DEPARTAMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING

FILIPE ALEXANDRE FRANCISCO VIEIRA

BSc in Mechanical Engineering

PROPOSAL OF A MATERIAL HANDLING SYSTEM DESIGN METHODOLOGY – AN INDUSTRIAL APPLICATION ON A PACKAGING AND DEPALLETIZING SYSTEM

MASTER IN MECHANICAL ENGINEERING

NOVA University Lisbon

December, 2022

DEPARTAMENT OF MECHANICAL
AND INDUSTRIAL ENGINEERING

PROPOSAL OF A MATERIAL HANDLING SYSTEM DESIGN METHODOLOGY – AN INDUSTRIAL APPLICATION ON A PACKAGING AND DEPALLETIZING SYSTEM

FILIPE ALEXANDRE FRANCISCO VIEIRA

BSc. in Mechanical Engineering

Adviser: João Fradinho
Assistant Professor, NOVA School of Science and Technology

Co-advisers: António Mourão
Associate Professor, NOVA School of Science and Technology

Hélder Silva
Chief Engineer, Metal-Conser Lda.

Examination Committee:

Chair: Alberto Martinho
Assistant Professor, NOVA School of Science and Technology

Rapporteur: António Santos
Assistant Professor, NOVA School of Science and Technology

Adviser: João Fradinho
Assistant Professor, NOVA School of Science and Technology

MASTER'S IN MECHANICAL ENGINEERING
NOVA University Lisbon
December, 2022

Proposal of a Material Handling System Design Methodology – An Industrial Application on A Packaging and Depalletizing System

"Failure is an option here. If things are not failing, you are not innovating enough." (Elon Musk)

ACKNOWLEDGMENTS

I would like to thank the following people, without whom I would not have been able to complete this project and without whom I would not have made it through these last five years.

My university, NOVA School of Science and Technology, for providing the opportunity to get this master's degree.

My adviser, assistant professor João Fradinho, for the consistent support and guidance during the duration of this project.

Associated professor António Mourão, for accepting being an additional co-adviser for this dissertation and for the thoughtful comments and recommendations provided.

The team at Metal-Conser, for all the help they provided during my internship at the company, and I would especially like to thank my co-adviser, chief engineer Hélder Silva, for instantly making me feel at home as soon as I stepped in at that door and for all the shared knowledge essential for developing this dissertation.

"Alentejanus", the friend's group formed in college, for all the amazing memories and for helping each other during the most challenging times.

My girlfriend and all my friends outside of college for helping me keep my sanity with constant group activities.

My sisters, who both finished college many years ago, for all the advice they provided me and for setting my career expectations high.

My parents for providing me with the education they were not allowed to experience and for always caring for me even when I am not the most affectionate son in the world.

ABSTRACT

In modern competitive environment, cost reduction across various production functions is imperative. Material handling is no exception, as achieving a well-designed MHS (Material Handling System) is key for lowering operational costs and improving the work environment.

Companies offering services such as the design of MHSs often find themselves developing MHS design concepts to present to their customers before proceeding with the remaining systems' development. Although there are currently several approaches to the design of MHSs, most of these approaches are tailored to design and develop these systems to completion.

The present dissertation proposes a MHS design methodology suitable for designing MHSs both up to a concept stage and a detailed stage (complete design). The proposed methodology mainly differs from conventional approaches by identifying, prioritizing, and evaluating key system metrics before proceeding with the equipment selection and validation processes. Doing so increases the likelihood of detecting unforeseen problems or opportunities for improvement sooner in the design process. In addition, if performed, these steps allow the companies mentioned above to achieve and propose design concepts truer to the eventual complete systems.

This dissertation was performed within the scope of an internship at Metal-Conser, a company that designs and manufactures material handling systems.

To evaluate the proposed MHS design methodology, the last was applied to a packaging and depalletizing system and compared to a design concept of the same system proposed by Metal-Conser.

Additionally, during the methodology application, simulation software was used both to simulate the system's pick and place operations and to model and simulate the system's operations. Both of these applications had the intent to validate the use of these tools in future operations at Metal-Conser.

Keywords: material handling system, material handling equipment, packaging system, depalletizing system, MHS design concepts, simulation tools.

Resumo

No ambiente competitivo moderno, a redução de custos em várias funções associadas com produção é imperativa. A manipulação de materiais não é exceção, visto que projetar corretamente um sistema de manipulação de materiais é fundamental para reduzir custos operacionais e melhorar a logística operacional.

Empresas que oferecem serviços como o projeto de sistemas de manipulação regularmente desenvolvem conceitos de projeto para apresentar aos seus clientes antes de prosseguir com o restante desenvolvimento do projeto. Embora existam atualmente várias abordagens para o projeto deste tipo de sistemas, a maioria destas abordagens é adaptada para os projetar e desenvolver até ao fim.

A presente dissertação propõe uma metodologia de projeto de sistemas de manipulação de materiais adequada para projetar estes sistemas tanto na fase de conceito de projeto como na fase de projeto de definição de pormenor (projeto completo). A metodologia proposta difere das abordagens convencionais principalmente por identificar, priorizar e avaliar os principais parâmetros do sistema antes de prosseguir com o processo de seleção e validação de equipamento. A aplicação dos passos propostos, aumenta a probabilidade de detetar problemas imprevistos ou oportunidades de melhoria mais cedo, durante o desenvolvimento do projeto. Como consequência direta da aplicação destes passos as empresas previamente mencionadas, podem alcançar e propor conceitos de projeto mais fiéis aos eventuais sistemas completos.

Esta dissertação foi realizada no âmbito de um estágio na Metal-Conser, uma empresa que projeta e fabrica sistemas de manipulação de materiais.

Para avaliar a metodologia de projeto proposta, esta foi aplicada a um sistema de embalamento e despaletização, sendo depois comparada a um conceito de projeto proposto pela Metal-Conser, para o mesmo sistema.

Adicionalmente, durante a aplicação da metodologia, recorreu-se ao uso de software de simulação, tanto para simular operações de *pick and place*, como para modelar e simular as operações do sistema projetado. Ambos os casos tinham como objetivo validar o uso destes *softwares* em futuras operações na Metal-Conser.

Palavras-chave: sistema de manipulação de materiais, equipamento de manipulação de materiais, sistema de embalamento, sistema de despaletização, conceito de projeto de sistema de manipulação de materiais, ferramentas de simulação.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

MH	Material Handling
MHS	Material Handling System
MHE	Material Handling Equipment
SADT	Structured Analysis and Design Technique
TCP	Tool Center Point

1 Introduction

1.1 Motivation

In modern competitive environment, cost reduction across various functions of production is imperative, material handling being no exception. Material Handling (MH) is a systematic and scientific method of moving materials from one place to another for the purpose of processing, packing, and storing in appropriate and suitable locations. These materials are of different shapes, sizes as well as weights, and their transport is either done manually or through an automated process.

The global material handling equipment market was valued at 24.2€ billion in 2020 and is projected to expand at a compound annual growth rate (CAGR) of 7.4% between 2021 and 2028 [1].

By assuring the right product to the right place at the right time in the right quantity and condition, companies can eliminate/decrease unnecessary buffers on the shop floor and, as a result, lower their operational costs [2]. Furthermore, an efficient material handling system leads to improved product quality and an improved work environment [3], [4].

Over the last decades, several researchers, such as Apple, Hassan, and Thompson, have provided comprehensive dissertations [3]–[5] with MHS design methodologies that can serve as a path to developing a well-designed MHS.

Companies that offer MHS design services frequently find themselves developing MHS only up to a concept stage, as this is usually a requirement from the MHS customer, who wants to compare different companies' MHS concepts before deciding the one to move forward with. For scenarios such as the described, traditional MHS methodologies are only applied to a certain extent, as there is no need to develop the MHS to completion. However, these conventional methodologies were not developed for this intent and, in turn, don't necessarily lead to the best MHS concept outcome.

This dissertation took place at Metal-Conser, as a result of a partnership with the Department of Mechanical and Industrial Engineering (DEMI) of FCT-UNL. Metal-Conser is a company that offers MHS design and fabrication services and often finds itself in the scenario mentioned above. As part of their resume, they've worked with a vast list of customers and provided them with MHS solutions tailored to their needs. However, due to the competitive nature of this market, not all Metal-Conser clients have selected their proposed MHS design concepts to move forward with.

This dissertation has as its primary objective the development of a MHS design methodology more suitable for developing MHS design concepts. To evaluate the performance of the proposed methodology, the last will be used to develop a MHS system based on one of Metal-Conser's MHS design concepts that were not selected to move forward with.

1.2 Company and Case-study Description

1.2.1 Company

Metalomecânica Metal-Conser, Lda, was founded in 1989 as the result of a contract established between the company ORMIS – actual Crown, Cork & Seal – and four of its former employees [6]. This contract aimed to provide technical assistance services to customers and the manufacturing of tools for this metal packaging factory.

At the present day, Metal Conser is able to offer services in the MHS industry, all the way from system design and development to final product. Additionally, the company is also known for its services in:

1. Reverse engineering of parts and tools;
2. 3D modeling and rapid prototyping;
3. Design and fabrication of parts, tools, molds, dies, and cutters;
4. Technical assistance and sale of metal packaging machinery and equipment.

1.2.2 Case Study

This case study corresponds to a MHS concept that Metal-Conser proposed to a client but was not selected to move forward with. For privacy reasons, the client's name will remain undisclosed.

This MHS concept aimed to automate a large section of a packaging and depalletizing system for hot dog buns. The section in question corresponds to a conveyor system that brought in packs of six hot dog buns (also referred to as *Packs*; see Figure 1.1), which were manually picked from a transport conveyor and placed inside plastic crates (also referred to as

Crates), depicted in Figure 1.2. These *Crates* were brought in pallets (see Figure 1.3), then manually depalletized and made available to the workers handling the *Packs*. These workers would then place the *Packs* inside the *Crates*, completing the packaging process.

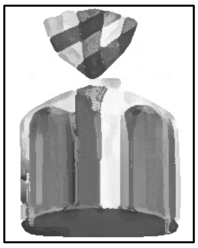


Figure 1.1. Pack of hot dog buns.

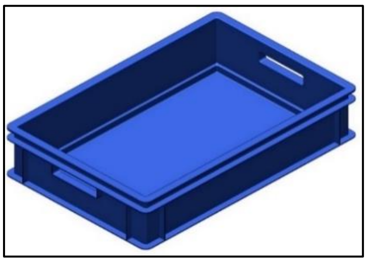


Figure 1.2. Crate.

Figure 1.3. Pallet full of Crates.

Figure 1.4 depicts a schematic representation of the preliminary design concept developed by Metal-Conser.

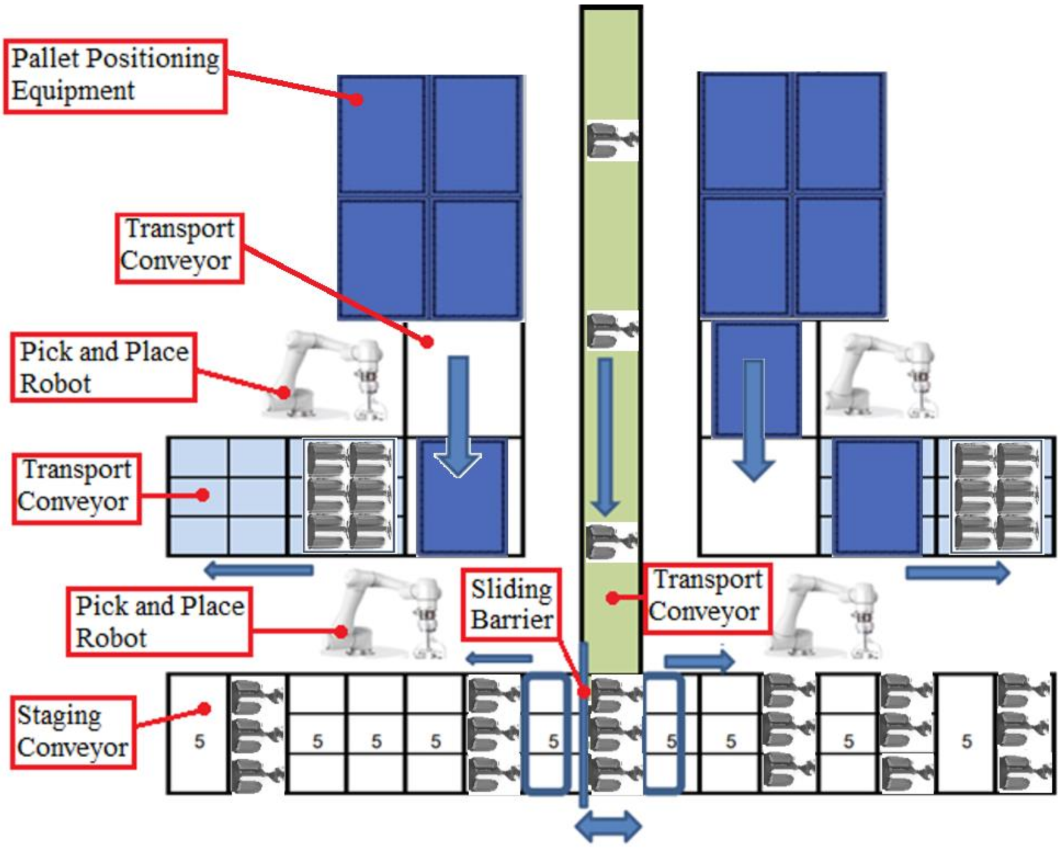


Figure 1.4. Metal-Conser's schematic representation of the proposed packaging and depalletizing design concept.

The system presented above is mirrored in relation to the transport conveyor in the center (highlighted in green). It can be decomposed into two depalletizing workstations, two packaging workstations, and one *Packs'* batching workstation. The operations performed in these workstations (also referred to as stations) are presented further ahead.

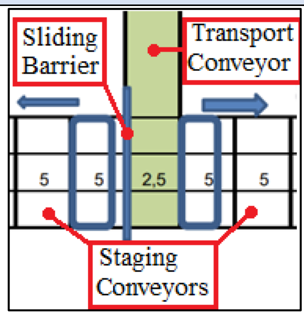
The reader should note that the partition of the system in the stations presented above was only performed to help describe their operations. These stations share equipment, which, from an operation designation standpoint, makes creating a division between them a complex and, to some extent, a subjective task.

Additionally, throughout this study, equipment designations are slanted (in *Italic* type) and capitalized when referring to specific equipment, part, or operation.

1) *Packs' Batching Station:*

The proposed packs' batching station concept is composed of the following equipment (see Table 1.1):

Table 1.1. Equipment of Metal-Conser's Packs Batching Station concept.

Equipment designation	Number of units	Illustration
Transport Conveyor (pre-existing)	1	
Sliding Barrier	1	
Staging Conveyor	2	

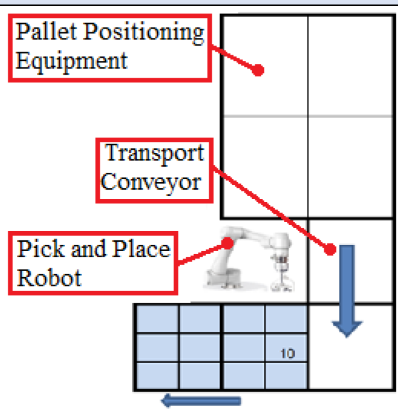
The *Packs* are brought in at a rate of 70 packs per minute on a pre-existing *Transport Conveyor* featuring an end stop barrier. Once they arrive at the end of this *Transport Conveyor*, the packs run into the *End Stop* and start accumulating. This is made possible due to the smoothness of pre-existing *Transport Conveyor* belt surface, which provides low friction between the *Packs*' surface and the belt's surface, allowing the *Packs* to rest against the *End Stop* without stumbling excessively.

At every 3-pack accumulation (also referred to as *3-Pack-Column*), the *Packs* are pushed either to the left or right *Stagging Conveyors* by the pneumatic actuated *Sliding Barrier*. This operation is performed in an alternating mode.

2) *Depalletizing Station:*

The proposed depalletizing station concept is composed of the following equipment (see Table 1.2):

Table 1.2. Equipment of Metal-Conser's Depalletizing Station concept.

