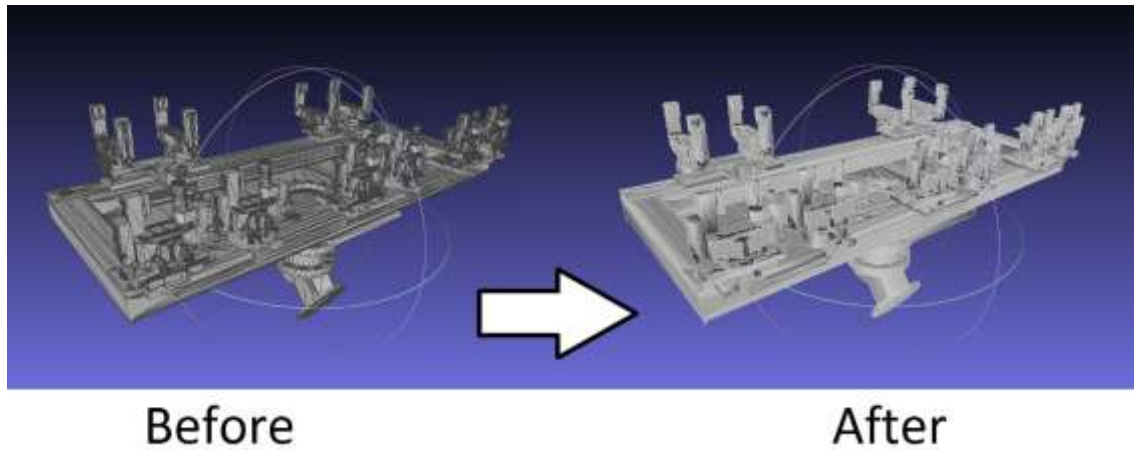
Figure 17. Example of 3D model simplification: Robot gripper for small parts

5.3   Ground Layout

The first step for building the emulation model was to integrate the different layouts provided by Volvo on the ground of the emulation model. This way, the layouts are scaled and the exact position of the different elements can be known. Once installed the conveyors of the lower level properly, there's no need of using the layout, as the upper-level ones are placed on them. The layouts from the factory also provided useful information such as the name and measures of the different conveyors, some sensors position and the place for doors and windows in the cover walls.
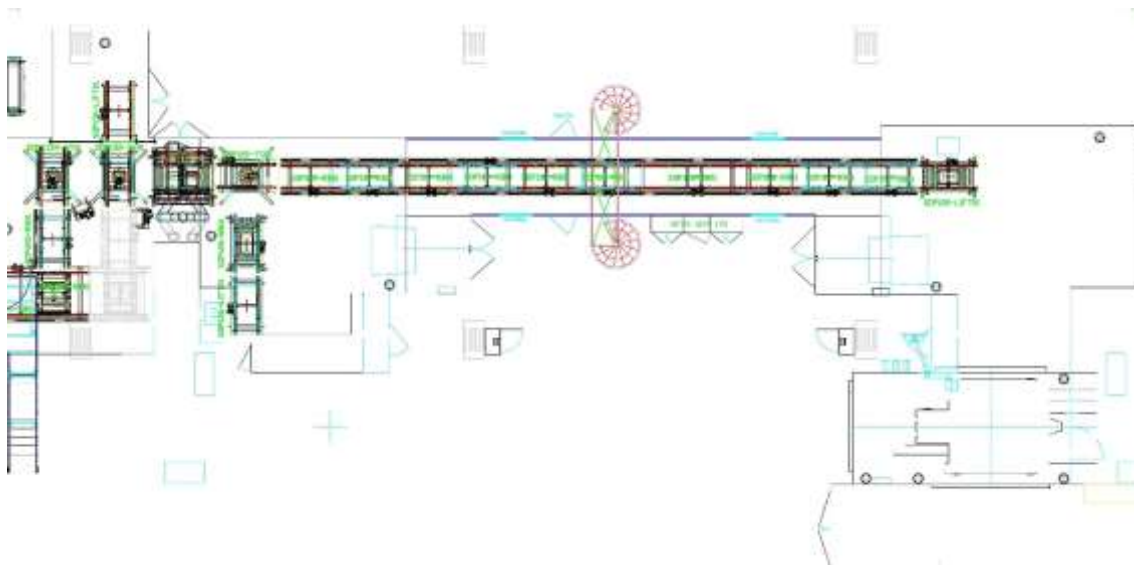
Figure 18. The layout of the G2 foundry. OP035 and surrounding operations

In *Figure 18,* the layout used for the installation of all the elements in the production line can be distinguished. This layout contains the upper-level production line components as the conveyors, walls, doors, windows and different elements in the factory.

5.4   Conveyors and moving elements

Just like in the factory production line, four types of conveyors are distinguished in the model: there are simple and double conveyors, turning conveyors, transfer conveyors and lifting conveyors. For the integration of them, Simumatik3D has a library where is possible to find basic conveyors and other tools to add movements to them. It is also possible to change their color, the traction mechanism (belt, chain, and rollers) and add legs to them, achieving a higher level of imitation. In this case, chain conveyors have been used, with white color and green stoppers on each side. Thanks to the drawings, it is possible to know the exact position of the sensors in the different conveyors.

Depending on the functionality (type of movement) of the movable part, a specific joint has been added. Simumatik3D has different joint types which can be connected to the basic conveyors. In that way, it gives the possibility to convert a single way conveyor into a lifting conveyor, a turning conveyor or a transfer conveyor. The different conveyors and movable parts of the system are enlisted and explained below:

5.4.1   Basic Chain Conveyors

This is the most used material handling system in the industry and in this case, they use chains attached to mechanical elements in order to move the required products. These types of conveyors can be simple (only capacity for one pallet) or double (capacity to transfer two pallets at the same time). Simple chain conveyors are located on the upper level of the OP035, whereas the double chain conveyors are located on the lower level. Simple chain conveyors are 1525mm high, 700mm wide and 1800mm long. Double chain conveyors are lower than simple ones, they are 700mm high. For the movement of the chains, an AC motor is used. This one is driven by an Armorstart. Both conveyor types have a power of 0.37 kW and a nominal speed of 16m/min. A pair of sensors is installed at the end of the conveyors. One for proximity, which slows down the speed of the conveyor, and the second one for positioning, which stops the conveyor with the pallet loaded in the correct position. Double conveyors have two pairs of these sensors, one for each pallet buffer.

These conveyors are the most frequent ones used in the OP035 model. They have two directions (forward and reverse) and two speeds (fast and slow) to make the pallets move along the line. Regarding connections, the conveyors are connected to an AC motor driven by an armorstart. Both the armorstart and the motor of the conveyor are fed by an AC source, representing the power line of the installation. Each conveyor has its sensors to ensure an automatic operation.

In *Figure 19*, the two levels of conveyors can be seen. As mentioned before, this conveyor line has two levels, a lower level with double conveyors and the upper one with single capacity conveyors. It can be also appreciated that the sensors go in pairs (in yellow); one of them to detect the pallet approximating and the other one for positioning the pallet.
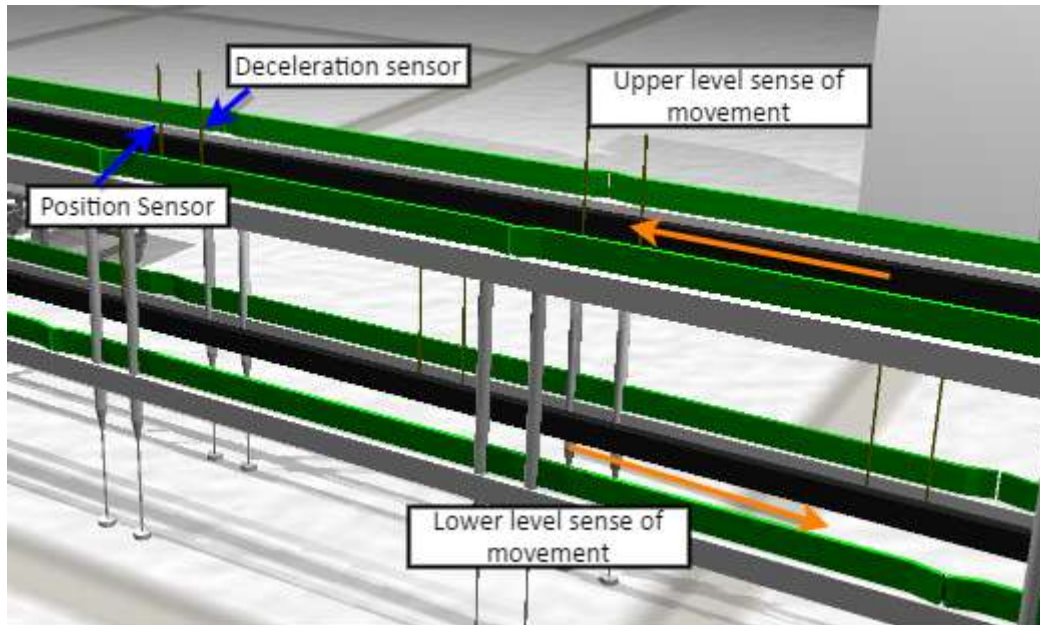
Figure 19. Basic chain conveyor with its sensors

5.4.2   Lifting Tables

In the OP035 three lifting tables can be found. This type of conveyors automatizes the process of moving the pallets from the different levels, allow pallets to be raised from the lower level to the upper level and vice versa. Lifting tables are simple chain conveyors with a hydraulic system for lifting operations. This means that they will have two sensors for the pallet movement control (proximity and positioning sensor) and five for the lifting operations. Protuberance sensor detects if a pallet gets stuck between two conveyors, whereas the other four sensors are used to control the lifting movement (up proximity and positioning sensors, and down proximity and positioning sensors). Their power source is pressurized hydraulic fluid. These types of source also require and hydraulic pump in order to manage them. Their lifting mechanism is scissor based, with double acting cylinders. The pressurized hydraulic fluid goes to the base of the pantograph making to expand the table supports and making the table go up. Their power requirement for lifting is higher than the one for transferring the pallets, 3 kW for lifting operations and 0.37 kW for the transfer operation. The sizes are the same as a simple chain conveyor, however, its height varies from 700mm to 1525mm as it is lifted.