Equipment designation	Number of units	Illustration
Transport Conveyor (shared with *Packaging Station*)	1	
Pick and Place Robot	1	
Pallet Positioning Equipment	1	

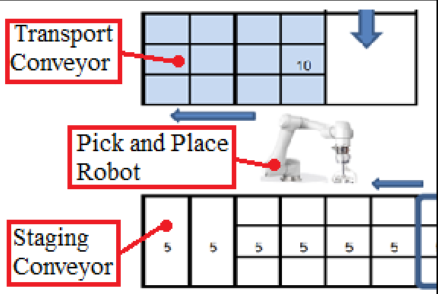
The pallets full of *Crates* are unloaded into the *Positioning Equipment*, which is responsible for positioning the pallet so it can be depalletized correctly. The depalletizing operation itself is performed by the *Pick and Place Robot*, which makes use of a mechanical gripper to pick the crates from the pallet and place them on the *Transport Conveyor*, one by one.

After all the *Crates* are removed from a pallet, a worker is responsible for replacing it with another pallet full of *Crates*.

3) *Packaging Station:*

The proposed packaging station concept is composed of the following equipment (see Table 1.3):

Table 1.3. Equipment of Metal-Conser's Packaging Station concept.

Equipment designation	Number of units	Illustration
Transport Conveyor (shared with *Depalletizing Station*)	1	
Pick and Place Robot	1	
Staging Conveyor (shared with *Packs' Batching Station*)	1	

As soon as two *3-Pack-Columns* reach the end of a *Staging Conveyor*, they are picked by the *Pick and Place Robot* through a vacuum gripper and placed inside a *Crate* that is made available by the *Depalletizing Station.*

After a crate gets filled with *Packs*, it moves down the *Crate's Transport Conveyor*. The handling of the *Crate* performed from that point on is out of the scope of the system design.

For the proposed system concept to perform according to the customer requirements, Metal-Conser considered the performance parameters displayed in Table 1.4 as equipment operating specifications. These values were proposed based on empirical knowledge gathered by the Metal-Conser team while working with equipment similar to the one in question.

Table 1.4. Design Parameters considered by Metal Conser in their system concept.

Concept System Design Parameters (Duration)	Time (seconds)
3-Pack-Column formation	2.60
Two 3-Pack-Column formation	5.10
Pick packs/crate	3.00
Move packs/crate	2.00
Place packs/crate	3.00
Move back to picking position	2.00

1.3 Objectives

This dissertation has the following main objectives:

- Proposal of a MHS design methodology suitable for developing MHS design concepts.
- Application of the proposed MHS design methodology on a packaging and depalletizing system concept developed by Metal-Conser (case-study).

Additionally, the application of pick and place robots in this dissertation's case-study, as well as the research performed on MHS evaluation approaches, led, respectively, to the additional objectives:

- Implementing a robot simulation software in the evaluation of pick and place operations.
- Implementing a simulation software to model and simulate the operation of the system.

Both of these applications intend to validate the use of these software in future operations at Metal-Conser.

1.4 Outline

The present dissertation is structured in a coherent sequence of chapters with the intent to achieve the objectives at hand. These chapters are the following:

- In chapter 1, the motivation and objectives are presented. In addition, the company where this dissertation took place is presented, followed by the MHS case-study description. At last, an outline of the dissertation structure is given.

- Chapter 2 is dedicated to the background research and review of literature related to the contents of the dissertation. It starts it the presentation of the purposes of MHS, followed by the presentation of several MHS design approaches. Afterward, pick and place robots and their operations are briefly explained, as they are relevant to achieve this dissertation's objectives.
- Chapter 3 is dedicated to the proposal of a methodology for designing MHSs. First, the diagram (SADT) used to illustrate the methodology is explained, followed by the presentation of each of the activities/steps and sub-activities/sub-steps that compose this methodology.
- In chapter 4, the MHS achieved with the application of the proposed design methodology is presented for the reader to grasp the system as a whole, which in turn will provide adequate context during the application of the design methodology steps presented in the succeeding chapter.
- Chapter 5 is dedicated to presenting and explaining the application of the proposed design methodology to the MHS case study. Each of the design methodology's steps is approached individually, starting with the establishment of control data for the system's design and ending with the evaluation of the achieved design.
- In chapter 6, the results achieved by the proposed design methodology application and the simulation software are discussed, including a comparison between the MHS concept developed by Metal-Conser and the MHS achieved in this dissertation, in an attempt to validate the use of the proposed design methodology for the development of MHS' concepts.
- Chapter 7 contains the conclusions this dissertation achieved and some future work suggestions to ensure the continuity of the study. Some suggestions are made regarding the development of new design methodologies and the simulation software used in this project.

2 BACKGROUND AND REVIEW OF LITERATURE

2.1 Purpose of Material Handling Systems

Although there is no unique definition that englobes all the features and activities in an internal MHS, most researchers agree that a Material Handling System is a comprehensive concept that entails the movement, storage, control, and protection of material with the purpose of providing time and place utility [3] [7].

The primary purpose of a Material Handling System design is to reduce production costs and improve safety conditions. This is done through the achievement of several objectives:

- Facilitate the reduction in material damage to improve quality.
- Reduce overall manufacturing time by designing efficient material movement.
- Improve material flow control.
- Create and encourage safe and hazard-free work conditions.
- Ensure the availability of materials when and where they are needed.

Similarly, and in addition to these objectives, James A. Tompkins et al. [3] enumerates nine factors that should be taken into account when trying to eliminate material handling problems inside a factory:

1. **Right amount** - The right amount of material inventory needed in a warehouse depends on the type o inventory management system. The right amount should be what is required and not what is anticipated.
2. **Right material** - It is important to recognize that an accurate identification system must be implemented for moving, storing, protecting, and controlling the right material.
3. **Right condition** - It should be ascertained what each customer's expectations are in terms of the condition of the material served by the handling system to be able to deliver on those expectations without damages or defects.
4. **Right place** - Decisions should be made regarding where a material is placed/stored to avoid undesired movements. While there might be more than one right place for material to be placed, the number of wrong places far exceeds the number of right places.

5. **Right time** - Due to time-based competition, the need for the material handling system at the right time is increasingly important. Excess capacity in a MHS is generally required to satisfy the requirements for timely responses.
6. **Right position/orientation** - Rearranging a product's physical orientation is often part of some worker's job. By changing the design of a part through the addition of locator holes or pins, the automatic orientation of parts might become feasible and save valuable time.
7. **Right sequence** - The impact of the sequence of activities performed in a MHS operation is very evident. An increase in productivity can be achieved by eliminating unnecessary steps in an operation and improving the remaining ones.
8. **Correct cost** - The objective of a company shouldn't necessarily be achieving the lowest cost of MH. The MHS should be designed with competitive advantages so that it can be a revenue enhancer rather than a cost contributor.
9. **Right methods** - For everything to work right, it is necessary to use the right method. The right method is not necessarily the most sophisticated, the newest, or the least expensive method. The right method only needs to satisfy the points mentioned above.

2.2 Design of Material Handling Systems

According to Hassan [4], a well-designed MH system helps manufacturing and logistics facilities improve their productivity, enhance the quality of products, and reduce operating costs. Therefore, having a well-designed MHS is of most importance.

Most researchers categorize the design approach to MHS according to three different conditions [8].

1. The layout is already given.
2. The material handling system is already given.
3. Neither the material handling system nor the layout is given.

The first and second approaches are highly dependent on the given part of the problem since material handling systems and plant layout are highly intertwined concepts. This is because the movement of materials between points in a facility is part of what makes a MHS, and the positioning of these points in the facility is determined by the plant layout [2].

Although plant layout and material handling systems have the common objective of cost minimization, dealing with an existing plant layout poses a constraint in the MHS design, as it results in a loss of a degree of freedom and, therefore, the overall optimal solution becomes harder to achieve.

Nadler [9] proposes that when considering MHS design, the "*ideal systems approach*" (see Figure 2.1) should be implemented:

1. Aim for the theoretical ideal system: It is a perfect system with zero cost, excellent quality, no safety hazards, no wasted space, and no management inefficiencies.
2. Conceptualize the ultimate ideal system: It is a system that probably would be achievable at some point in the future but is not attainable at the present time because of a lack of available technology.
3. Design the technologically workable ideal system: It is a system for which the required technology is available; however, costs or other conditions may prevent some components from being installed now.
4. Install the recommended system: It is a cost-effective system that will work now without obstacles to its successful implementation.

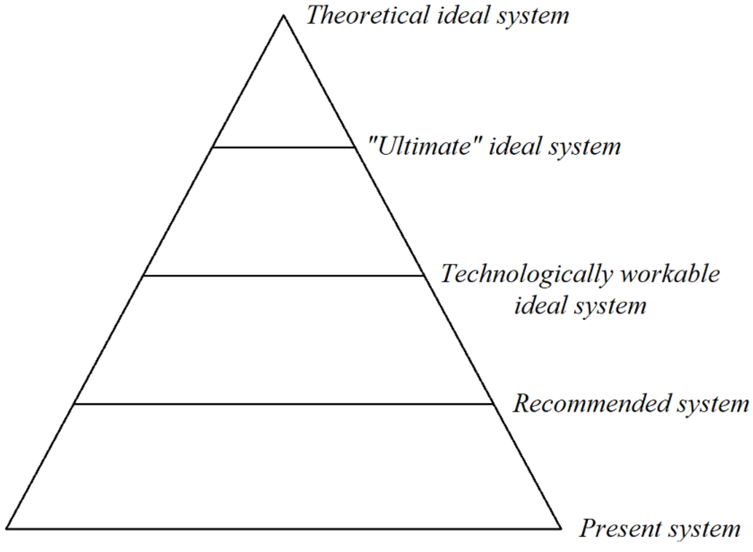


Figure 2.1. The ideal systems approach (adapted from [9]).

Other researchers, such as James A. Tompkins et al. [3], suggest that using the material handling system equation, depicted in Figure 2.2, provides a framework to approach material handling problems. In this equation, the what defines the type of materials moved, the where and when refers to the place and time requirements, and the how and who point to the material handling methods. The answers to these questions should lead the MHS designer to the recommended system.

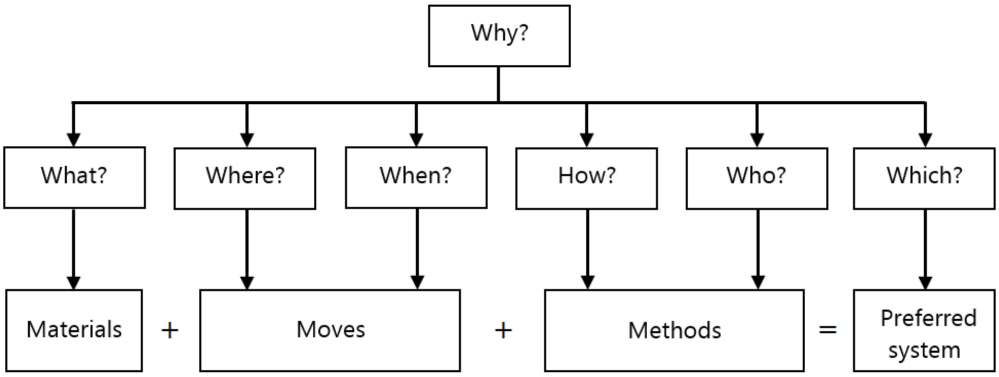


Figure 2.2. Material handling system equation (adapted from [3]).

Researchers such as Hasan have proposed more in-depth MHS design approaches that are more methodological in nature than the ones mentioned up to this point [4]. Hassan's approach is divided into three main phases: conceptual design, preliminary design, and detailed design with corresponding steps (see Table 2.1).

Table 2.1. Framework for selection of material handling equipment in manufacturing and logistics facilities [4].

Design phase	*Step*
Conceptual design	1. Specify and prioritize requirements
	2. Set and decompose objectives
	3. Establish performance measures
	4. Functional decomposition
	5. Determine candidate equipment classes
	6. Design subsystems
Preliminary design	7. Select equipment type from a class
	8. Determine the number of units of an equipment type
Detailed design	9. Determine specifications of the selected equipment
	10. Evaluate the design

Although MHS design approaches can vary from author to author, there's a set of principles and guidelines to effectively plan and control MH that most authors agree on. These principles provide concise statements of the fundamentals of material handling practice. They result from decades of material handling experience and provide guidance and perspective to material handling system designers. The College-Industry Council on Material Handling Education (CIC-MHE), in cooperation with the Material Handling Institute (MHI), created a list of the first ten principles. Several authors, James A, Tompkins, et al. [3] and Coyle J. [2], have thereafter used and modified this list. Currently, twenty fundamental guidelines and principles can be used to effectively design material handling systems (see Table 2.2.).

Table 2.2. Fundamental MHS design principles [2].

Principles	Definition
1. Planning Principle	Plan all material handling and storage activities in order to achieve maximum overall operating efficiency.
2. System Principle	Integrate these activities into a coordinated system of operations, including receiving, inspection, storage, production, assembly, packaging, warehousing, shipping, and transportation.
3. Materials Flow Principle	Provide an operation sequence and equipment layout that optimizes materials flow.
4. Simplification Principle	Simplify handling by reducing, eliminating, or combining unnecessary movements and equipment.
5. Gravity Principle	Utilize gravity to move material wherever it is possible.
6. Space Utilization Principle	Make effective utilization of all cubic space.
7. Unit Size Principle	Increase the quantity, size, or weight of unit loads or their flow rates.
8. Mechanization Principle	Mechanize handling operations.
9. Automation Principle	Provide automation that includes production, handling, and storage functions.
10. Equipment Selection Principle	While selecting handling equipment, all aspects like material handling, movement and the used methods should be considered.
11. Standardization Principle	Standardize the handling methods as well as types and size of handling equipment.
12. Adaptability Principle	Use the methods and equipment that can adapt to the widest variety of tasks and applications, except where special methods and equipment are necessary.
13. Deadweight principle	Avoid unnecessary run of equipment and machines.

Table 2.3. Continuation of the table - Fundamental MHS design principles [2].

Principles	Definition
14. Utilization Principle	Plan for maximum utilization of handling equipment and labor.
15. Maintenance Principle	Plan for preventive maintenance and schedule repairs of all handling equipment.
16. Obsolescence Principle	Replace the obsolete handling methods and equipment when more efficient ones in order to improve the operations.
17. Control Principle	Use material handling activities to control production, inventory, and order handling.
18. Capacity Principle	Use handling equipment to improve production capacity
19. Performance Principle	Determine the handling performance effectiveness in terms of expense per unit handled.
20. Safety Principle	Provide suitable methods and equipment for safe handling.

2.3 Material Handling Equipment

According to Hasan [4], "MH system consists of hardware, software, human, and management sub-systems that work together to perform all activities associated with handling". Hardware is the largest sub-system and englobes all types of MH equipment, as illustrated in Figure 2.3.

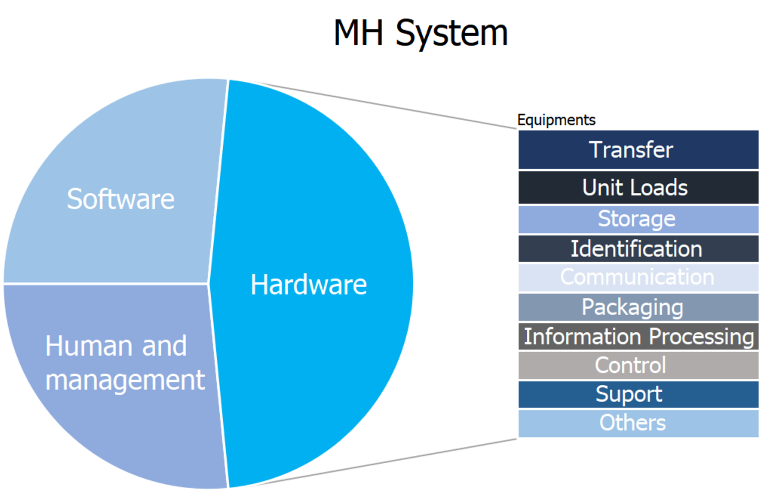


Figure 2.3. MHS sub-systems.

James A. Tompkins et al. [3] emphasize that when designing an MHS, the focus should be first on the material, second on the move, and third on the method, being equipment selection one of the last steps in the process. Nevertheless, knowing and understanding MH equipment is essential, and MH designers must keep up with current technology as new MH equipment is continuously being developed.

As is to be expected, not all researchers classify material handling equipment into the same categories. Differences in categories result from different approaches to material handling and the need to create new categories for newly developed equipment. Hassan [4] classifies MH equipment into five categories, as shown in Figure 2.4.

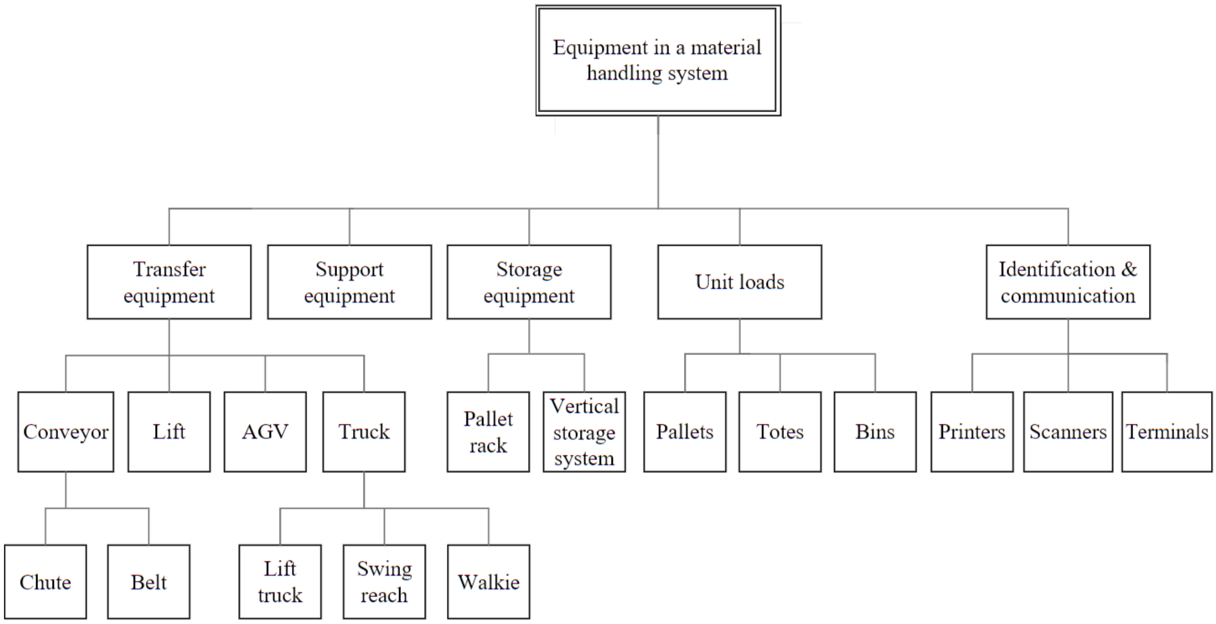


Figure 2.4. Material handling equipment [4].

As a large portion of MH systems, MH equipment has dedicated approaches. Saputro et al. reviewed 42 dissertations on MHE Selection approaches, methods, and tools and identified three distinct levels of MHE selection:

1. High level: MHE selection problem is focused on seeking a suitable MHE among the categories, e.g., conveyors, AGV (Automated Guided Vehicle), forklifts, etc.
2. Intermediate level: The MHE selection problem focuses on seeking a suitable type of MHE within a category, e.g., selecting the best alternatives among mechanical grippers categories (angular or parallel).
3. Low level: The MHE selection problem focuses on seeking a suitable model of MHE within a type, e.g., selecting the best alternatives among robot types in terms of payload capacity (Model *EC66* or *EC612*).

2.4 Pick and Place Robots

2.4.1 Types, Features, and Applications

A pick and place robot is any robot that can pick up parts or items from one location and drop them in another one. Pick and place robots frequently used in modern manufacturing environments are based on the Delta robots, first introduced to the food packaging industry in the early 1980s. These robots were designed by a research team led by Professor Reymond Clavel at EPFL, Switzerland, and started being mass-produced in 1987 [10].

Nowadays, pick and place robots can be configured with a variety of end-of-arm tooling options and a range of sensor systems for use in different industrial applications such as moving, packaging, sorting, and stacking products.

A common alternative to pick and place robots is dedicated pick and place machines. These machines are fast, highly accurate, and consistent. However, they are too restrictive, expensive, and unsuitable for most pick-and-place tasks. Pick and place robots can be customized to meet specific production requirements and are easily programmable for multiple applications.

These robots typically handle monotonous, repetitive work while freeing up associates and operators to focus on more complex and, usually, less labor-intensive tasks. In addition, using a robot for pick and place presents even more benefits when compared to manual pick and place. Such benefits include:

1. **Throughput:** A robot can consistently pick and place more objects than a human operator and can operate round the clock, with little to no downtime, to increase throughput further.
2. **Safety:** Using a robot is safer than having humans move the objects, as repetitive motions such as those required by pick and place can cause health-related problems over time. Furthermore, robots such as the collaborative type can allow the robot to operate alongside workers, within guidelines, without representing a significant risk of injury.
3. **Speed:** Most robots will be much faster than humans at pick and place tasks, some significantly faster. Even robots that are slower than humans, such as the case of many collaborative robots, can keep up a consistent speed.
4. **Repeatability:** A robot can pick and place items at the exact same position for each routine it completes, which is crucial in high-precision activities.
5. **Return on Investment:** The return on investment of a pick and place robot can be achieved very fast and can generally be calculated by the amount it would have cost to employ a human to perform the same task.

2.4.2 Robotic Arms' Points-Based Motion Types

During pick and place path planning for operations with different points (also referred to as targets), one of the following three methods can be used [11]:

1. PTP: Point-to-point movement moves the joints in the most efficient way between two given points in 3D space and disregards the path of the robot's Tool Center Point (TCP). Due to the randomness of this procedure, the movement that the robot will perform is not always predictable
2. Linear movements: Linear movements are the movements in which the robot's TCP moves along a straight line between two points in 3D space.
3. Circular movement: The robot's TCP moves along a circular path, or a circular arc created with a starting point, a mid-point, and an end point, in 3D space.

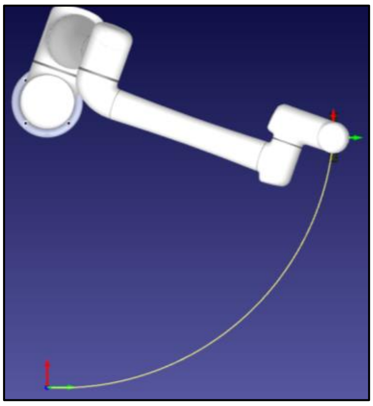


Figure 2.5. Point-to-point movement tool path.

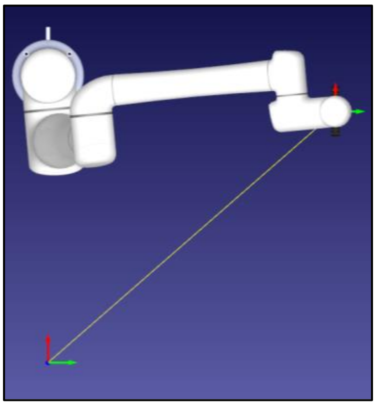


Figure 2.6. Linear movement tool path.

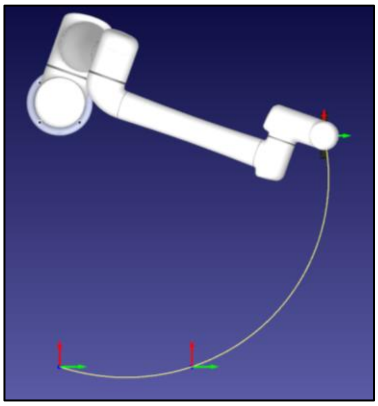


Figure 2.7. Circular movement tool path.

3 PROPOSAL OF A METHODOLOGY FOR THE DESIGN OF MATERIAL HANDLING SYSTEMS

3.1 Design of the Study

The main objective of this dissertation is the development of a MHS design methodology, more suitable for developing MHS design concepts. To achieve this objective, the following tasks were/will be performed (see Figure 3.1):

1. The MH system design concept developed by Metal-Conser was presented and analyzed. This MHS is the case-study for the methodology application.
2. Based on the background research and related works involving the subject, a MHS design methodology will be proposed.
3. The proposed methodology will then be applied to the case-study.
4. Finally, the achieved MH System Design will be assessed according to the system's objectives and compared to the Metal-Conser's initial design concept. The proposed design methodology's performance will also be evaluated.

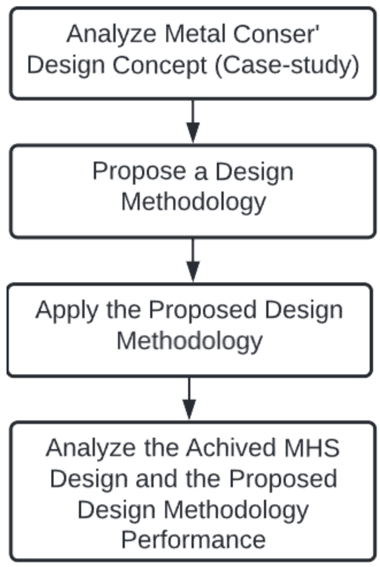


Figure 3.1. Diagram of the design of the study.

3.2 Diagrammatic Representation Model: SADT

To describe and showcase the MHS design approach implemented in this dissertation, an SADT diagram (Structured Analysis and Design Technique) is used.

This diagrammatic notation was introduced by Douglas Taylor Ross from 1969 to 1973, having seen, at the time, the most used by the US Air Force Integrated Computer Aided Manufacturing program[12]. The SADT diagram is used to model actions, processes, and operations of, among others, manufacturing systems in a structured graphical form. It presents a powerful tool for the understanding, analysis, improvement, or replacement of a system.

This type of diagram is represented through activity boxes and arrows, as displayed in Figure 3.2. The inputs enter from the left side of the activity box and represent data or consumables needed by the activity, while the outputs exit by the right side and represent data or products produced by the activity. The controls enter from the top and represent commands or conditions that influence the activity's execution. At last, the mechanisms or means used to carry out the activity enter through the bottom.

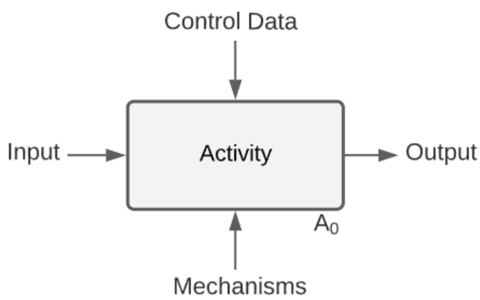


Figure 3.2. SADT diagram concept.

The SADT diagram developed in this dissertation implements a strategy based on a multi-level hierarchical decomposition of activities. Each activity can be decomposed into smaller activities to detail each step of the MHS design process, making the last easy to understand compared to the complexity of the whole SADT diagram model.

3.3 Proposed methodology for the design of MHSs

Currently, Metal Conser doesn't have an established and systematized design approach. However, during discussions with their team about the topic, one aspect stood out, the need to evaluate some design parameters during the concept design stage.

The proposed design methodology presented in this sub-chapter addresses both of the points made above as it mainly differs from conventional approaches by identifying, prioritizing, and evaluating key system metrics before proceeding with the equipment selection and validation processes.

Considering the research performed on MHS design' approaches, the proposed methodology is based on the *"Framework for selection of material handling equipment in manufacturing and logistics facilities"*, developed by Hassan [4]. This author's framework is well structured and organized and achieves a significant level of detail in each step.

The proposed methodology for the design of material handling systems is presented in Figure 3.3 and represents the activity A_0. Activity A_0 can be decomposed in four main activities, each one representing a major step in the MHS design process:

- Activity A_1- Establish Control Data;
- Activity A_2- Functional Decomposition of Objectives.
- Activity A_3- Equipment Selection.
- Activity A_4- Design Evaluation.

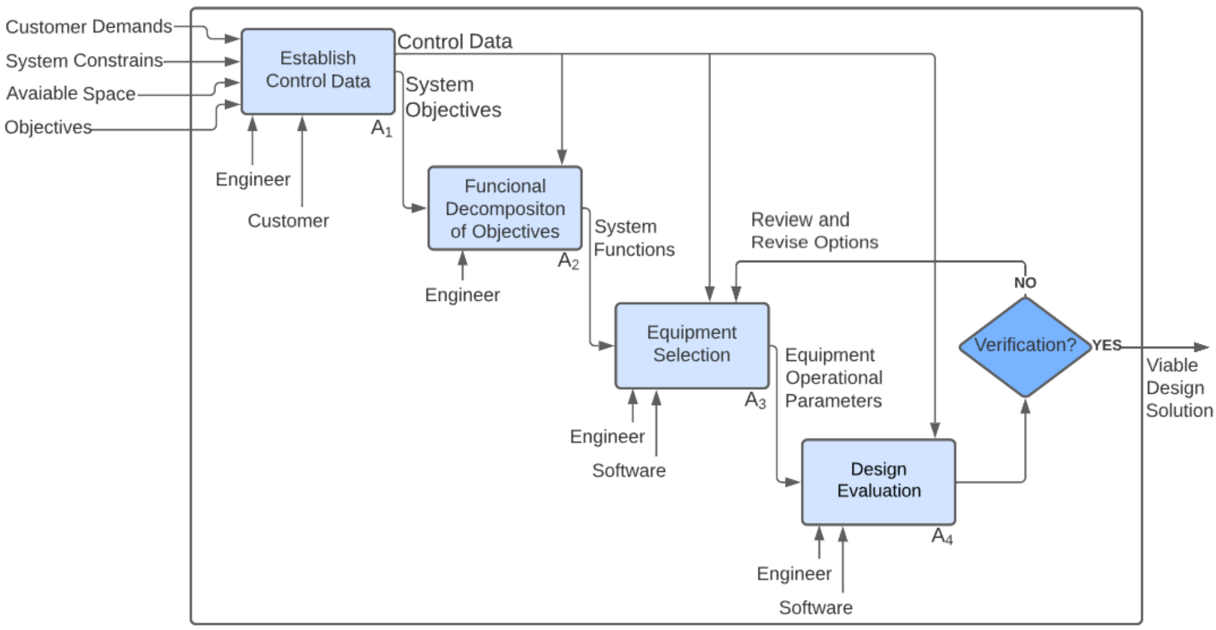


Figure 3.3. Activity A_0- Proposed methodology for the design of MHSs.

3.3.1 Activity A_1: Establish Control Data

Activity A_1 is the first step of the proposed methodology. This step is responsible for processing information such as customer demands, system objectives, design constraints, and other parameters. In turn, this step's execution provides control data for the remaining steps of the methodology as well as the objectives the system is required to achieve.

The SADT diagram of this step is represented in Figure 3.4., where the following sub-steps can be depicted:

- *Specify and Prioritize Requirements (Activity $A_{1.1}$):* In this step, the customer and the project's engineer should clearly specify the functional requirements and prioritize them according to the customer's demands.
- *Specify Design Constraints (Activity $A_{1.2}$):* This step is dedicated to specifying the design constraints. The customer and the project's engineer should specify already known constraints, such as the available space, and analyze the system's objectives to determine any other constraints not yet established.
- *Establish Performance Measures (Activity $A_{1.3}$):* To perform this step, the customer and the project's engineer should identify the parameters to be determined in the design evaluation step based on the results of the previous two steps. These parameters can be related to maintenance, equipment cost, system input/output, etc.

Both the steps associated with (Activity $A_{1.1}$) and (Activity $A_{1.2}$) can be performed in different orders as long as they are completed before the step associated with (Activity $A_{1.3}$).