In the emulation model, lifting tables are simple conveyors that move in the vertical axis. For this movement, a pneumatic actuator has been added. The movement speed is controlled with the pressure of the air coming from the compressor: low pressure for slow movement and high pressure for fast movement. In order to connect the pressure to the pneumatical actuator, this pneumatic cabinet has also two shuttle valves: one for lifting up and the other one to low down. Finishing with the pneumatic cabinet of the lifting conveyors, four different 3/2 way valves can be distinguished. Each one will be activated by the PLC depending on the move desired: down fast, down slow, up fast or up slow. When testing the functionality of lifting tables, an HMI panel with different buttons has been created. All the structure of the hydraulic cabinet of the emulation model is described in Figure 20:
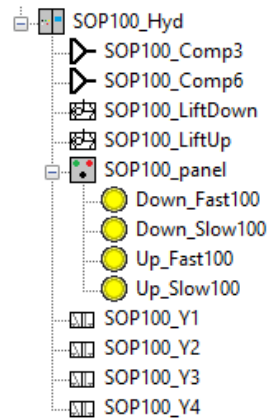
Figure 20. Structure from Simumatik3D of the hydraulic cabinet

Figure 21 shows a lifting table of the emulation model. Notice the translational joint located in the middle of the conveyor:
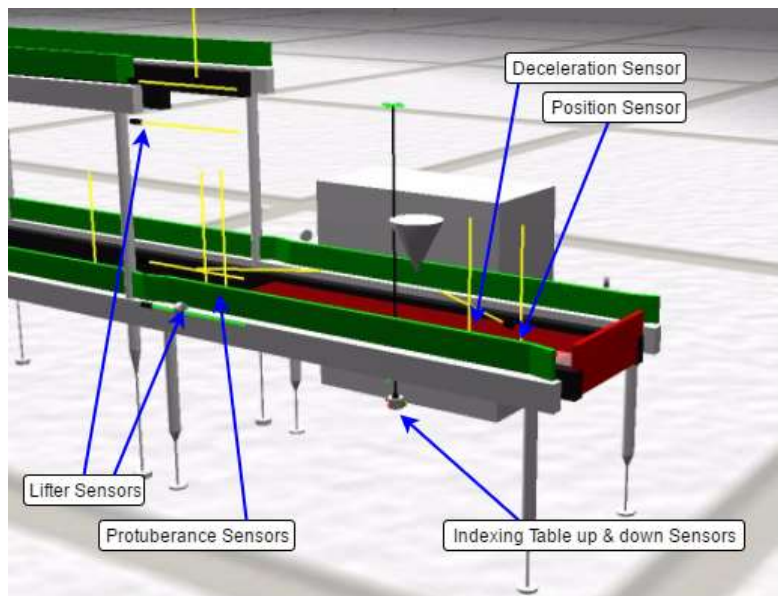
Figure 21. Lifting table with indexing plate from Simumatik3D

5.4.3   Turning Conveyors

The turning or rotary tables are also an essential element in the material handling applications. These ones move in the horizontal axis, being able to orientate the pallet. As the simple conveyors, turning tables use one AC motor connected to an Armorstart to drive the movement of the pallets. In addition, they have another AC motor and Armorstart to rotate the conveyor. Eight sensors are distinguished in this type of conveyors. Positioning and proximity sensors are required for the pallet movement. The turning of the conveyor requires two protuberance sensors, for detecting if the pallet is not stuck between conveyors, forward positioning, and proximity sensors, and reverse positioning and proximity sensors. The dimensions and power of these type of conveyor are the same as the single conveyors. They rotation nominal speed is 5rpm.

In Simumatik3D, the turning conveyors have one electric actuated motor for acting the conveyor chains and another one for the rotational movements. Two armorstarts are used to drive each of the AC motors. The movement of the pallets in the conveyor requires two sensors (one for proximity and

another one for positioning). For the turning movements, however, six sensors are used: two pairs of proximity and positioning sensors for the orientation of the conveyor and another pair for the protuberance of both sides. In the case of the turning conveyor, this one has a rotational joint that makes the conveyor turn 90°. The different elements of turning conveyors can be distinguished in *Figure 22*:
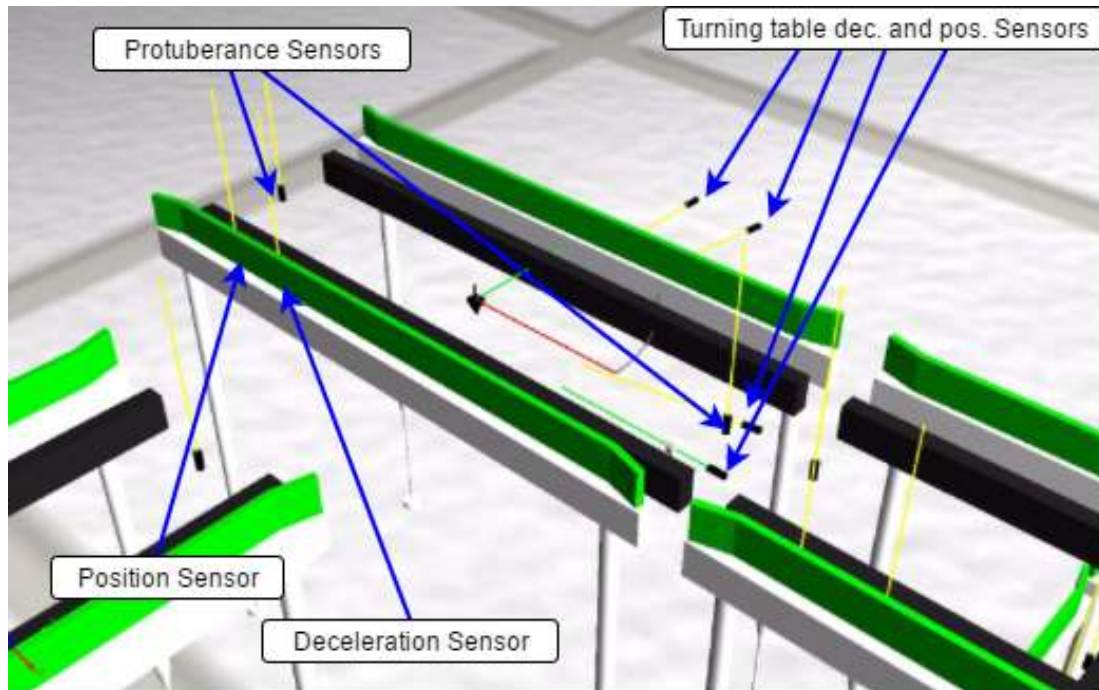
Figure 22. Turning table from Simumatik3D

5.4.4   Indexing Tables and Stoppers

In each of the two pallets indexing zones of the system, there is one indexing table. With same size and power as a simple conveyor, indexing tables have stoppers to ensure the correct positioning of the pallets. Also, a small lifter is included, which elevates the pallet from the chain when the pallet is being loaded. Both components, stoppers and lifting platforms, include sensors to detect the position. Apart from the position and proximity sensors for the pallet flow, indexing tables have one more pair of sensors making a cross above the pallet. This way, the pallet load can be verified and check if the pallet is ready to go ahead with the process.

In the emulation model, the indexing tables have been located close to the robot operations. The indexing plate is a pneumatically actuated cylinder that goes up when the pallet is to be loaded, thus the pallet is elevated from the chains when the cores are being placed. In Simumatik3D this element has been created using a pneumatic actuator connected to a translational joint. The stoppers ensure that the pallet is properly placed and aligned for the load operation. It is also pneumatically activated. It goes up when the pallet comes into the indexing table, and down when the pallet is loaded and ready to go. As well as the indexing table, it has been created using a pneumatical actuator connected to a translational joint.

In Figure 21*,* an indexing table (with the product input cone) and the red stopper in the lower position can be appreciated.