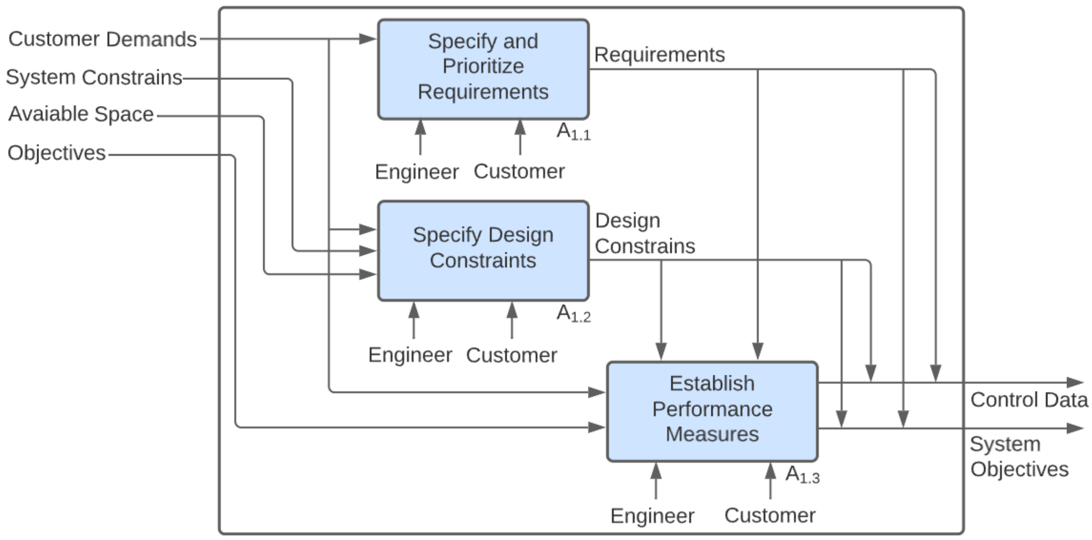


Figure 3.4. Activity A_1- Establish Control Data.

3.3.2 Activity A_2: Functional Decomposition of Objectives

Activity A_2 is the second step of the proposed methodology. This step is responsible for processing the system objectives and, in turn, determining the functions that the system is required to perform. This step is performed entirely by the project's engineer/s.

The SADT diagram of this step is represented in Figure 3.5., where the following substeps can be depicted:

- *Identify Major Functions of the System (Activity $A_{2.1}$):* In this step, the major functions that need to be performed in the facility should be identified.
- *Decompose Major Functions into Sub-functions (Activity $A_{2.2}$):* After the major functions' identification, these should be decomposed into sub-functions to determine the MH functional structure. This step should be achieved through a diagram (tree, block, SADT, etc.) to express the operations flow of the system better.

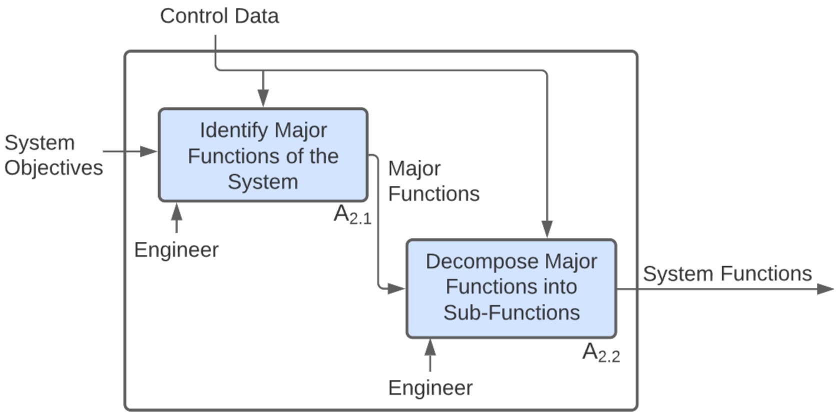


Figure 3.5. Activity A_2- Functional Decomposition of Objectives.

3.3.3 Activity A_3: Equipment Selection

Activity A_3 is the third step of the proposed methodology. This step determines what equipment and operational parameters are required to perform the system's functions and subfunctions determined in the previous step. This step is performed by the project's engineer/s and through the use of software in some of the sub-steps.

The SADT diagram of this step is represented in Figure 3.6., where the following substeps can be depicted:

- *Determine Candidate Equipment Classes (Activity $A_{3.1}$):* In this step, the classes of equipment suitable to perform the major functions of the MH system should be identified.

- *Design Sub-systems (Activity $A_{3.2}$):* Some of the classes of MH equipment identified in the previous design step are systems in their own right and include several components. In this design step, these sub-systems should be identified, and the classes of equipment adequate to perform these sub-systems' functions should also be determined.
- *Identify and Prioritize Key Metrics (Activity $A_{3.3}$):* The key metrics of the design concept achieved in the previous step should be identified and prioritized. The key metrics can constitute equipment choices, performance measures, and system requirements that significantly impact the system design. To perform this step, it is advised to establish criteria first and then identify and prioritize the key metrics.
- *Evaluate Key Metrics (Activity $A_{3.4}$):* In this step, the key metrics should be evaluated to determine if they meet the expectations of the project's engineer. As this is an equipment evaluation performed at a design concept stage, only approximate values for the key metrics need to be obtained.
- *Select/Model Remaining Equipment (Activity $A_{3.5}$):* In this step, the equipment not selected during the Evaluation of the Key Metrics step is meant to be chosen and validated. The selection process consists of selecting an off-the-shelf part or equipment or modeling a part with CAD software.
- *Set Operational Specifications of the Equipment (Activity $A_{3.6}$):* The operational parameters necessary for the correct operation of the system should be set in this step.

The *Equipment Selection* step is an iterative process. Suppose the results obtained in the Key Metrics Evaluation step are not as expected. In that case, the design process returns to the beginning of the *Equipment Selection* step, and the choices made along the process need to be reviewed and revised.

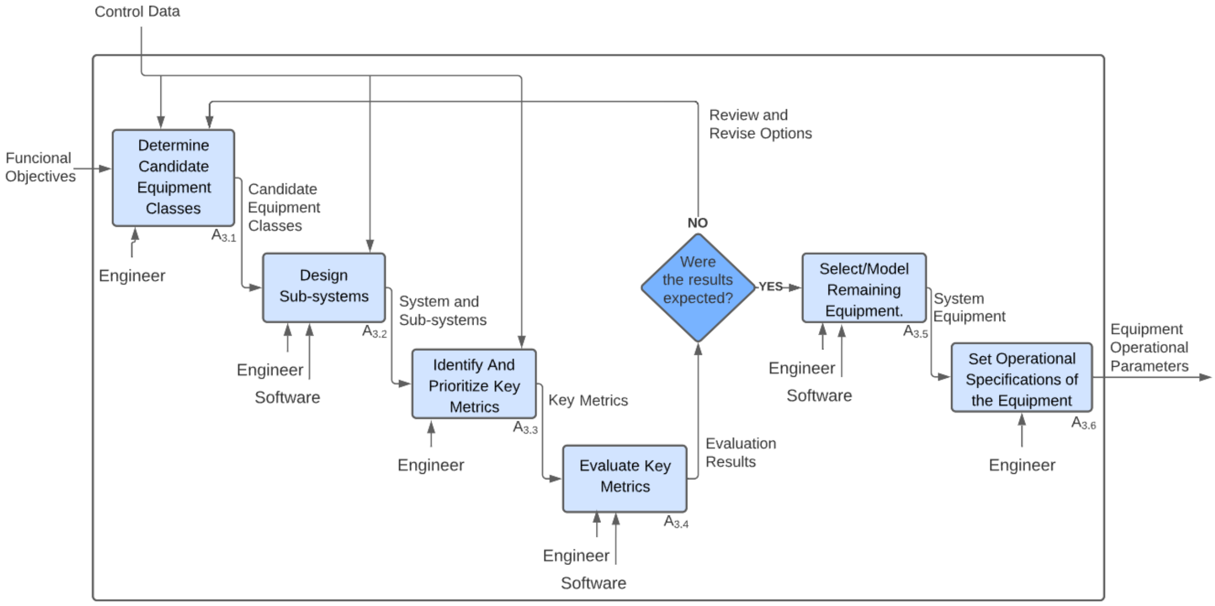


Figure 3.6. Activity A_3- Equipment Selection.

3.3.4 Activity A_4: Design Evaluation

Activity A_4 is the fourth step of the proposed methodology. This step attempts to validate the system design through simulation software and analytical methods.

The SADT diagram of this step is represented in Figure 3.7., where the following sub-steps can be depicted:

- Determine the Evaluation Model Parameters (Activity $A_{4.1}$): In this step, the parameters necessary to evaluate should be determined. These are the parameters that influence the performance measures.
- Create a Simulation Model (Activity $A_{4.2}$): To perform this step, a simulation tool should be selected to build a simulation model of either the complete MHS operation or individual operations.
- Run the Simulation and Interpret the Results (Activity $A_{4.3}$): In this step, the run setup parameters should be established, followed by the simulation of the model and interpretation of its results.
- Perform an Economic Evaluation (Activity $A_{4.4}$): This step is dedicated to performing an economic evaluation of the system. Depending on the customer's requirements, information such as purchase cost, maintenance cost, and operational cost should be determined in this step.
- Perform an FMEA on the System (Activity $A_{4.5}$): A failure mode and effect analysis (FMEA) of the system should be performed in this step.

The results of this step should then be assessed according to the system's objectives to verify if it constitutes a viable solution for the customer's needs. If it doesn't, the design process needs to return to the *Equipment Selection* step and the choices made along the process need to be reviewed and revised to improve the system design until it can be validated.

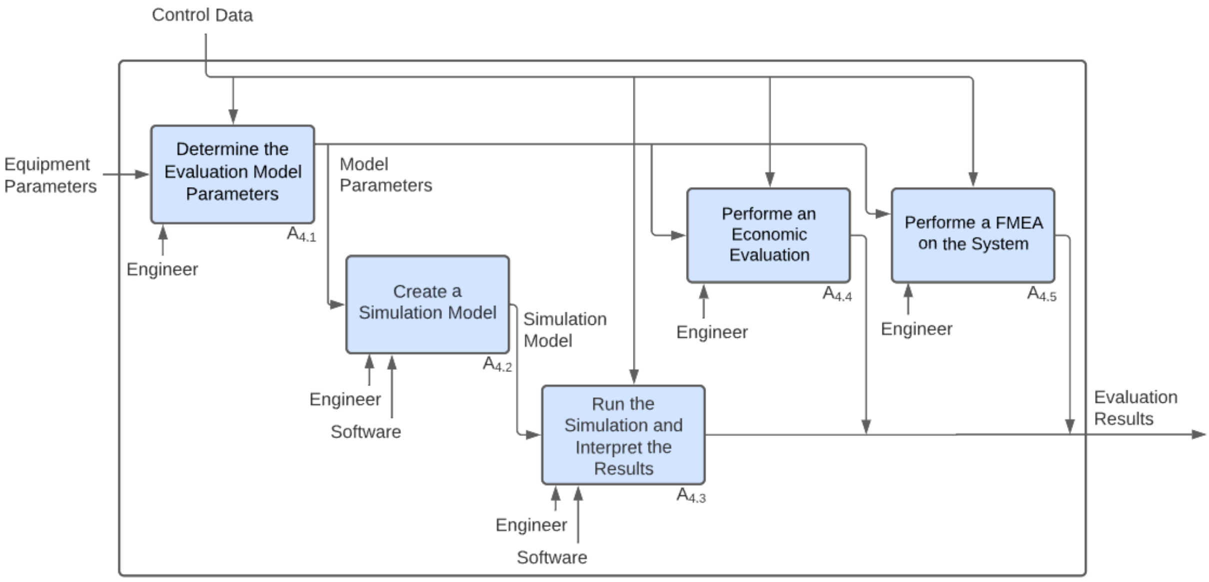


Figure 3.7. Activity A_4- Design Evaluation.

4 Proposed Design Solution for the Packaging and Depalletizing System

In this chapter, the design solution that resulted from the application of the proposed MHS design methodology will be presented before the methodology application itself. This change in the order of presentation was performed so the reader can understand the system as a whole, which will provide adequate context during the application of each design methodology step.

In the following sub-chapters, an overview of the proposed design solution will be performed, followed by the presentation of its most relevant systems and sub-systems.

4.1 System Overview

Before presenting the systems and sub-systems that compose the proposed solution, it's necessary to understand what material the system is meant to handle. Two materials are handled as single units in the system:

1. **Packs of hot-dog buns:** The *Packs* are illustrated in Figure 4.1 and will be represented in the CAD model of the system, as the 3D model depicted in Figure 4.2. The arrow present in the model represents the side of the pack opening.
2. **Plastic crates:** The *Crates* that the system will handle are similar to Figure 4.3, being this figure's model, the model used in the 3D model of the proposed MHS solution.

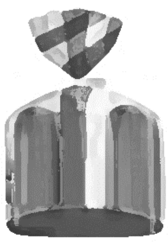


Figure 4.1. Illustration of a pack of hot dog buns.

Figure 4.2. 3D model of a pack of hot dog buns.

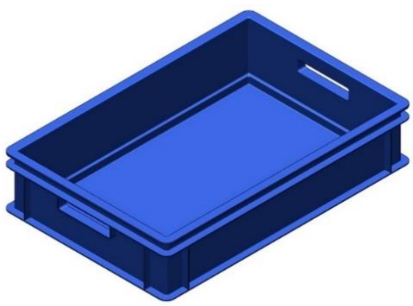


Figure 4.3. Crates' 3D model.

Now that the material handled by the system is known, the system itself can be presented. Figure 4.5 depicts the top view of the proposed design for the material handling system, which is composed of two main workstations, namely:

1. **Packaging Workstation:**

   This station receives the packs of hot-dog buns from the pre-existing system at a rate of *70 Packs per minute*. They are then reoriented into a packaging layout by the *Pack Column Forming Equipment* and *Two-Columns Forming Equipment* and finally packed into the *Crates* through *the Packs Pick and Place Equipment.* Furthermore, this station is responsible for receiving *Crates* from the *Depalletizing Workstation* and handling them during the packaging operation.

2. **Depalletizing Workstation:**

   In the *Depalletizing Workstation*, two primary operations are performed: *Crates'* positioning and the depalletizing operation itself. This station is supplied with pallets full of *Crates* from a worker operating a hand pallet jack. The pallets full of *Crates* are unloaded into a *U-Shaped Structure* whose shape helps with the pallet's unloading. After unloading, the stacks of *Crates'* position and orientation are corrected by the *Crate's Positioning Equipment,* allowing for the depalletization of the *Crates* through the *Crate's Pick and Place Equipment.*

   Finally, the *Crates* are transported to the *Packaging Workstation* through a transfer system referred to as *Crate's Transport Equipment.*

Figure 4.4 depicts the 3D model of the proposed packaging and depalletizing system, featuring the *Packaging Workstation* at the left and the *Depalletizing Workstation* at the right.

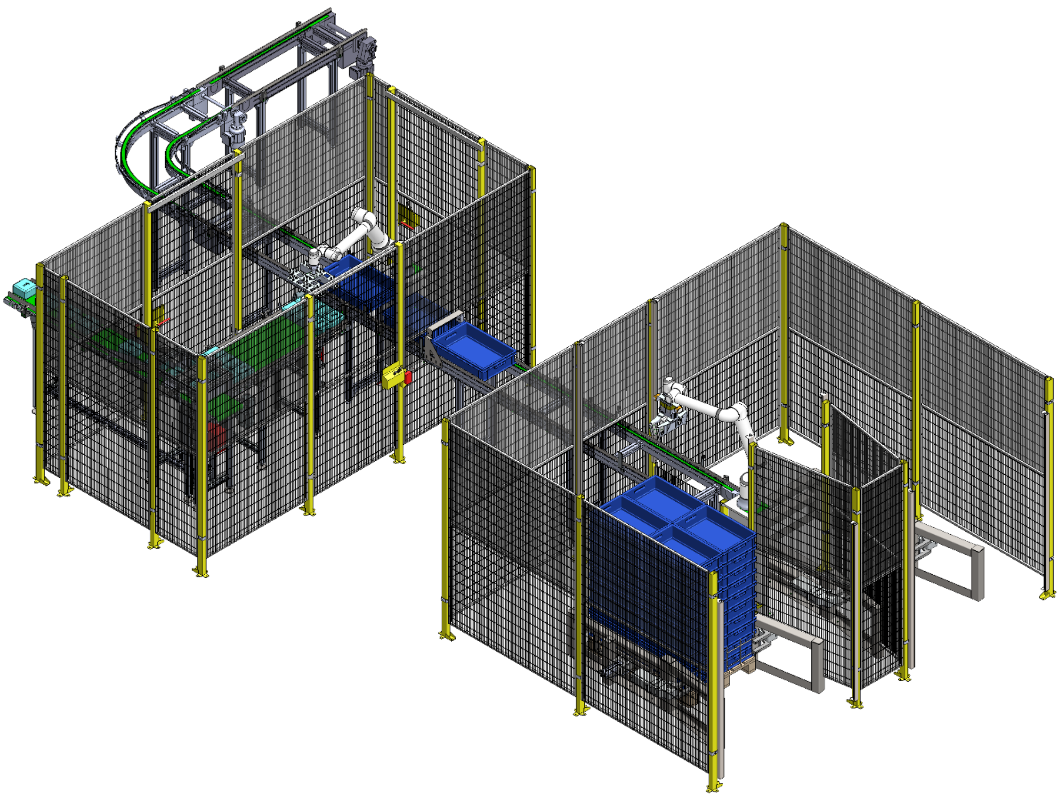


Figure 4.4. 3D model of the proposed packaging and depalletizing system.