5.4.5   Transfer Conveyors

Transfer conveyors are used to turning the pallets 90 degrees while moving them from one conveyor to another. There are two transfer conveyors at the entrance of the Storage (between OP035 and OP060). As can be seen in Figure 23, this is a combination of a lifting rollers conveyor with a chain conveyor. They are placed perpendicularly, one against theother, turning 90 degrees the pallet when changing from roller to chain conveyor. Four sensors are used for the roller conveyor (approximation, positioning, up position and down position) and three for the chain conveyor (approximation, positioning and pallet detection). Two armorstart are used, one for each part of the conveyor, and a pneumatical actuator for the lifting of the rollers.
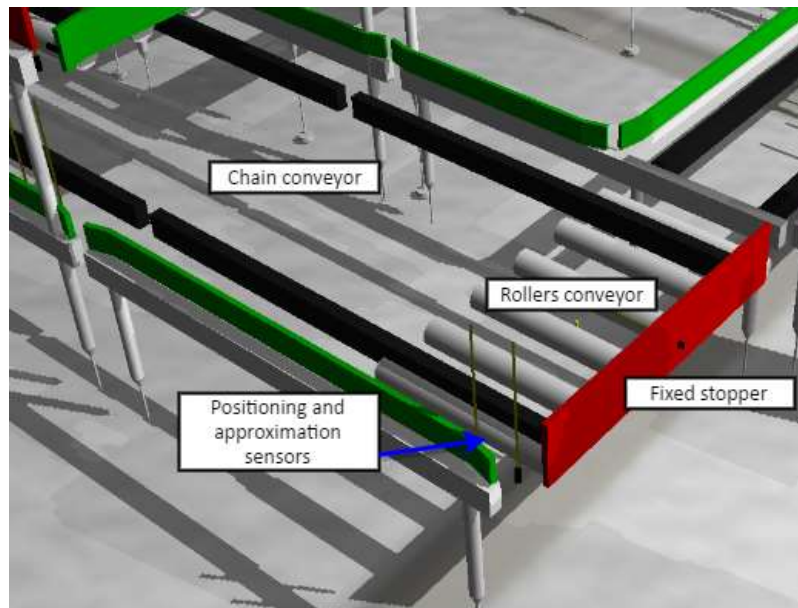
Figure 23. Transfer conveyor from Simumatik3D

5.5   Products

5.5.1   Pallets

The pallets are the main movable object of the conveying zone. They are the responsible for transporting the cores along the conveyors. The dimensions for the pallets are critical measures when building the emulation model, as an imbalance in the pallet dimensions can lead to stuck pallets during operation. The 3D model for the pallet was provided by Volvo, however, this model was detailed in exceeding, making it impossible for the program to run smoothly. The decision taken was to create a simple shape for the pallets with the dimensions from the real one. This way, the simulation will be running unaffected.

5.5.2   Cores

This concrete operation handles the sand cores that are created in the foundry, this is why cores are considered an essential part of the simulation. The 3D models used for it have been the real cores models provided by the company. There are two core shooting machines, and two different cores are produced in each one. The first machine produces the cores for water channels and other small parts from the cylinder heads, whereas the second machine produces the cover and the assembly parts. All

the models have been simplified in order to import them into Simumatik3D. The robots have also special grippers to handle and hold the different type of cores coming out from the machines. In *Figure 24*, there can be seen the various parts produced in the second core shooting machine: the assembly and its cover.
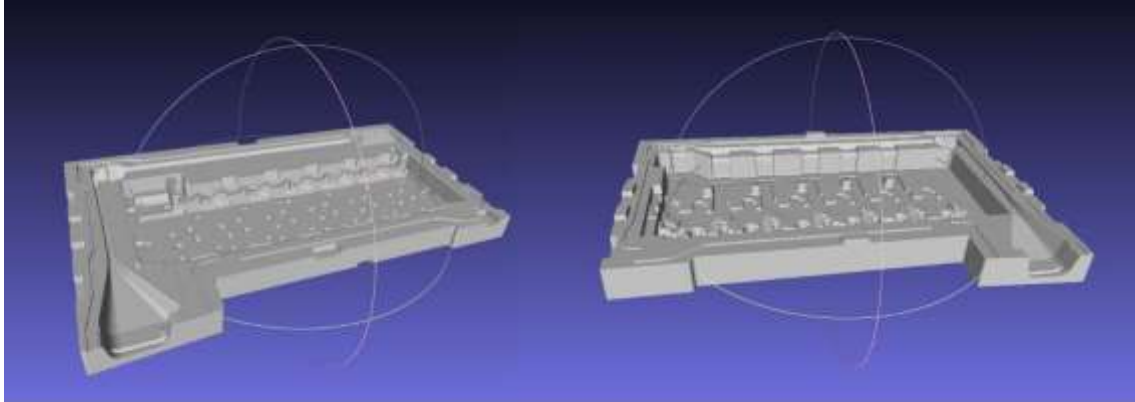
Figure 24. 3D models of the assembly and the cover

5.6   Robots and robot stool

In this operation, there are two robots with the same functionality, both are handling the sand cores coming out from the machines. The first robot is located on the SOP030, at the exit from the first core shooting machine, whereas the second robot is located on the SOP050. Both robots are standing on a stool, which is the same for both robots. The 3D model for this element was provided by the company. Then, a simplification by the MeshLab program was needed before importing it into Simumatik3D.

The robots used in this application is the ABB IRB 6640.

5.7   Robot Grippers and Holders

The implemented robot uses specifically designed grippers in order to hold securely the cores and load them into the pallets. The 3D models for the grippers and holders were provided by the company. OP030 robot will use the gripper for picking up the small parts of the cylinder head core, whereas the OP050 robot tool is a holder for the cover and assembly parts. The CAD models give a more realistic look to the emulation model.

In *Figure 25*, small parts gripper and assembly holder can be seen:
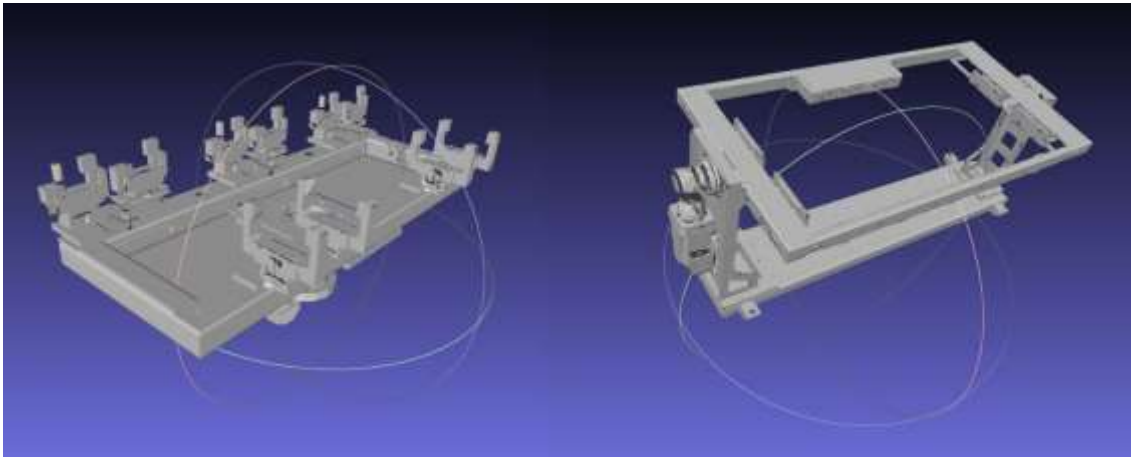
Figure 25. Grippers of the robots OP030 and OP050

5.8 HMI panel

One of the essential parts of the simulator is the HMI panel which is incorporated into the model. This HMI virtual panel will represent the real HMI with physical buttons that it is installed in the line. From here is possible to control the starting and the stop of the operation, the reset of the alarms, the power into the line, etc. In the *Figure 26* can be seen the developed HMI panel compared to the real one. As it can be seen, the virtual twin of the HMI panel looks similar to the real one, so as the positioning of the buttons, colors, and names are practically the same.

Figure 26. Real HMI in comparison with the virtual HMI panel

Apart from this basic HMI panel, it is also installed a real Allen Bradley HMI panel in the Operator Training Simulator. This HMI panel is the same used on the real line, and both are running the same program. This makes it possible to control specific parts of the cell manually when needed. For that, the used HMI panel used is the Allen Bradley Panelview Plus 700 and has a touchscreen to make easier the working experience.

In *Figure 27* it can be seen the program that is installed in this panel, considering that is the same used on the real line and has been specifically created for this line.
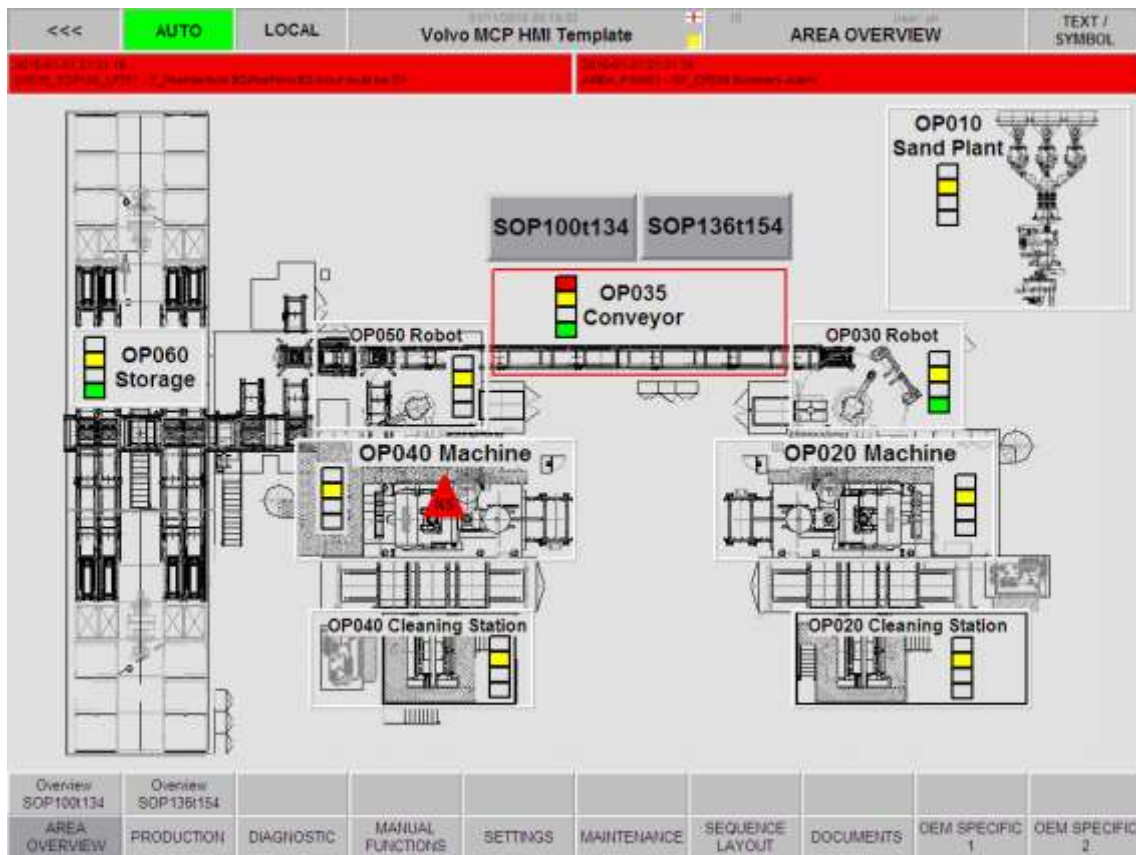
Figure 27. Program installed in the HMI panel