Figure 4.5 depicts a top view of the system and its general dimensions. These dimensions were taken considering the end of the *Main Transport Conveyor* as a reference, as this conveyor is part of both the customer's previous installed system and the new MHS proposed in this dissertation.

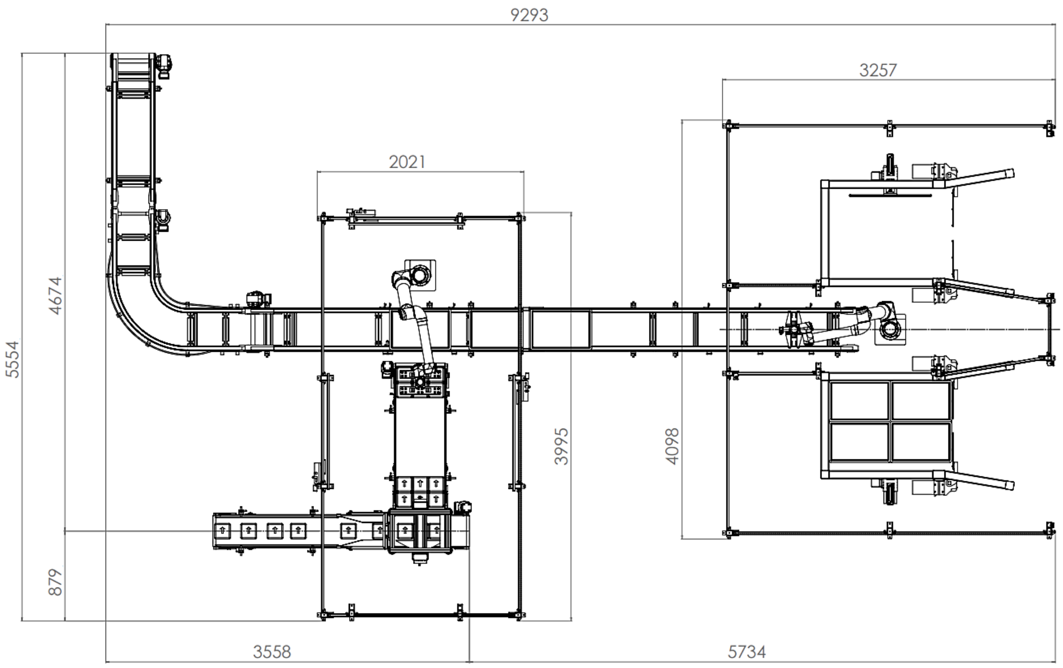


Figure 4.5. Top view and dimensions (in mm) of the proposed packaging and depalletizing system.

4.2 Packaging Station

4.2.1 Pack Column Forming

The *Pack Column Forming Equipment* receives packs of hot-dog buns (also referred to as *Packs*) from the *Main Transport Conveyor* and creates batches with three *Packs* (also referred to as *3-Pack-Column*). Following the *3-Pack-Column* formation, the equipment pushes the *3-Pack-Column* to an adjacent transport conveyor so that they can be picked by a pick and place robot further down the line.

Figure 4.6 represents the *Pack Column Forming Equipment* and labels several main components that work together during the equipment operation.

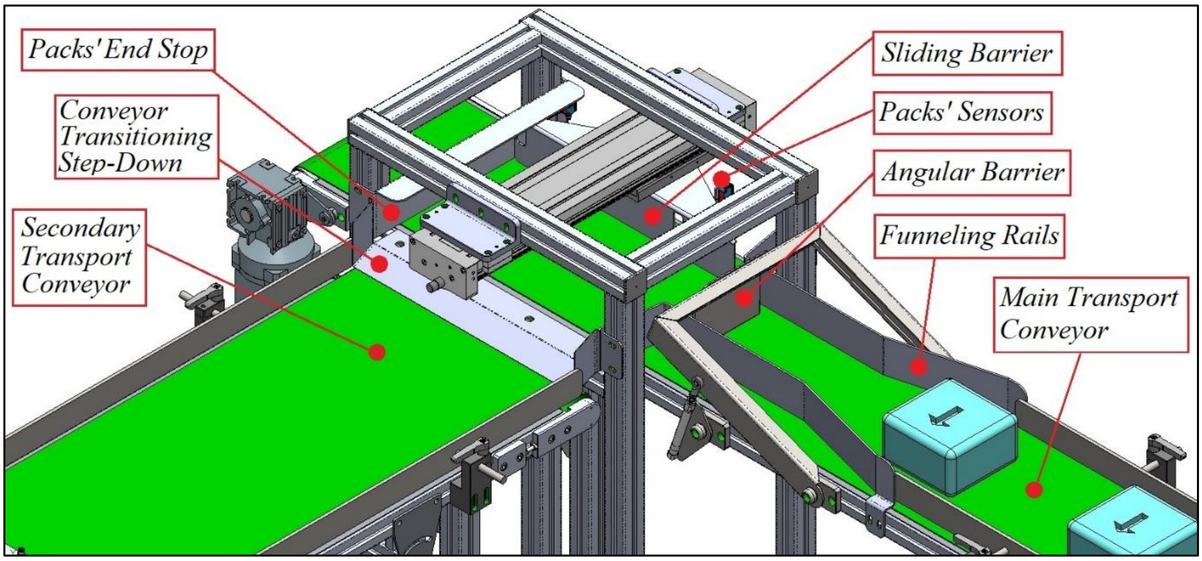


Figure 4.6. Pack Column Forming Equipment.

Each of the components depicted in Figure 4.6 serve the functions presented ahead (see Table 4.1):

Table 4.1. Pack Column Forming Equipment functional decomposition.

Equipment	Functions
Main Transport Conveyor	Brings the *Packs* to the system at a rate of *70 Packs/min*, connecting the newly proposed portion of the system with the pre-existing one.
Funneling Rails	Corrects any misalignment of the *Packs* with the longitudinal axis of the *Main Transport Conveyor*.
Packs' End Stop	Stops the packs coming in the *Main Transport Conveyor*.
Packs Sensors	Detects the presence of each *Pack* comprising the 3*-Pack-Column.*
Tilting Barrier	Stops any *Packs* coming in the *Main Transport Conveyor* in case there's a delay further ahead in the system.
Sliding Barrier	Pushes the *3-Pack-Column* to the *Secondary Transport Conveyor.*
Secondary Transport Conveyor	Transports the *3-Pack-Column* to the *Packs*' pick and place location.
Conveyor Transitioning Step-Down	Connects both transport conveyors, all while facilitating the movement of the *3-Pack-Column* (due to the slope it features) between transport conveyors.

To help the reader understand the *3-Pack-Column Formation*, six instances of the equipment operation were depicted in Figure 4.7. These instances are as follows:

a) This instance represents the arrival of the *Packs* at the *Pack Column Forming Equipment*. In this instance, the *Tilting Barrier* is opened, and the *Sliding Barrier* is retracted.
b) In this instance, the most forward *Pack* on the *Main Transport Conveyor* is stopped by the *End Stop*, and a *Pack* accumulation starts taking place.
c) While the equipment is operating, three sensors try to detect each Pack's presence. This instance represents the moment when the third *Pack* arrives, and all three sensors are aware of the *Packs* presence.
d) Once all the sensors detect the presence of the *Packs,* the *Sliding Barrier* pushes the *3-Pack-Column* to the *Secondary Transport Conveyor*. The *Sliding Barrier* then retracts back, and the *3-Pack-Column Formation* starts again (instance a)).

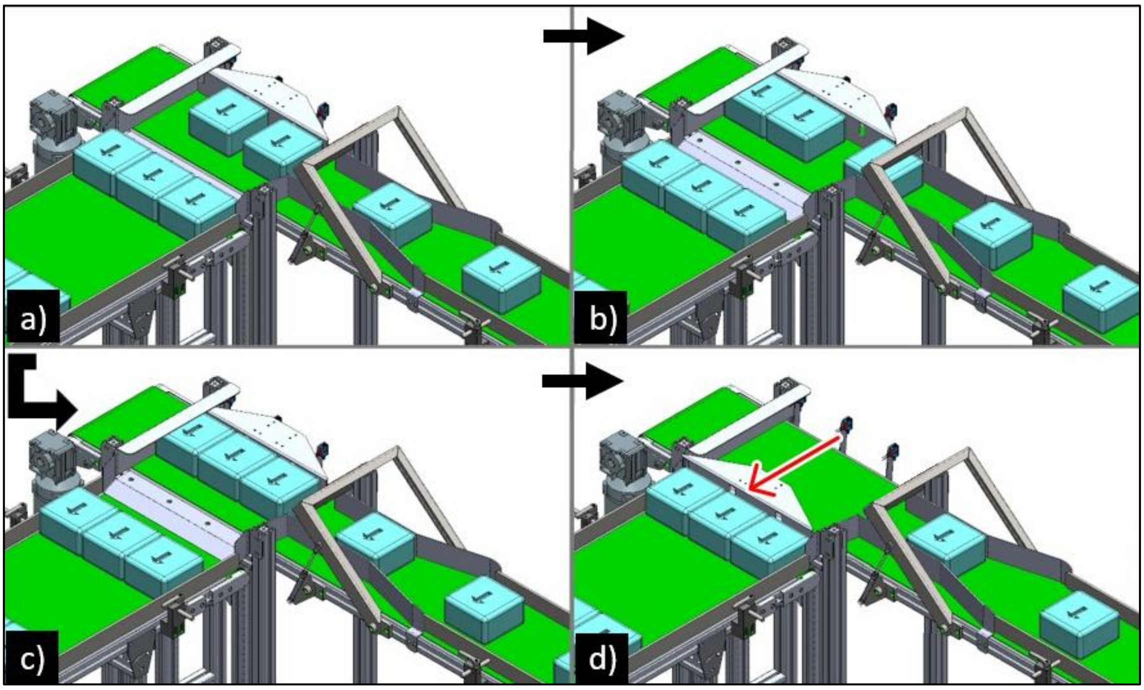


Figure 4.7. Illustration of the Column Forming Equipment operation. Instance a) the Tilting Barrier is opened, the Sliding Barrier is retracted, there are no Packs against the end stop; instance b) the Tilting Barrier is opened, the Sliding Barrier is retracted, there are two Packs against the end stop; instance c) the Tilting Barrier is opened, the Sliding Barrier is retracted, there are three Packs against the end stop; instance d) the Tilting Barrier is opened, the Sliding Barrier is deployed.

To manage the number of *Packs* that accumulate at the *End Stop* location in case of a delay further ahead in the system, the *Tilting Barrier* is deployed as depicted in Figure 4.8' instances. These instances are as follows:

e) Once a third *Pack* arrives, forming a *3-Pack-Column*, the *Tilting Barrier* moves down to a closed position, as depicted in Figure 4.9. Once the *Tilting Barrier* is closed, the *Packs* start accumulating against it.
f) After the *Tilting Barrier* is closed, the remaining equipment will operate as described in Figure 4.7-instance d). Once the *Sliding Barrier* is retracted, the *Tilting Barrier* opens, and the *3-Pack-Column Formation* process starts again.

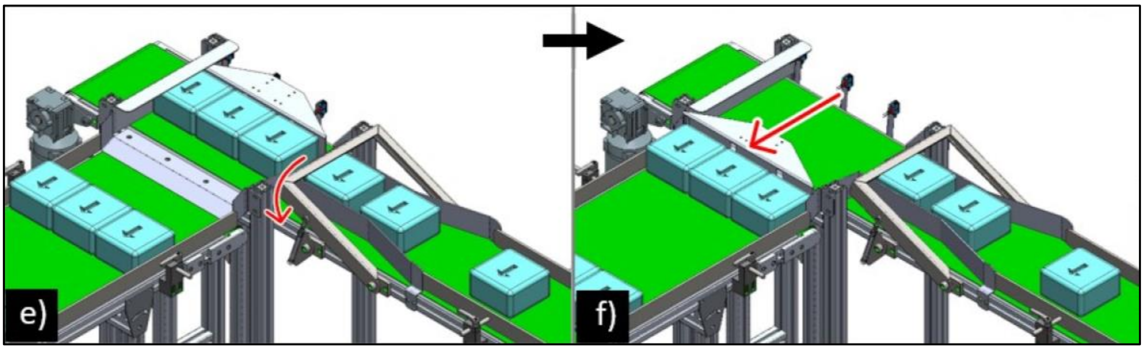


Figure 4.8. Tilting Barrier Equipment operation. Instance e) the Tilting Barrier is closed, the Sliding Barrier is retracted; instance f) the Tilting Barrier is closed, the Sliding Barrier is deployed.

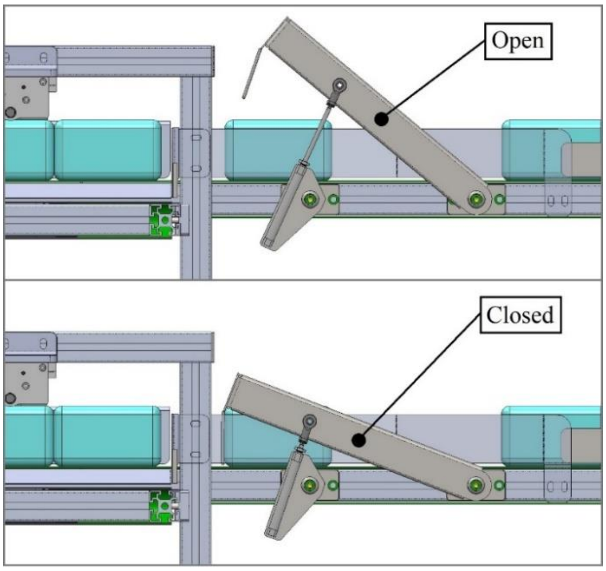


Figure 4.9. Tilting Barrier open and closed states of operation.

Detection of Packs

To detect the presence of the *3-Pack-Column*, photoelectric sensors are used. Each of these sensors detects the position of one *Pack,* and the system will only be sure that a *3-Pack-Column* is present when all three sensors detect the *Packs*' presence, at the same time, for a duration of 200 milliseconds.

The sensors are placed at a distance of 170 mm apart (see Figure 4.10) and interact with the *Packs* through cut-outs in the *Sliding Barrier*'s sheet metal surface*,* as depicted in Figure 4.11.

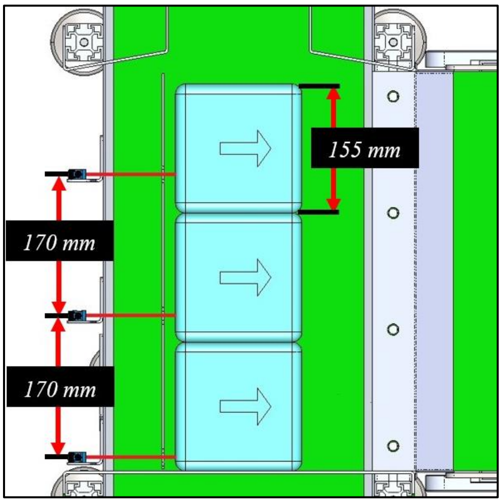


Figure 4.10. Illustration of the distance between the Packs' Sensors.