5.9 Model finery

In order to give a more immersive experience and give a much better quality to the representation of the real model, many decorations and added elements were introduced to the model. In this way, the user can recognize the working area much better to the one that he is preparing so as it looks really similar to the real foundry. Although these models have no relevance in the system, their importance in the application of learning is considerable. If they were no decoration elements, it would be hard for the trainee to locate himself in the situation and the elements that need to repair or the problem where needs to fix. As it can be seen in *Figure 28*, the emulation model increases a lot in realism with the finery:

Figure 28. Emulation model before and after the finery addition

6   Control program and communication interface

In this chapter, the implementation of the control program to the emulation model is explained. An in-depth analysis of the communication between different software used and the conditioning of the original PLC program is done.

6.1   Communication Interface

Once the simulation model is finished, communications must be established between all the devices in the emulation model. This setting should be done both at the physical level (connecting the hardware with Ethernet cable) and in digital level (finding the proper way to communicate the software). For this process is necessary to have analyzed the signals coming from the PLC and have chosen the ones that are going to be implemented to the emulation model.

Consequently, the communication between different parts of the emulation project is explained. As an introduction, the importance of having all the signals properly connected will be stressed.

6.1.1   PLC Inputs and Outputs

As mentioned before, the PLC program has 185 I/O signals from which 175 are going to be used in the emulation model. Important information from the controller Tags list, such as variable type and bits used, must be noted before starting with the communication settings. This step is crucial if any signal is unproperly connected to the emulation model errors will appear in the system functionality and the proper execution of the PLC program will be jeopardized.

When working with a lot of signals, mistakes can be easily made. A list with all the signals and information regarding each one was used in this part of the project. It provided useful as a checklist to ensure that all the signals were properly connected.

6.1.2   HMI to PLC

From the touchscreen, the operator can visualize the state of the different variables of the system in real time, as well as actuate on it. The HMI communicates directly with the PLC. Both the control program for the PLC and the HMI are loaded by their respective software (RSLogix 5000 and Factory Talk View) to the devices. The connections layout between the HMI and the PLC can be seen in *Figure 29*:
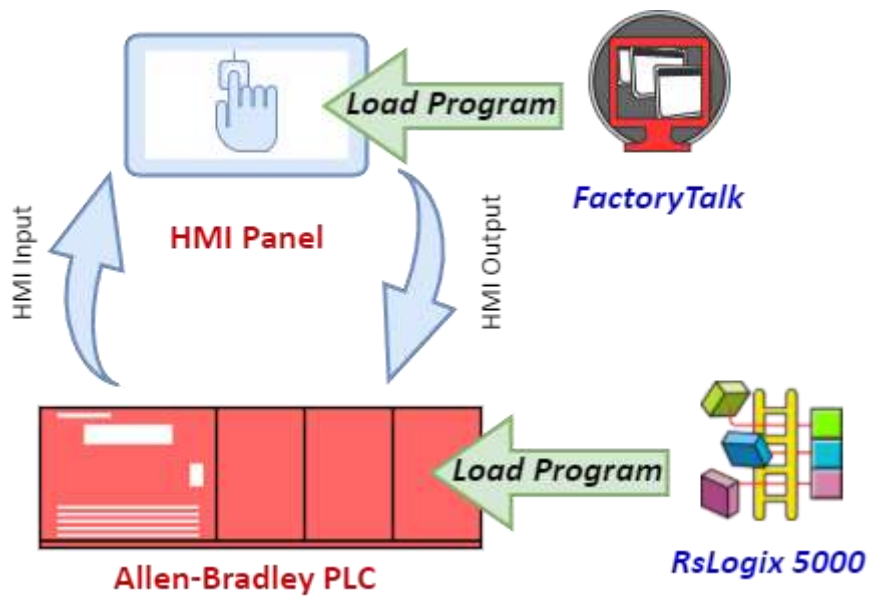
Figure 29. Communications layout between the HMI panel and the PLC

The operator gives orders using the touchscreen, these HMI inputs are sent to the PLC, which actuates accordingly to the command. The PLC sends the information regarding the system (outputs to HMI) in order to be visualized in the HMI. Both the HMI and PLC programs are also running on the PC, from where the execution can be visualized.

6.1.3   PLC to Simumatik3D

The communication between the PLC and the Emulation model has been done using an OLE for Process Control with Unified Architecture (OPCUA). This communication protocol allows the data exchange between different platforms regardless their operative systems or programming language. The OPCUA server used has been developed specifically to be used with Simumatik3D and includes the necessary drivers to communicate with Allen-Bradley PLCs. In *Figure 30* the communications layout between PLC and emulation model in Simumatik3D can be visualized:
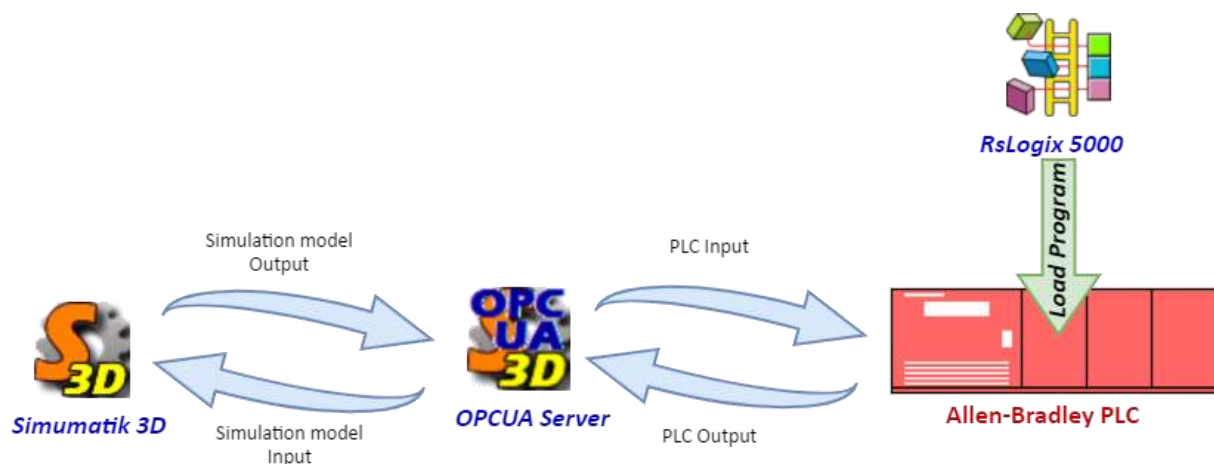
Figure 30. Communications layout between PLC and emulation model

As can be seen in *Figure 30*, all the data exchange between PLC and the emulation model goes through the OPCUA server. The name and variable type of the tag in the PLC must be copied in the OPCUA server, so it can be identified. In addition, the name and type of the signal in Simumatik3D should be the same as in the PLC and OPCUA server. This way, the data stored in the PLC is read by the OPCUA Server and sent to the Emulation model and vice versa. PLC Inputs such as sensors, Armorstart status words, and buttons are sent from the emulation model to the PLC. The PLC is simultaneously reading the inputs, running the control program and sending the commands to Simumatik 3D (PLC Outputs).

6.1.4   RoboDK to Simumatik3D and PLC

For the industrial robot's operations, the real program has not been used. Instead, an approximate sequence has been developed using RoboDK software. This program executes the robot sequence and communicates with the emulation model and PLC, using the OPCUA server as an intermediary. The OPCUA has the drivers for the communication with RoboDK software. This way, the communication setup only requires the name of the RoboDK controller (robot name in the RoboDK program) and the signals name to be the same in Simumatik3D, OPCUA server, and RoboDK program.
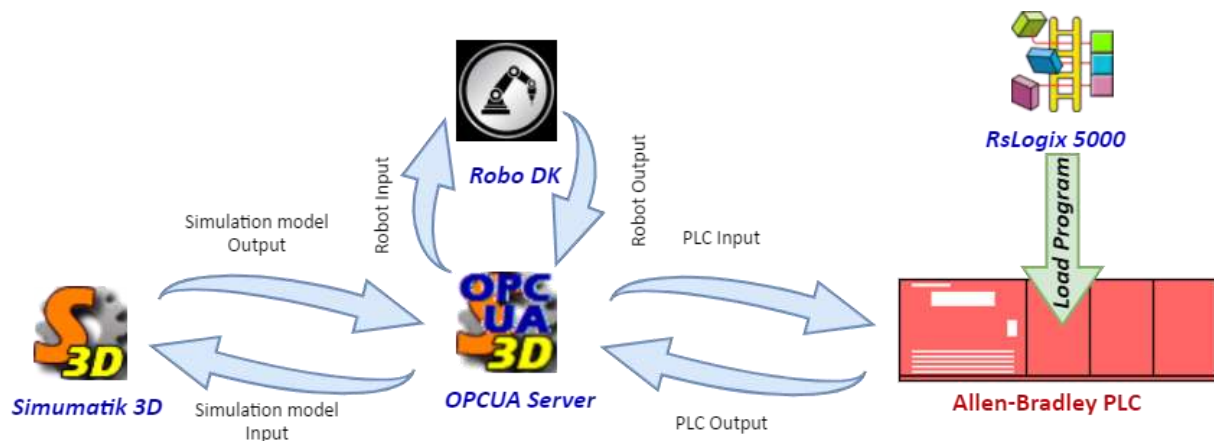
Figure 31. Communications layout between RoboDK, emulation model and PLC

As can be seen in *Figure 31* the RoboDK software sends the robot outputs to the OPCUA and then to the Simumatik3D. In the same way, RoboDK software communicates via OPCUA server with the PLC, reading and writing the correspondent signals of the robot sequence. The robot in the emulation model will move according to the sequence determined by the RoboDK and PLC program.