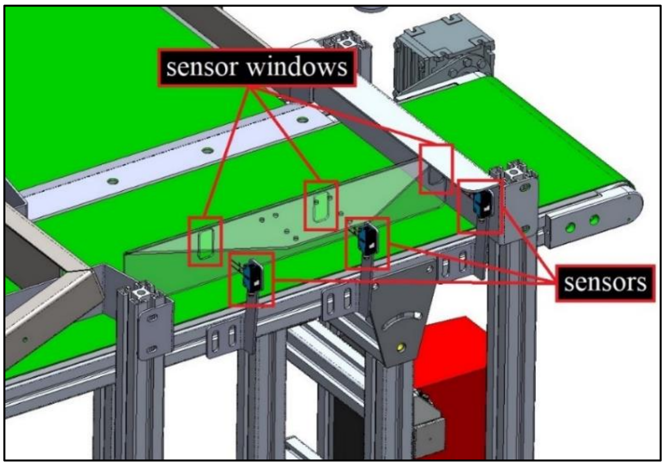


Figure 4.11. Illustration of the 3-Pack-Column detection equipment.

Referring to Figure 4.10, although the width of a pack is 155 mm, the distance between sensors was made larger (170 mm) to avoid the problems depicted in Figure 4.12. In this figure, the sensors are placed 155 mm apart, and two different scenarios are described:

a) In this scenario, a problem occurs when, for some unexpected reason, a *Pack* enters the *Column Forming Equipment* misaligned. This misalignment causes the Pack's width projected on the *Sliding Barrier* to be bigger than it is, which could trigger two sensors simultaneously. In turn, as soon as another *Pack* arrived, its presence would be detected by the sensor that hadn't been activated yet, and the system would mistake the presence of two *Packs* for the presence of a *3-Pack-Column.*
b) This scenario is similar to the previous one, however, instead of a misaligned *Pack*, there's a *Pack* with a width superior to the technical *Pack's* width. This unexpected width would also make the system mistake the presence of two *Packs* for the presence of a *3-Pack-Column.*

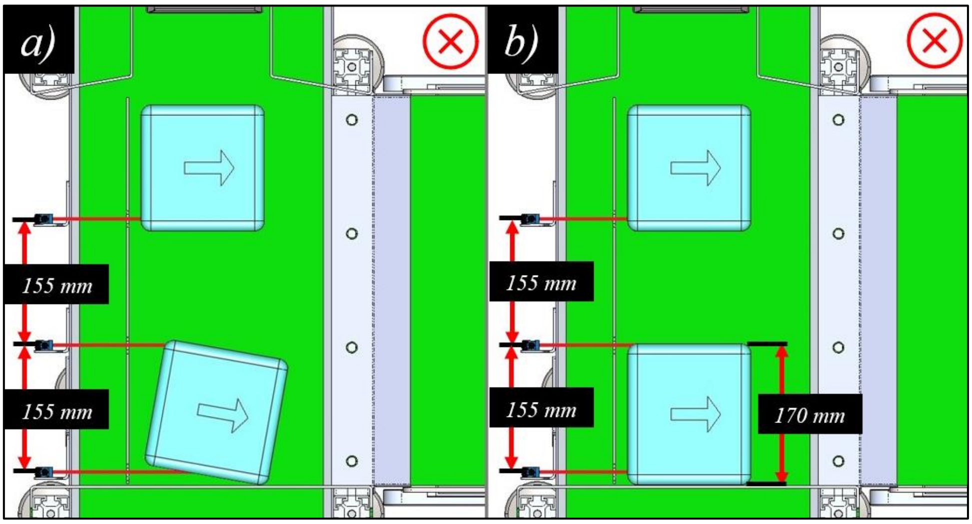


Figure 4.12. Illustration of incorrect pack detection scenarios. Instance a) a Pack enters the Column Forming Equipment misaligned; instance b) a Pack with a width superior to the technical Pack's width enters the Column Forming Equipment.

Considering the information above, the following points should be considered:

1. Besides the exposed scenarios, more scenarios could present a problem to the *Pack's* presence detection.
2. The distance between sensors isn't required to be 170 mm, it only needs to avoid the problematic scenarios above, and it should be adjusted based on the real-world testing of the system.

4.2.2 Two-Columns Forming and Packs' Pick and Place

The *Two-Columns Forming Equipment* is responsible for the following functions:

1. Forming a set of 6 *Packs* (stopping two *3-Pack-Columns*)*;*
2. Detecting the presence of the two *3-Pack-Columns;*

The *Packs' Pick and Place Equipment* is responsible for the following functions:

1. Picking every set of 6 *Packs*,
2. Detecting the presence of every *Pack* during the pick and place robot movement.
3. Placing each set of *Packs* inside a *Crate*.

Figure 4.13 represents the *Two-Columns Forming Equipment* and *Pack Column Forming Equipment* and labels several main components that work together during the equipment operation.

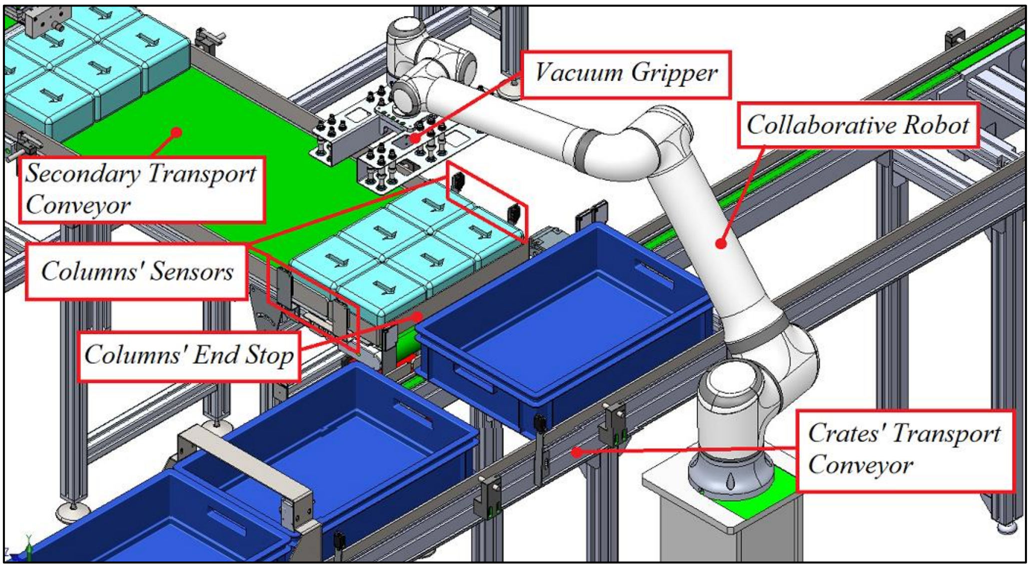


Figure 4.13. Two-Columns Forming Equipment and Pick and Place Equipment.

Once the first *3-Pack-Column* approaches the end of the *Secondary Transport Conveyor,* it is stopped by an end stop (*Columns' End Stop*). When a second *3-Pack-Column* arrives, it stops against the first column, forming a set of 6 *Packs* in the correct packaging orientation.

Aligned with both *3-Pack-Column's* positions are two sets of photoelectric sensors. These sensors use retroreflectors on the opposite side of the transport conveyor to reflect the sensor's emitted light beam. As soon as both sensors detect the presence of both *3-Pack-Columns*, for a duration of 500 milliseconds, simultaneously, they give the system the instruction to proceed with the pick and place operation.

The *Packs' Pick and Place* operation relies on a vacuum gripper equipped with suction grippers to pick each set of 6 *Packs* from the *Secondary Transport Conveyor.* After being picked, the *Packs* are placed inside a *Crate* that is stopped on a transport conveyor (*Crates' Transport Conveyor*).

During the movement between the pick and place targets, the system can detect if a Pack is missing by monitoring the vacuum pressure generated in the *Vacuum Gripper*.

Packs' Pick and Place Path Planning

Figure 4.14 represents the targets created for this pick and place application, and the path the robot TPC (tool center point) generates when it hits them.

For the Packs' Pick and Place Path planning, an approach target strategy was implemented with a series of linear, joint (also known as point-to-point), and circular movements. Considering this approach, the TCP path depicted in Table 4.2 was developed.

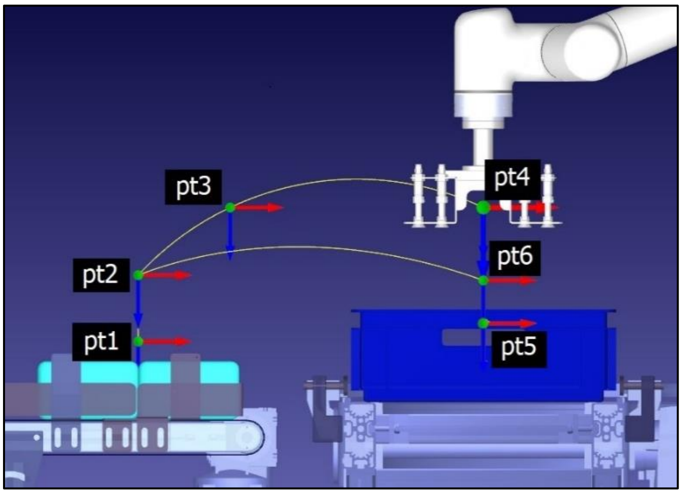


Figure 4.14. Packs Pick and Place path.

Table 4.2. Packs Pick and Place path movement types.

TCP move	Move type
pt1-pt2	Linear
pt2-pt3-pt4	Circular
pt4-pt5	Linear
pt5-pt6	Linear
pt6-pt2	Joint
pt2-pt1	Linear

Some of Figure 4.14's depicted targets and Table 4.2' TCP movement types have important considerations behind their selection. This is the case with the following:

a. Packs Target 1 (pt1): This target corresponds to the pick target, where the surface of the suction cups meets the surface of the set of six packs.
b. Packs Target 2 (pt2): This target is the picking approach target. If the *Packs* are not ready to be picked, it's in this target that the *Vacuum Gripper* will wait until they are.
c. Linear Movement (pt2-pt1): In the *Packs' Pick and Place* operation, the *Vacuum Gripper* generates a vacuum during the picking approach. Therefore, if the approach movement isn't done vertically, the vacuum gripper could catch the *Packs* sooner than it should, resulting in an incorrect picking.
d. Linear Movement (pt1-pt2): This movement allows the vacuum gripper, with the packs attached to it, to clear the *Columns' End Stop*, with a clearance of 40 mm, as depicted in Figure 4.15.
e. Packs Target 3 (pt3): Target pt3 is the middle target for the circular movement pt2-pt3-pt4, and it ensures the *Vacuum Gripper,* with the *Packs,* doesn't strike the side of the *Crate* while approaching it. The clearance provided by this target is 40 mm and can be depicted in Figure 4.16.
f. Packs Target 4 (pt4): Target pt4 is the placing approach target. If a *Crate* is not available for packaging, it's in this target that the *Vacuum Gripper* will a *Crate* is available.
g. Packs Target 5 (pt5): Target pt5 corresponds to the place target, where the *Packs* are dropped inside a *Crate.*

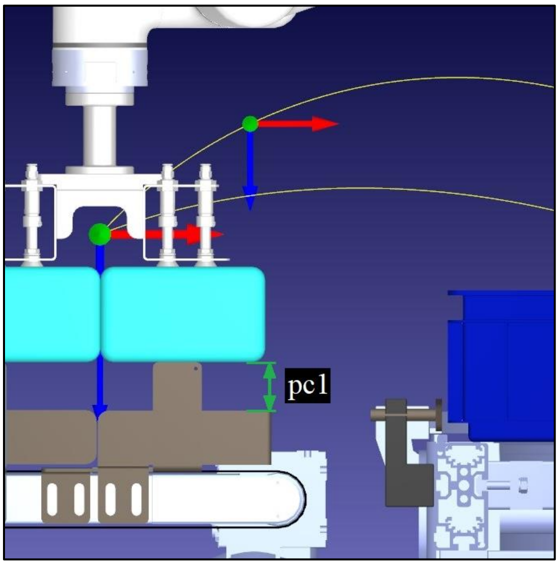


Figure 4.15. Columns' End Stop clearance.

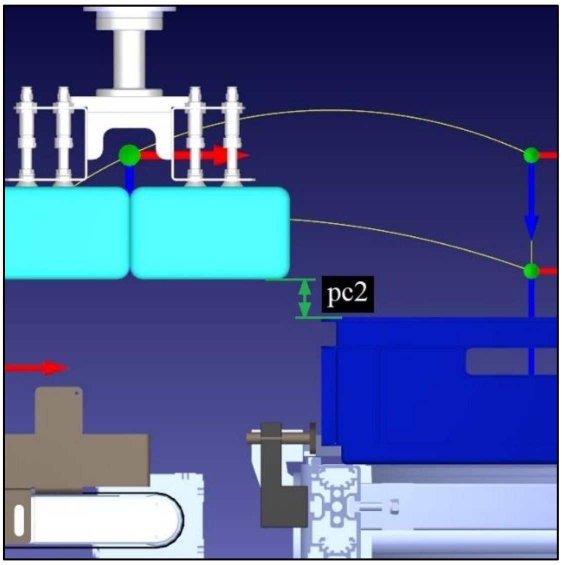


Figure 4.16. Crate clearance.

4.2.3 Crates' Indexing

The *Crates' Indexing* operation is responsible for making one *Crate* available at-a-time for the *Packs*' packaging.

Figure 4.17 represents the *Crates' Indexing Equipment* and labels several main components that work together during the equipment operation.

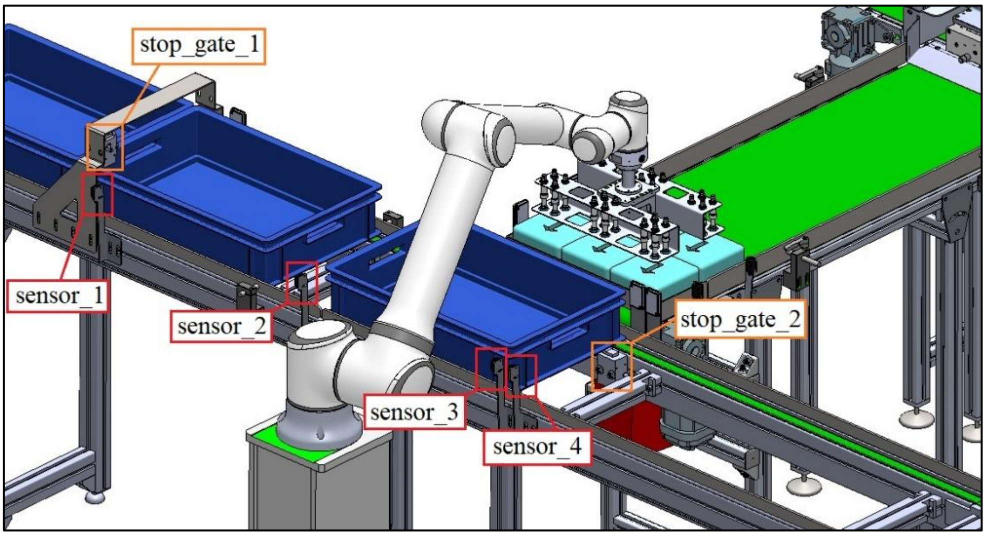


Figure 4.17. Crate's stop-and-go operation.

In order to make one *Crate* available at-a-time, the equipment relies on four sensors and two stop gates. The functions that each stop gate performs are described ahead:

a. *Stop_gate_2* is responsible for stopping the *Crates* for packaging by deploying a mechanical "finger," which stops the crate on its bottom edge, as depicted in Figure 4.19.
b. *Stop_gate_1* is responsible for stopping all the *Crates* besides the one heading for packaging (*stop_gate_2*). To stop all these *Crates*, the *stop_gate_1* only needs to stop one *Crate,* as depicted in Figure 4.18, and all the *Crates* behind it will stop by accumulating against it. Contrary to *stop_gate_2, stop_gate_1* stops the crates trough their top inside edge, as depicted in Figure 4.17. The reason behind this difference is that *stop_gate_2* needs to stop *Crates* that travel together, where there's no available space for the safe and reliable deployment of the mechanical "finger" though the bottom of the transport conveyor.