6.1.5   General Communications Layout

As mentioned before, setting the communication between the different devices in the system must be done both with the software and the hardware. The different programs used should be able to "talk" to each other and the hardware must be well connected.

Ethernet/IP is the communications protocol used on the local network. The first step when creating the local network was to define an IP address for each of the nodes. Regarding the hardware, the network is composed of three personal computers, a PLC, HMI and a switch to interconnect the devices (see *Figure 32*):
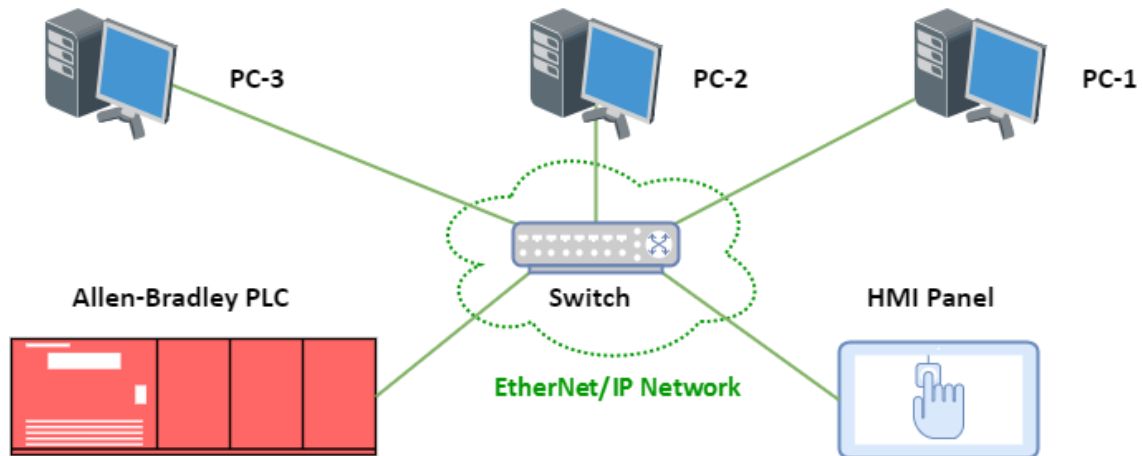
Figure 32. Operator training station network layout

All the hardware is connected to the switch using Ethernet cable. This way, the network created has a Star topology, a simple architecture that eases the mounting, and enables the adding of new devices by simply connecting them to the switch.

Each PC is responsible for the execution of specific programs. PC1 is used to download the PLC program and HMI programs to the hardware, as well as to visualize the execution of the control program when the simulation is running. PC2 runs the OPCUA server which manages the communications between the programs. The RoboDK software is also running on this computer. PC3 runs the emulation model in it (see *Figure 33*):
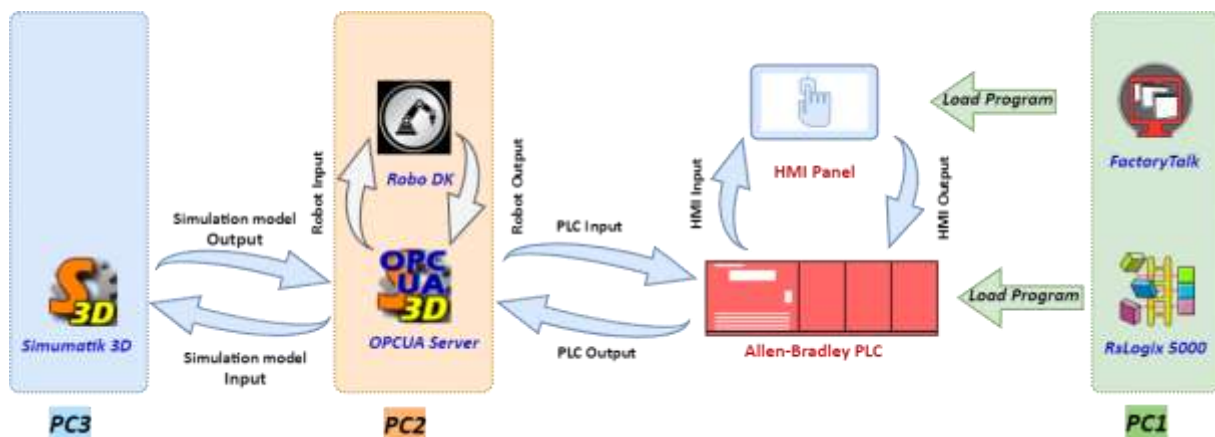
Figure 33. General communications layout

6.2   PLC Program

The control program running in the PLC is the one provided by Volvo. Even though bridges has been added to inhibit some of the functions, the highest effort has been taken in order to keep the program as similar as possible to the original in the factory.

The PLC program is structured in 3 main tasks plus a safety task running in parallel. *Main Program task* executes the principal routine of the program, including the communications with the HMI panel and the diagnostics of the general faults. The *OP035 task* is responsible for communicating with all the equipment in the conveying line, as well as to control the actuators in it. Both tasks, *Main Program* and *OP035* have a medium level of priority. The last task ensures the communication between the other upstream or downstream PLCs in the production line and has the lowest priority level.
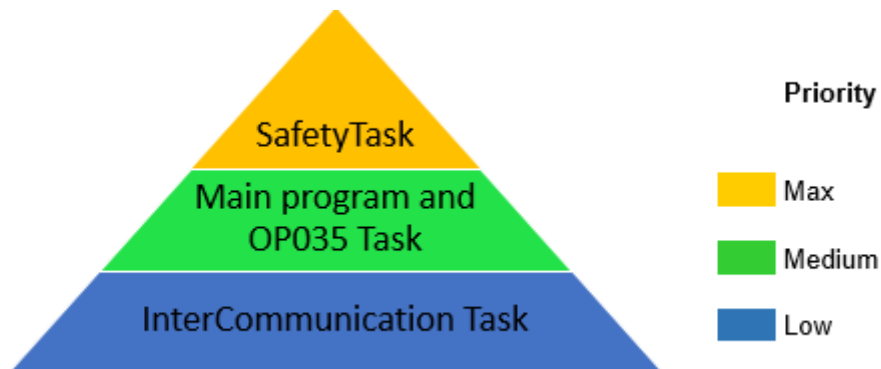
Figure 34. Priority level for the PLC program tasks

The safety task runs the safety program, which as can be seen in *Figure 34*, has the higher priority. Due to some difficulties emulating the safety hardware and signals, such as Emergency Stops, Light Curtains or gate entry lockers, this program has had some modifications so the control program could work normally. These elements have been bridged in the program resulting in the inhibition of the safety function.

7 Operator Training Station

In this chapter, the implemented Operator Training Station's structure and functionality are described. In addition, the market integration for this concept is addressed.

7.1 Faults and Alarms Study

In order to make the training station as effective as possible, the best idea when implementing the failure situations is to choose the most common ones. In a factory, some problems tend to happen more than others. With the aim of finding which faults happened more in the production line, an interview was held with the operators from the Volvo's G2 foundry. Very interesting conclusions were drawn from these interviews, in which the operators mentioned a list of alarms and faults. The failures enlisted below were deduced to be the most common ones as they were frequently commented by the expert operators:

- One of the most common fault in the system is the **pallet data shift**. It sometimes happens that the information of a pallet is not correctly transferred from one conveyor to the next one. Because of this, the PLC program has a mismatch between the information and the pallet position (the sensors of the next conveyor detect that a product has already reached there but pallet data is missing), so a failure situation occurs.

- Another usual failure of the system is the **break of different components**. All the processes in the line are timed, and any imbalance will cause a fault. If a component breaks down, the sequence execution is compromised, the timing is mismatched and a **timeout** fault is generated in the control program. In the *Simumatik3D* software, many components can be easily "force broken" to emulate this failure. Breakdown of sensors, motors, and pneumatical components have been implemented to the training station.

- The safe operation of the production line is a key factor for any company. The conveying line can be accessed from several points along the factory. For safety reasons, if any **door** is **not properly closed** a failure will be generated and a part of the operation will be stopped working until the door is closed.

- Another possible fault of the production line can be that the **movable units**, like the turning tables or lifting tables, do **not move properly** or they get **stuck in half-way**. The turning tables sometimes do not align with the following conveyors. In the case of the lifting tables, the pneumatic system suffers a power drop, not elevating as they should, stopping before reached the upper position. In this case, the failure situation will also be generated because of a timeout if the production line.