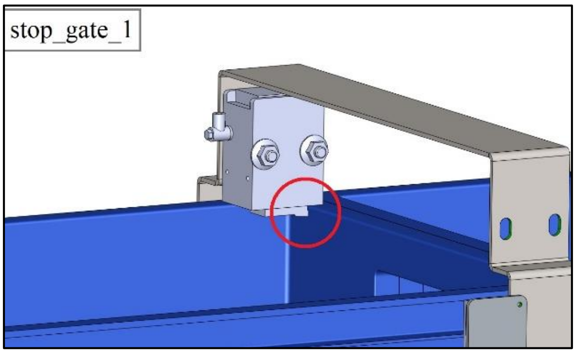


Figure 4.18. Close-up of the stop_gate_1.

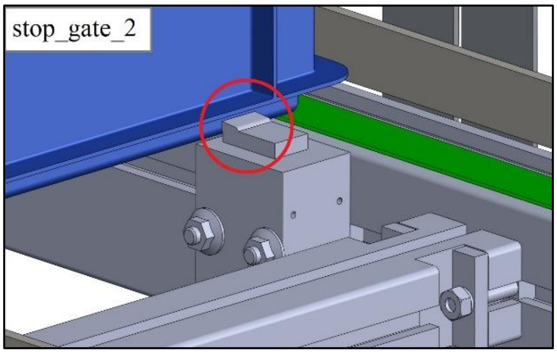


Figure 4.19. Close-up of the stop stop_gate_2.

To control the actuation of these stop gates, four sets of photoelectric sensors and retroreflectors were used. The process in which the sensors detect the presence of the *Crates* and control the stop gates deployment is depicted in Figure 4.20. To explain the indexing process present in this figure, a short code program was written (see Figure 4.21).

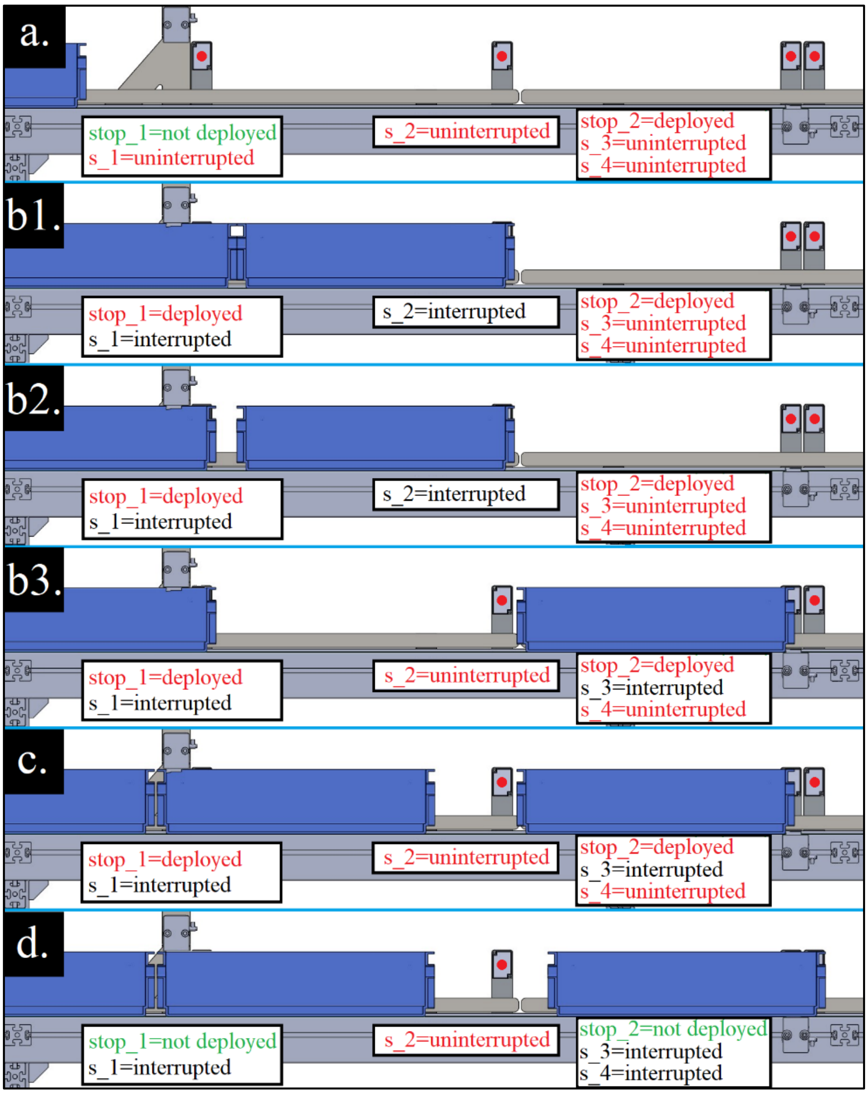


Figure 4.20. Crate's indexing operation instances. Instance a. stop_1 is not deployed, stop_2 is deployed, s_1 is uninterrupted, s_2 is uninterrupted, s_3 is uninterrupted, s_4 is uninterrupted; Instance b1. stop_1 is deployed, stop_2 is deployed, s_1 is interrupted, s_2 is interrupted, s_3 is uninterrupted, s_4 is uninterrupted; Instance b2. stop_1 is deployed, stop_2 is deployed, s_1 is interrupted, s_2 is interrupted, s_3 is uninterrupted, s_4 is uninterrupted; Instance b3. stop_1 is deployed, stop_2 is deployed, s_1 is interrupted, s_2 is uninterrupted, s_3 is interrupted, s_4 is uninterrupted; Instance c. stop_1 is deployed, stop_2 is deployed, s_1 is interrupted, s_2 is uninterrupted, s_3 is interrupted, s_4 is uninterrupted; Instance d. stop_1 is not deployed, stop_2 is not deployed, s_1 is interrupted, s_2 is uninterrupted, s_3 is interrupted, s_4 is interrupted;

```python
#crate_ready_for_packaging = False -> Crate is not indexed
#system.on() == True -> System is operational
#s_1.interrupted() == True -> Sensor is detecting a Crate
#robot.ended_packaging() == False -> Packs have not been placed inside a crate yet
#stop_2.deploy() -> comand for the deployment of stop_2
#stop_2.retract() -> comand for the retraction of stop_2

def pack_indexing(system.on(),robot,s_1,s_2,s_3,s_4):
  crate_ready_for_packaging = False
  while system.on() == True:
    while robot.ended_packaging() == False :
        while s_3.interrupted() == False and s_4.interrupted() == True:
            stop_2.deploy()
            if s_1.interrupted() == True and s_2.interrupted() == True:
                stop_1.deploy()
        if s_1.interrupted() == True and s_3.interrupted() == True and s_4.interrupted() == False:
            stop_1.deploy()
            crate_ready_for_packaging = True
        elif s_3.interrupted() == True and s_4.interrupted() == False:
            crate_ready_for_packaging = True
    stop_1.retract()
    stop_2.retract()
    crate_ready_for_packaging = False
    wait(1000) # wait 1 second so sensor s_4 can detect the crate.
               #This value can be adjusted upon real-word testing.
```

Figure 4.21. Code written in python to demonstrate the Crates' indexing logic.

4.3 Depalletizing Station

The operations that take place in this station can be described in the following steps:

1. A worker, through the use of a pallet jack, brings pallets full of *Crates* (each with four stacks of ten *Crates)* to unload in both of the *Crates' Positioning Equipment*. This equipment positions the *Crates* by pushing them against two reference surfaces.
2. Once the *Crates* are in position, the depalletizing operation takes place. A robot arm with an angular gripper picks two *Crates* simultaneously through their handles and proceeds to place them in a transport conveyor.
3. After there are no *Crates* left in a pallet to pick, the robot switches sides and proceeds to pick *Crates* from the pallet on the opposite side (assuming it's full of *Crates*). Once the robot changes picking sides, the worker can proceed with the replacement of the empty pallet with a full one. This step repeats every time a pallet is emptied.

4.3.1 Positioning Operation of the Crates

The *Crates' Positioning* is responsible for positioning the *Crates'* stacks in order for the *Crates' Pick and Place* operation to proceed.

Figure 4.22 represents the *Crates' Positioning Equipment* and labels several main components that work together during the equipment operation.

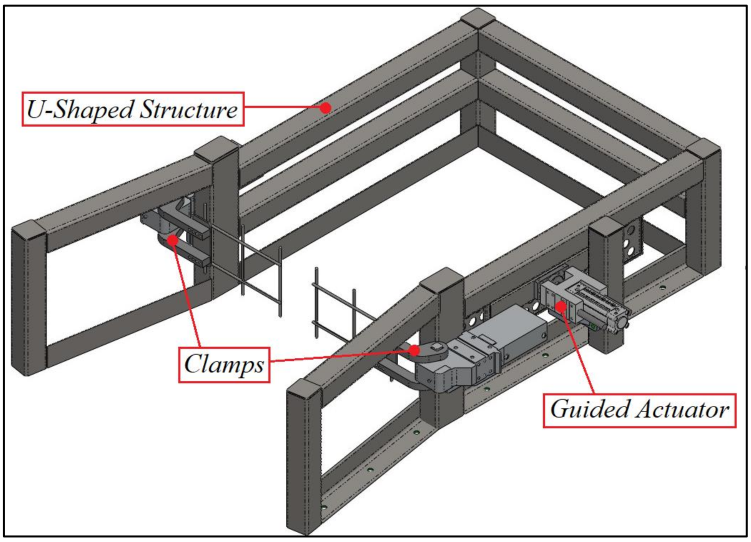


Figure 4.22. Crates' Positioning Equipment components.

During the equipment operation, a worker is responsible for unloading a pallet full of crates inside each *Crates' Positioning Equipment* through the use of a pallet jack. In addition, the worker is also responsible for removing the pallets from the equipment when they are empty.

During the pallet unloading, the operator must insert the pallet into the *U-Shaped Structure*. This structure was designed with both sides extending outwards to funnel the approaching pallet and provide easier unloading. Furthermore, the *U-Shaped Structure* is 80 mm wider than the pallet, allowing for some room margin during unloading. These features allow for a fast pallet replacement and account for any pallet distortion or extra width that might have resulted from day-to-day damage.

To position the *Crates'* stacks, after unloading, the equipment uses two sides of the *U-Shaped Structure* as reference surfaces to push the *Crates'* stacks against. These surfaces, depicted in Figure 4.23, share the equipment's back corner closest to the pick and place robot.

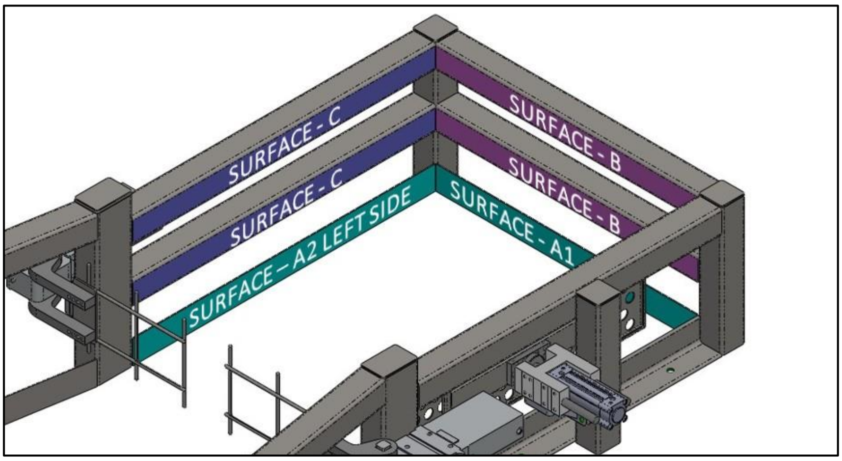


Figure 4.23. Reference surfaces of the Crates' Positioning Equipment.

To position the *Crates'* stacks against the reference surfaces, the equipment relies on two pneumatic clamps (referred to as *Clamps*) and one pneumatic guided actuator (referred to as *Guided Actuator*). This is a sequenced operation as follows:

1. The *Clamps* push the *Crates'* stacks against reference surface-*B.*
2. The *Guided Actuator* pushes the *Crates'* stacks against reference surface-*C.*

Since the *Crates* are stacked, each column behaves approximately like a unit load. Additionally, it was considered that the positioning equipment doesn't need to interact with every single row of *Crates* to position them. As a result, both the *Guided Actuator* and *Clamps* only interact with the bottom two rows of the *Crates'* stacks.

Figure 4.24 depicts and highlights (in green) the surface of the *Crates* that will interact with the positioning equipment. Due to the nature of the *Crates'* application, these surfaces may acquire some deformations during their lifetime, potentially resulting in a slight overall length or width increase. To account for this variable, the *Crates' Positioning Equipment* doesn't push the *Crates* completely against the reference surfaces, leaving a 2 mm clearance between them and the *Crates'* surfaces (see Figure 4.25). This clearance assures that the *Clamps* aren't actively exercising force on the crates during the *Guided Actuator's* operation and the *Packs'* pick and place.

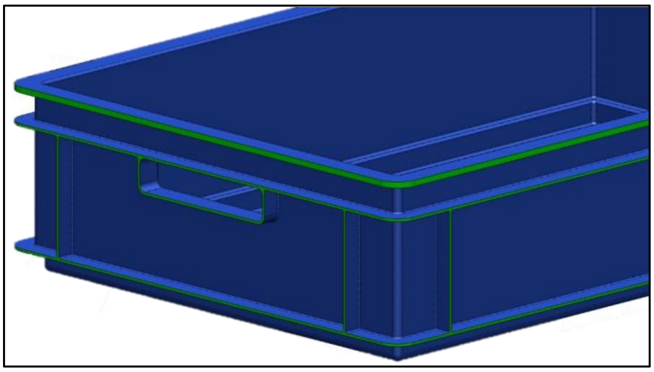


Figure 4.24. Crate's most outwards surfaces.

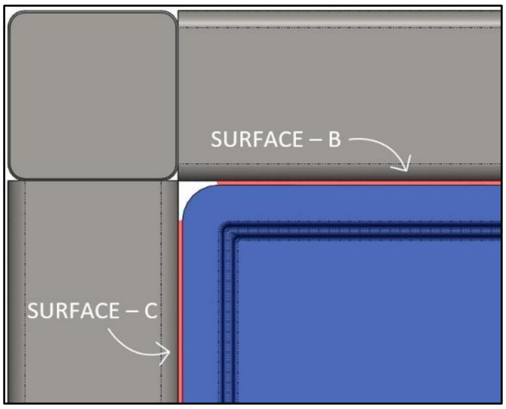


Figure 4.25. Gaps between Crates' surfaces and positioning equipment.

4.3.1.1 Clamps' Operation

Referring to Figure 4.23, once the pallet is unloaded into the *U-Shaped Structure*, the *Crates'* stacks may not be parallel with or pushed against the reference surface-*B*. The purpose of the *Clamps*' Operation is to reduce this gap.

Figure 4.26 depicts three clamping operation instances, highlighting the clearance between the reference surface-*B* and the *Crates* and the movement executed by the *Clamps* between instances.