7.2 Training Station

Even though the most common application for emulation models might be the virtual commissioning of manufacturing operations, the chosen use for the OP035 emulation model is operator training. The idea of this emulator is to work and behave the same as the real operation, even including some of the real components such as the HMI and the PLC from the factory. For a better imitation of the real operation, more hardware would be required (pushbuttons from the HMI panel, Emergency Stops, door lockers…), however, the emulation model itself offers a way of visualizing the system in the real time, that is a tool of great educational value.
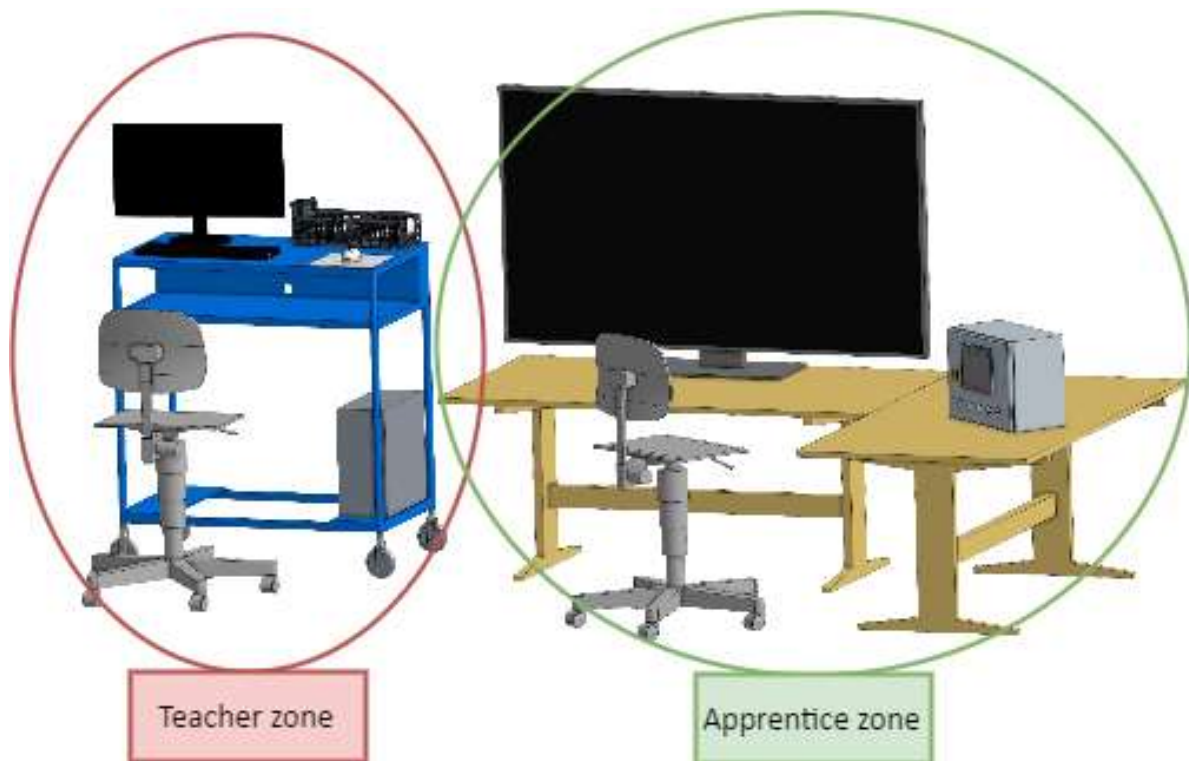
Figure 35. Operator training station concept design

As seen in *Figure 35*, there can be distinguished 2 zones in the OTS concept. The first one is the teacher area (left side), from which the expert operator can follow the training program, generating faults in the system for the trainee to fix them. Here the PLC program and emulation model are executed and visualized. The second zone is the apprentice area (right side). Here the rookie operator has the HMI panel and a big screen with the emulation model in it. Actuating in both the HMI panel and the emulation model, the apprentice must fix the failures and alarms that the teacher generates.

In order to create the operator training simulator mentioned in this project, different hardware and software elements have been used:

7.2.1 Hardware requirements

Regarding the hardware of the simulator, and as mentioned above, some of the factory hardware has been implemented into the station with the material provided by the University and the own material from the authors. The main intention was to set up the basic structure possible within the need to fully complete the operator training station.

In the hardware structure of the simulator the next components can be distinguished: a desktop computer with the PLC program software (RSLogix5000), an Allen-Bradley PLC and HMI, a PC with the OPCUA Server and RoboDK software on it, and another PC with the emulation model running on it (Simumatik3D software).

The emulation model has been run in two different type of computers. These tests have concluded that for the smooth running of the emulation model, some hardware requirements are strongly recommended:

- Up to 16GB of Ram
- Video graphics module with 2GB memory size and DDR5 memory type.
- Intel Core i7 processor unit

7.3   User Manual

For easy future modifications or set up of the OTS solution, the distinct aspects and configuration process of the training station have been explained in a user manual. The user manual goes through hardware, software, and communications set up required at the beginning when initializing the operator training station. Then, the procedure to start the process sequence (display virtual HMIs, resetting the system, introducing the pallets…) is explained in the second part. The different failures that are integrated into this simulator are also described in this manual and how to generate them. In the last part of the user manual, the proper and safe shut down and power off process for the station is clarified.

7.4   Market Introduction

As part of this thesis, it has been analyzed the possibility to integrate this operator training station into the market. First of all, it must be pointed out that the operator training station developed in this project is just a concept to evaluate the affordances of emulation into training applications. It has never been a goal to develop a competitive product, however, it might be interesting to analyze the budget and draw practical conclusions. Several assumptions must be borne in mind before assuming that put the product on the current market will be worthwhile.

The product will not only consist on this concrete operation developed, but it will also consider the possibility to include the whole production line into the station. The prospective buyers are considered any company that has a production line already, a company that is planning to build one or even the line's manufacturers itself. This way, if both the manufacturer and the company get involved in the process, the benefits afforded by the operator training station will be maximized.

The production line manufacturer should be committed to selling its line together with the emulation model and instructions to easily connect to the company's PLC. Thus, the company will get the line installed as well as the emulation model. An emulation engineer will be necessary to get the training station set up and to implement any future changes in the line to the emulation model.

7.4.1   Budget of necessary elements

For this market study, is not possible to create an exact budget of the operator training station. Some factors, such as different licenses for the programs that are normally available in the company, can have a huge impact on the final budget. Ideally, the manufacturer responsible for building the production line will sell the required software licenses as well, however that cannot be granted.

In the following table, the approximated cost of every element involved in the station is shown:

Table 2. Budget approximation for the operator training solution

Element	Prize
Desktop computer	≈ 600 €
Screen	≈ 400 €
Allen Bradley HMI panel	≈ 1300 €
PLC	≈ 1500€
Communication Accessories	≈ 50€
Program licenses	--- (the company should have it)
TOTAL	≈ 3350 €

As can be seen in *Table 2*, creating an Operator Training Station costs less than 3500 € in material elements. Including the price for the time consumed setting up the station and the costs of the station and digital model maintenance that would be the total budget estimation.

7.4.2   Marketing Techniques

For a better commercialization of the product, it has been thought that it would be better to sell the training station in two ways. The first option would be to include both software and hardware elements in the sale, whereas the second option would be just to sell the software (Simumatik3D emulation model, OPCUA server) together with the installation manual. As many companies tend to have available hardware in the factory, the second option would be an adequate one and would skip quite important costs from the hardware.

7.4.3   Product budget summary

In conclusion, the complete solution, including both hardware and software, which has a budget of less than 3500€ apart from the engineering work cost, does not have a competitive budget for the integration to the market. However, in the cases where the companies have their own hardware available to set up the station, the budget will be reduced by more than 80%. It would be an interesting idea since it does not involve a huge investment and it can bring benefits for both the company and the workers from the factory.

8   Testing, Verification and Validation of the emulation model

In this chapter, the main experiments conducted to validate the emulation model are explained and reasoned.

8.1   Experiments

There were two objectives when conducting experiments with the emulation model. One was to prove that the model could execute the real system's sequence with no errors. The second goal was to assess and qualify the degree of realism of the emulation model in comparison with the real production line. In order to accomplish both goals, three different experiments have been conducted for each one. The first three tests from below allude to emulation model sequence, whereas the last three experiments are related to the model's grade of realism. All the tests were conducted following the instructions in the Operator Training Station user manual, and all the information regarding the experiments was gathered in the Test and experiments sheets.

8.1.1   Functionality

This test was conducted both in the emulation model and the PLC. The system was loaded with 10 pallets and put into two different modes of operation; empty and normal production modes. The sequence must be executed perfectly and no pallets should get stuck. The objective of this test was to prove that the system could be running for a long period of time (2 hours) without having any error neither in the emulation model nor in the PLC control program.

The experiment resulted in a success. It was proved that the Training Station could be running with a considerable pallet load for up to 2 hours. The satisfactory result from the test was obtained in both operation modes.

8.1.2   OP060 PLC code integration

As the new code was added for the OP060 PLC, it must be verified. This test was conducted both in the emulation model and the PLC. OP060 works as an empty pallets feeder for the OP035. For testing this part, 10 pallets were introduced at the end of the OP035 line. The OP060 must read the information in those pallets, take them from the upper to the lower level and send their information back to the OP035 PLC. One of the authors checked the new PLC code execution while the other was checking the pallets flow along the conveyors. The goal of this test was to check if the PLC code added was properly executed and if the OP060 part from the emulation model worked as expected.

The results of this experiment were positive. The emulation model run smoothly and the OP060 pallet feeder worked as expected. No collisions nor stuck pallets occurred during the test. Regarding the PLC, both programs communicated properly, transferring the pallets information without errors.

8.1.3   Stops Test

This test was conducted in the emulation model and supervised in the PLC. Different stop sequences were tested; cycle stop button and halt stop. Each stop type was tested in different scenarios and studied how it affected to the production. The main goal of this test was to prove if the different production stops could be reproduced in the emulation model and if the PLC will react accordingly to the stop orders. The emergency stops could not have been tested, as the Emergency safety buttons are not implemented in the OTS.

The scenarios in which the stop procedures were tested are the followings:

- The pallet is moving from one conveyor to another and no sensor is detecting it.
- Lifting table is in halfway from upper and lower position (no sensor detecting).
- The pallet is being transferred from OP035 to OP060.

The results of this test were as expected. For the cycle stop button, the pallets stopped after finishing the execution (at the end of their respective conveyor). All the movements were finished before stopping, stopping the pallets in an orderly manner. For the halt button, the processes were stopped instantaneously, despite the position of the pallets. Some of them stopped in between operations.

8.1.4   Failure replication

The failure replication experiment has been conducted in the Operator Training Station, and both the emulation model and the PLC were tested. Different faults and alarms situations have been generated in the emulation model and PLC program, using in some cases an excel file as a support tool. The main objective of this test was to prove that the emulation model was able to generate the most common failures from the real production line and that the PLC reacted accordingly to each failure in the emulation model.

The failures and alarms generated in this test are enlisted below:

- Timeout alarm. Different ways of generating this alarm were tested; component breakdown (sensors, motors, and pneumatic device) and pallet stuck.
- Data shift. When the pallet information lags from the pallet this fault is triggered.
- Power Line Shutdown

The failure replication's result shows that the simulator reacted as the real system, shown or emerging the same error message in the HMI panel.

8.1.5   Troubleshooting

This test is based on the ability of the system to repair the failures replicated in the emulation model. Troubleshooting experiment has been conducted in the emulation model and HMI panel, and its main objective was to demonstrate that the failures generated in the Failure replication test can be solved as in the real production line. The experiment was conducted by the operators from the Volvo GTO factory, during one of their visits to the University. For this, the operator will need to find the source of the problem in the Simumatik3D emulation model and try to solve it using the HMI panel. This test has been conducted together with the Failure replication test, by putting the line into operation after each failure was generated.

This test has evidenced that, all the failures generated can be solved using the HMI panel and actuating in the emulation model. This result proves the validity of the emulation model to be used as an operator training tool.

8.1.6   Robot Integration

Despite the robot is a primordial element in the real production line, this test has only focused on its appearance. The RoboDK program implemented to the robots in OP030 and OP050 and emulation model have been tested in this experiment. The expected result for this test was to validate the robot's

behavior; it must pick the cores and place them in the pallets at determined times during the execution. With this purpose, some pallets were loaded in the emulation model, and the robot behavior was monitored.

The robot placed successfully the cores in the respective pallets, respecting the timing of the sequence and properly communicating with the PLC and emulation model. The movements were approximations to the real robotic equipment ones, and that's why some of the movements (grippers open-close movements, tool changes or emergency stops) were not implemented in the robot sequence.

8.2   Verification and Validation

The aim of the different tests conducted at this phase of the project is to verify the emulation model and validate it as an operator training station. The first point is the verification of the emulation model as an accurate representation of the real system. This means that the model must fulfill the specifications and customer requirements enlisted at the beginning of the project, as well as follow the sequence of the real production line. The second point regards the validation of the operator training station, which will check if the model can be used as an OTS.

The integration of the PLC and HMI hardware with the emulation model has been successful as proved by the experiments, in which the system communicated perfectly with both parts. The software used for building the emulation model was suitable for this application, as it worked properly without issues. As seen in the Experiments, the correct function of the emulation model has been verified. The emulation model has been tested in different scenarios without any errors or malfunctions during operation, proof of the correct implementation of the emulation model.

A high face validity model was aimed when building the emulation model, it must be valid for the application it was designed. For the validation, different aspects must be considered. Firstly, one of the main aspects when creating the operator training station was to properly implement the different faults and alarm situations from the real production line. As the Failure replication test has proved, these alarms can be generated in the system and then corrected by the operator. In addition, the appearance of the emulation model has been improved to a level that resembles the real factory. Secondly, for the OTS to be validated, it must be approved by the factory operators. To this end, a sensitivity analysis has been carried out, in which the operators from Volvo GTO tested the training station. They reviewed the model by looking for deficiencies and concluded that it was an accurate representation of the conveying line in the factory.

All these characteristics and operators statement, provide evidence of the emulation model's validity, and proof that it can be used as an Operator Training Station.

9 Evaluation of the Training Station

In this chapter, the Operator Training Station is appraised both from the visual point of view and the behavior under execution. The simplifications made to the model are also explained in this section.

9.1 Appearance

Visually, the model must look as close as possible to the real production line, and for the correct execution, the sequence of the PLC program must be followed rigorously.

Due to privacy policy from the company, images of the real foundry cannot be displayed. It would be interesting to make the comparison between the original system and the emulation model, as it would bring some relevant conclusions. Despite this fact, in the virtual model developed a clear picture of the system can be obtained. The reason behind this is that each element from the factory has been represented. These objects give the emulation model a similar appearance to the original. Despite not having any operative functionality, these elements enhance the system providing a reasonable grade of realism to it. (See Figure 36)

Figure 36. View of the complete emulation model

The true appearance of the simulator is also found in moving parts such as conveyors, stoppers, robots, turning tables and indexing tables. These elements really have to be both visually and functionally similar to the real system. Dimensions of the tables, speed for the conveyors and execution timing for the operations are crucial factors when ensuring the correct function of the PLC program. All these measures have been respected, thus, the PLC program functions correctly without any failure during execution.

9.2   Sequence

The sequence of the simulation program is the same as that of the real system in the factory, despite having modified some aspects of the PLC program. The safety task from the original control program has been inhibited, respecting the execution sequence in its entirety even though the program used is slightly different.

If the sequence of the model was not absolutely the same as that used in the Volvo factory, the virtual twin would no longer be a success, since it could not be implemented as a copy of the real production line. Having a functional model that respects the real sequence is by far the most important part of this project since otherwise the system could not be given as valid.

In the appendix of this project, a video with both the sequence and the appearance demonstration is shown.

9.3   Simplifications

For a one term project, time management is crucial, meaning that the time dedicated to each part should be previously calculated and efficiently distributed. When building the emulation model, some simplifications have been made to reduce the time required for each task.

It is also necessary to keep in mind that this project will have some limitations. These are usually due to several factors such as software, hardware budget, knowledge and time limitations for the developers of the project.

In *Table 3* a list of the overall limitations may have been found throughout the development of this project can be appreciated. Together with the limitations are also stated the simplification considered:

Table 3. Considerations and simplifications took in the project

What was simplified?	How was it simplified?	Why was it simplified?
Conveyors' turning and lifting mechanism	Using simple axis (linear for lifters and rotational for turning) instead of the complex mechanisms of the real system (e.g. scissors lift)	They are easier to model and implement in Simumatik3D
Safety elements	Bridges in program code	In order to run the PLC program with fewer modifications as possible
Some hydraulic and pneumatic sensors	Bridges in program code	Do not fail often and not necessary for the functionality of the OP035.
Production line ending	Creating a loop for the pallets,	Because is a work which is not within reach of this project.
Grippers and holders of both robots	For the grippers, the real 3D models are used, however, the holding mechanism (movement of the different parts) is not implemented. Simplified with a locker object in Simumatik3D.	Because the real program of the robots was not used, and in order to save time.
Model finery (visual elements)	Creating 3D models as close as possible to the real elements or not including them.	In order to save time.

10 Discussions

In this chapter, the discussions of the project development are stated, including the problems that were faced and the impressions from the authors.

The time planning has been respected quite well throughout the project. The project has gone approximately as planned in the initial Gantt diagram. The initial long-term and broad-ranging deadlines were easy to meet. A more specific planning was done after the mid-term, in which the times for each part were specified in more detail. This time schedule was tighter, and we struggled to meet some deadlines we had set. This led to some delays in the planning (less than one week delay for the method and less than 2 weeks for the writing part), but we could manage to finish all the parts before week 21.

The division of labor has helped a lot in getting the job done on time. Being two people working on the same project is not functional or useful if both are work at the same time on the same task. In order to avoid this problem, the work has been divided accordingly to the specialty of the knowledge of each one, making the flow of the development of the project go faster and thus work more and better. In the distribution of work, one has focused on the emulation model and its operation, while the other has concentrate on the PLC program and its correct functionality.

At the time of developing the emulation model, there were no major problems. The knowledge of Simumatik3D software required was sufficient from the first day, and for the end of the project, it has been enlarged as well as the agility with it. This knowledge was obtained thanks to the course that both had completed at the University of Skövde, having Mikel Ayani as the main teacher, responsible for the software development.

PLC programming knowledge has been broadened and adapted to work with RSLogix5000 software. It has been necessary to adapt our PLC programming knowledge (CodeSys, Siemens TiaPortal, and OMRON) to the software used in this project, RSLogix 5000 from Rockwell Automation. Despite it was not a major difficulty, the given opportunity to obtain knowledge about other PLC manufacturer programming software is considered a very positive aspect.

The market integration of the solution can be done in two ways. When analyzing the market solution, the potential buyers were clearly defined. The objective of this solution is to focus on companies in which operators have a relevant role or companies that manufacture production lines and want to add an extra component to their service. From the manufacturer part, it will include the Operator Training Station with its corresponding specific manual as a part of their service when building the production line. The companies that want to incorporate it to their factory could get them also. Depending if the company has the required hardware or not the price will vary for this solution. The decision was to calculate or create two different solutions with their respective prices: one with the included hardware and the other one only with the emulation model and its specific manual.

Some simplifications of the production line were needed for the correctness of the simulation. This project is based on the behavior of Volvo's G2 foundry OP035 operation. Although it was intended to demonstrate that this project can go beyond this operation, due to the time limitation, the operations before and after OP035 has not been implemented. The emulation model created follows the sequence of OP035 and the following storage, OP060. This operation has been modified so the pallets

are brought back into the OP035, a simplification of the storage operation. Although in the OP060 the pallets go directly to the warehouse, a circular sequence has been created in which the pallets are looped.

The 3D models used for this project have mostly been simplified. The CAD models provided by the company of Volvo were models from the design department of the company. Therefore, these are models with an extraordinary resolution and a high grade of detail. Thus, when loaded these models generated a slow execution (lower speed of FPS during operation) of the simulator. For that reason, the models with higher details were decided to be simplified in MeshLab before importing them to Simumatik3D model.

Most of the development programs used for the simulation are free. In order to reduce costs in the final solution of the Operator Training Station, it is necessary to take into account that a great source of expenses is due to the software licenses. Therefore, many of the programs chosen for this project are free or are possible to use without a paid license. Considering the programs used, 5 of these can be used free of charge:

- *Simumatik3D* for the emulation model.
- *Simumatik3D OPCUA* Server for the connection between Simumatik3D and OPC UA.
- *OnShape* for the creation of the 3D models.
- *MeshLab* for simplifying the complex 3D models.
- *RoboDK* for the execution of the robots in the simulator.

It has been necessary to inhibit the safety task of the PLC program. The control program used in this simulator is the same as in the real production line. It is important to consider that the safety of the production line in Volvo's production line is tight and complex. This way, if something unusual happens during the production sequence, the line stops generating several alarms or faults. For this, it has been necessary to modify the control program. Bypassing some functions in the program the simulator was able to work with it. These changes do not affect to the original execution sequence.

The constant changes in the simulator are necessary for correct functionality. It is necessary to consider that in the company in which the simulator will be installed, there must be someone in charge that, if any modification is made to the original system, same must be done to the virtual model. The person responsible for the model maintenance will need to understand the Simumatik3D program, as the manual does not include these instructions, and will be responsible for applying all the changes to it. These should be informed of the service offered by the seller of the Operator Training Station. This is because often changes are made in the PLC program or new elements are installed to the production line. If these changes are not notified, the virtual twin sequence will not be the same and the simulator would lose its functionality.

This station can turn useful for PLC code errors detection. Although this is not its main functionality or aim, this program can be very useful to generate certain situations in which it is not known how the system would behave, and verify that the code is executed correctly. When creating a new PLC program, it is also possible to implement it first in the virtual emulator, and once it has been verified, install it in the real system. This can avoid the components break that the company could have for the incorrect installation of the program, and even more important: the possible failures that can be given in long time period due to the bad verification of the program on the real process.

The aim or the idea would be to implement Operator Training Simulator concept to all the factory. This project has been limited to a single part of the production line of the cores, however, a more ambitious idea would be to be able to implement this type of work to the whole production line. This would not only give the opportunity to verify the failures of the system, but it will also give the possibility to integrate trained operators at any point of the factory. With the model of the whole factory many benefits could be brought, such as executing the production at a faster speed, been able to obtain different data from the production line in order to improve the processing times, see how many workers or operators are really needed, be able to automate the line much more etc.

Sustainable development has been taken into account throughout the project. This is an important aspect of the project to whom industries should pay more attention. Using the emulation model as an Operator Training station can lead to several improvements in some fields of the sustainability development. The main benefits are in the economical field, as the training expenses of the operators and other staff can be reduced in the long run. The repairing times for some operations and line failures could be reduced as well, leading to an increase in the production. In addition, the social outcome relies on the reduction of the personnel stress while working. Despite all those aspects are beneficious for the company, a commitment should be desirable to reduce the environmental footprint. There is no direct effect of the project in this field, but the emulation model created could be used with other purposes. The author's proposed approach is to use the model to study the line energy consumption and different ways to minimize it. All the information needed to carry out this study can be obtained from the emulation model software. Furthermore, some projects related to this field have been developed this year, and it would be interesting to see which goals could be reached by working together.

11 Conclusions

In this chapter, the main results obtained during the project are summarized and conclusions are drawn.

11.1 Results

The principal conclusion that can be drawn from this project is that it has been a success. The **main objectives of the project have been achieved**, creating a visually attractive and completely functional operator training station for the OP035 from the Volvo G2 Foundry.

The visual appearance of the emulation model has reached a considerable level of realism. Respecting the layout and scale of the real factory, as well as importing some 3D models for the details, make the emulation model look very similar to the OP035 production line operation. Of course, it is far from being an exact copy of the original, but it is appropriate for the operator training application.

The real hardware elements, PLC and HMI, are properly integrated into the emulation model. The implementation of the real hardware from the factory has been done successfully. In fact, the control program running in the PLC is almost the same as in the real line. Changes in the code have been minimized as much as possible, only disabling the safety program. Despite these changes, the sequence remains unmodified, being completely original. Furthermore, the HMI panel, as well as the PLC, is the same used in the factory. It retains the original program and works exactly as it does in the real conveying line.

Most of the common failure scenarios in the real operation have been included. It has been proved that the main alarms and failures from the OP035 conveying line could be generated in the emulation model. This was one of the more interesting aspects when using the emulation model for the operator training application. The simulator would not be useful for testing the operators if the failure scenarios were not implemented appropriately. However, there has been an exception with the RFID devices. As the operators mentioned during the interviews, RFIDs were the root of many problems in the line. Unfortunately, due to time and knowledge limitations, it was not possible to include them in the emulation model, remaining for future work.

The operator training station has been successfully implemented. Combining the real factory hardware and the realistic emulation model of the OP035, an operator training station has been created. The different features from the OTS have been tested and verified with satisfactory results. The training station is considered to be valid for the application and it is ready to be used with operators from the G2 foundry.

This project has potential benefits for both the Volvo Group company and the operators. On the one hand, companies will benefit from the advantages that provide the emulation model and the operator training station. Operators and maintenance personnel will be better trained, even if these are for a short period of time. Thus, it will be possible to **increase the productivity and the safety** of the whole line. Unnecessary stops that happen when the line fails and the staff does not find the way to fix it, will be reduced. As the operators have been previously subjected to the different possible scenarios, they will know exactly how to face each one, reducing the likelihood of being involved in a hazardous

situation. Furthermore, the emulation model could be used to verify the PLC code by testing it in different scenarios.

On the other hand, **the operator training station provides an efficient and experimental way of learning for the operators**. The combination of the real factory hardware and the realistic emulation model of the OP035, make the training process comfortable and profitable for the rookie operator. As the risk-free environment it is, the emulation model can be tested and pushed to the limits with no fear of breaking components.

11.2 Future work

In order to continue developing this project, or at least a similar project based on a virtual twin of a production line, there are some factors which can be taken and improved. This emulator covers a part of the production line which is based on a material handling operation. In this concrete operation, the robotic cells do not play the main role, however, a factory like the one addressed in this project, usually has a lot of operations in which the robots are the main tools. For creating an Operator Training Station for one of these types of operations, the development in the ambit of robot programming must be higher. In this project's case, it has been analyzed to the point where it has been necessary and enough to deep into. If the robot had more importance than in this case, it should be compulsory for the emulator to use the same robot program as in the real system. For example, the picking and placing object or welding actions should become more realistic.

Going further in the hardware part, it can be considered that this project only uses the components of hardware that have been though as indispensable or necessary. With a higher budget, it would be also possible to add several objects to the Operator Training Station that would make it gain more resemblance to the actual workstation. This extra hardware will make the learner-operator feel more comfortable when it comes to working in the real station. These elements could be considered, for future integration, for example, real panels with physical buttons and emergency buttons, alarm lights or information about the state of the production line, sirens, real door handles etc.

Regarding virtual hardware, the RFID have not been implemented in this project. Despite the operators from the factory stated that this component gives them a lot of problems, it was impossible to integrate such system in the virtual model. It would be a significant improvement to the emulation model to create a virtual reader for the pallets. This way, the RFID from the real system could be emulated in the virtual model, and so the problems or failures could be reproduced in the Training Station. For this new feature, collaboration from both the Simumatik3D developer and the project authors will be required.

In a future project, when building Operator Training Stations, it would be interesting to consider integrating Virtual Reality goggles. This would make the training a more immersive experience for the operator when going through the investigation of the problem or the failure. For that purpose, the emulation model should have a higher level of realism and detail. For example, when a sensor broke, it should be displayed in a distinct color, texture, break in two parts or with a mark indicating the fault. This could happen with any type of failure such as a broken engine, a jammed pallet, etc.

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13 Appendices

The different elements attached with the report are enlisted in this chapter

13.1 Operator Training Station user manual

Check "***Operator Training Station User Manual.pdf***" in **Appendices** folder.

13.2 Video recording

Go to: https://vimeo.com/225914200?activityReferer=1

13.3 Test and experiments sheets

Check "***Tests and Experiments sheet.pdf***" in **Appendices** folder.