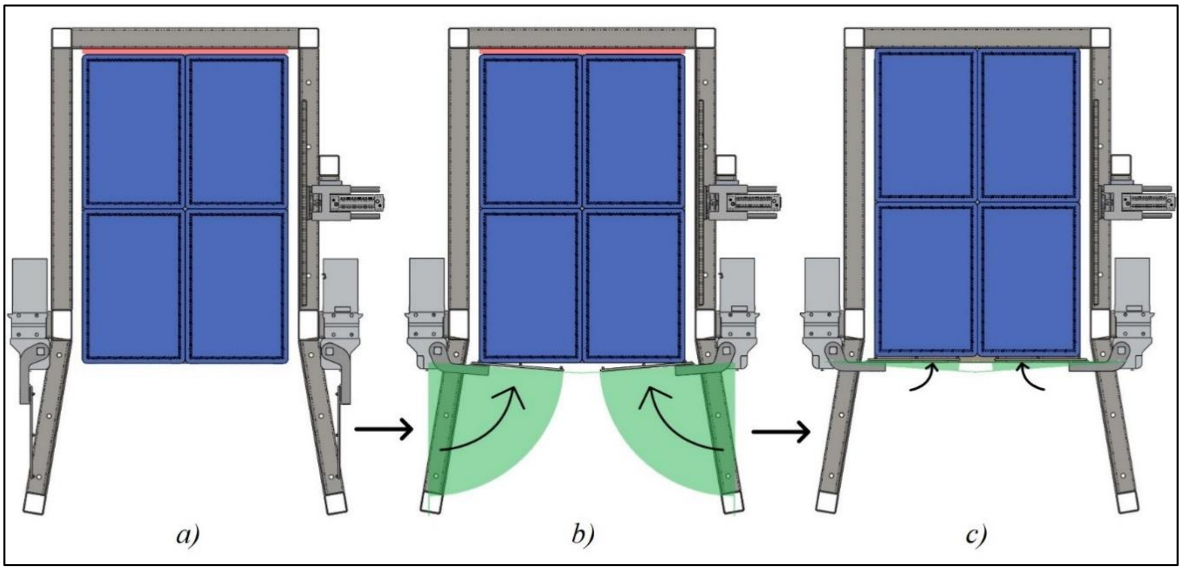


Figure 4.26. Clamps' operation instances. Instance a) Clamps opened, visible gap (highlighted in red); instance b) Clamps almost completely closed, visible gap (highlighted in red); instance c) Clamps completely closed, no visible gap.

These instances are described as follows:

a) Depicts the moment right after the unloading of a pallet full of *Crates,* where the *Clamps*' arms are in their opened position (parallel to the *U-Shaped Structure*).
b) Represents the instance after the *Clamps* started closing, where the *Clamps'* arms first enter contact with the *Crates'* surfaces. In this instance, the *Clamps'* arms have traveled almost 90 degrees from their opened position.
c) In this instance, the *Clamps'* arms have traveled the full 90 degrees, pushing the crates against reference surface-*B*, closing the gap highlighted in red.

To help the reader understand how the equipment interacts with the *Crates* during operation, Figure 4.27 and Figure 4.28 depict the interaction of the *Crates'* surfaces with the *Clamps'* arms and the *U-Shaped Structure,* respectively.

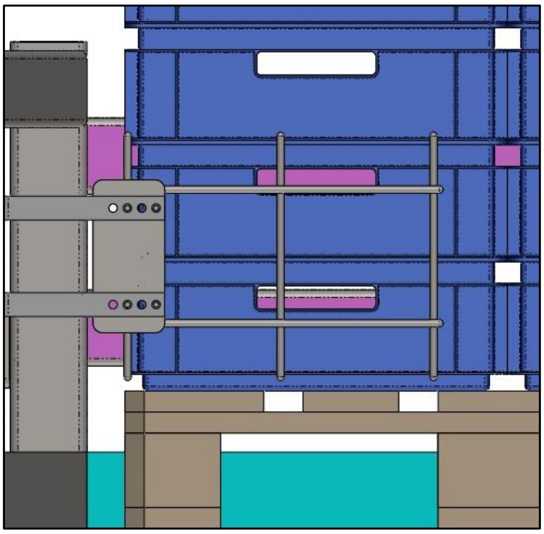


Figure 4.27. Interaction between Crates and Clamp.

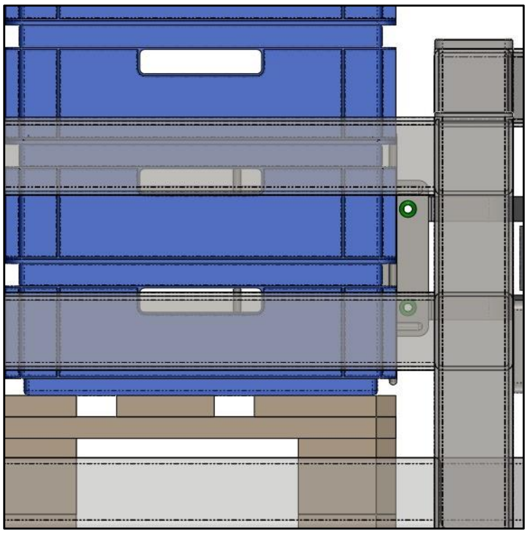


Figure 4.28. Interaction between Crates and surface-B.

4.3.1.2 Guided Actuator's Operation

Referring to Figure 4.23, once the *Clamps' Operation* is over, there might be a gap between the *Crates'* stacks and the reference surface-*C.* The purpose of the *Guided Actuator* is to reduce this gap.

Figure 4.29 depicts three clamping operation instances and highlights the clearance between the reference surface-B and the *Crates* and the movement executed by the *Clamps* between instances.

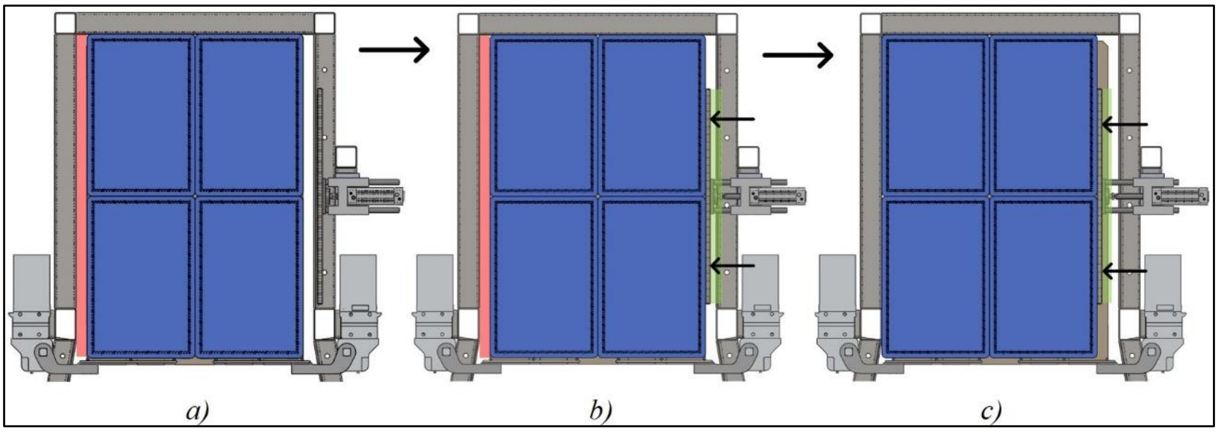


Figure 4.29. Guided Actuator's operation instances. Guided Actuator not deployed, visible gap (highlighted in red); instance b) Guided Actuator partially deployed, visible gap (highlighted in red); instance c) Guided Actuator completely deployed, no visible gap.

These instances are described as follows:

a) In this instance, both *Clamps'* arms are closed, and the *Guided Actuator's* pushing surface rests slightly inside the side of the *U-Shaped Structure* to be out of the way of the pallet unloading operation.
b) This instance represents the moment when the *Guided Actuator's* pushing surface starts interacting with the *Crates'* surfaces, performing a movement from right to left, in this particular case.
c) In this instance, the crates have been pushed against the reference surface-*C,* closing the red highlighted gap, while the *Guided Actuator'* performed the remaining of its entire 100 mm extension.

To help the reader understand how the equipment interacts with the *Crates* during operation, Figure 4.30 and Figure 4.31 depict the interaction of the *Crates'* surfaces with the *Guided Actuator's* pushing surface and the *U-Shaped Structure,* respectively.

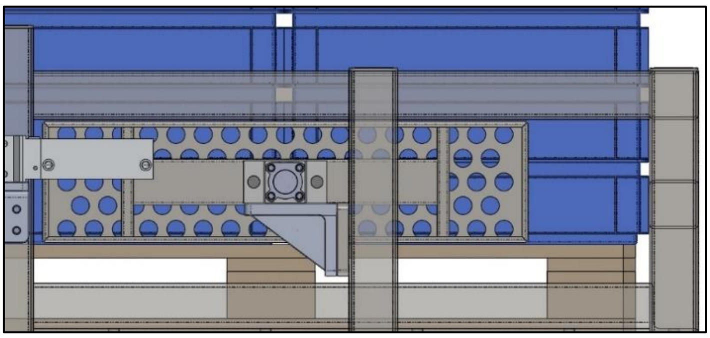


Figure 4.30. Interaction between Crates and Guided Actuator.

Figure 4.31. Interaction between Crates and surface-C.

4.3.2 Pick and Place Operation of the Crates

The *Crates Pick and Place Operation* aims to take the Crates from the Crates' pallet and put them on the Crates' Transport Equipment, which will transport them to the *Packaging Station*.

Figure 4.32 represents the *Crates' Pick and Place Equipment* and labels several main components that work together during the equipment operation.

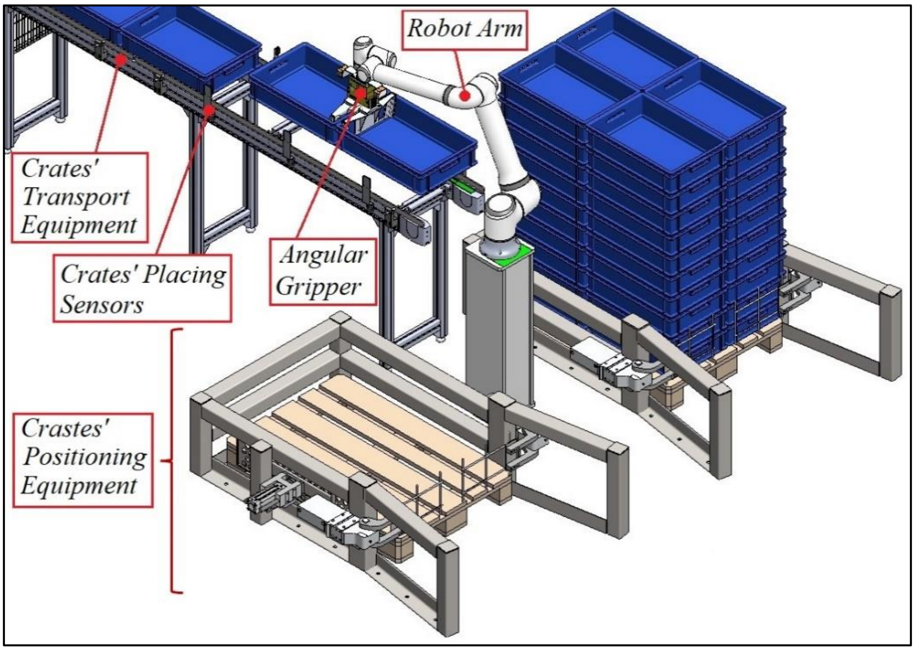


Figure 4.32. Crates' Pick and Place components.

Once the *Crates' Positioning Equipment positions the Crates*, the pick and place robot picks two *Crates* simultaneously using an angular gripper. It then proceeds to place them on the *Crates' Transport Equipment.*

4.3.2.1 Crates Pick and Place Trajectory Planning

Similarly, to the Packs' Pick and Place Path Planning, a series of targets and linear, joint, and circular movements were implemented in the Crates' Pick and Place Path Planning. However, this application's pick and place operation is more complex, as the TCP targets are placed in two different planes instead of just one (see Figure 4.33).

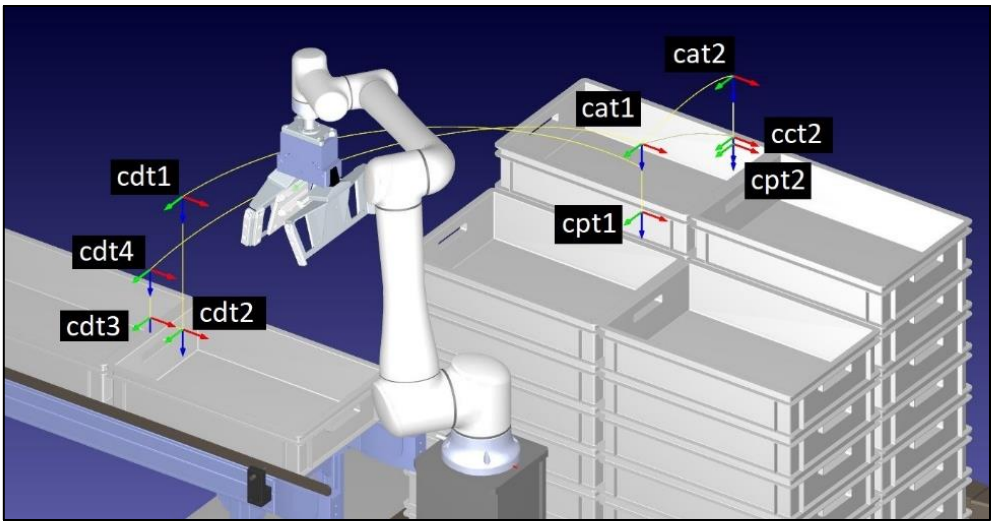


Figure 4.33. Crates' Pick and Place targets.

Since this is a complex set of target coordinates, the target planning explanation will be divided into two parts: the *Crates' Pick Targets* and the *Crates' Place Targets*.

4.3.2.1.1 Crates' Pick Targets

Since the *Crates' Pick and Place* is a depalletizing operation, the pick targets will change according to the *Crates* the robot is trying to pick. To avoid collisions and provide a reliable pick and place operation, the target picking sequence for the *Crates* closest to the pick and place robot differs from the target picking sequence of the *Crates* further away from it (see Figure 4.34).

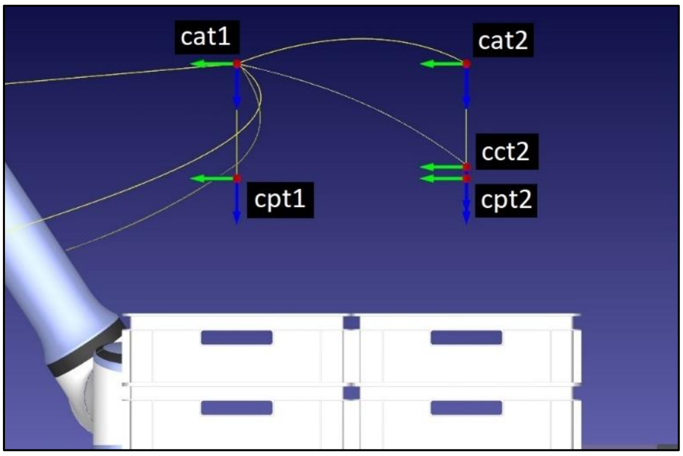


Figure 4.34. Crates' picking targets for the first row of Crates.

Considering the information above, the TCP paths depicted in Table 4.3 and Table 4.4 were developed. These paths are for the top row of *Crates,* of the sets of *2-Crates* in the closest and furthest picking position from the robot, respectively.

Table 4.3. Crates' Pick and Place path movement types for the closest set of 2-Crates to the robot, on the top row of Crates.

TCP move	Move type
place targets-cat1	Joint
cat1-cpt1	Linear
cpt1-cat1	Linear
cat1-place targets	Joint

Table 4.4. Crates' Pick and Place path movement types for the furthest set of 2-Crates to the robot, on the top row of Crates.

TCP move	Move type
place targets-cat1	Joint
cat1-cat2	Joint
cat2-cpt2	Linear
cpt2-cct2	Linear
cct2-cat1	Joint
cat1-place targets	Joint

For each of the remaining rows of *Crates,* the robot's TCP path will be similar to the ones presented in Table 4.3 and Table 4.4. However, the targets' coordinates will be one *Crate's* height lower than the targets on the row above.

Some targets and TCP movement types have important considerations behind their selection. This is the case with the following:

a. Crate set 1 approach target (cat1): This target represents the approach target for picking the first set of *Crates* and the pallet approach target. The pallet approach target is the last target hit by the robot's TCP before heading towards the placing targets, and it’s also the first target hit before proceeding to any picking targets. This is done to avoid collisions between *Crates* and the remaining equipment.
b. Crate set 1 pick target (cpt1): This target represents the pick target for the first set of 2-*Crates*.
c. Crate set 2 pick target (cpt2): This target represents the pick target for the second set of 2-*Crates*.
d. Linear Movement (cpt2-cct2): Since the *Crates* are stacked, this movement is necessary for the picked *Crates* to clear the *Crates* underneath them. The clearance provided by this movement is 2 mm, as depicted in Figure 4.35. This scenario doesn't apply to the *Crates'* columns nearest to the pick and place robot as, after being picked, their next movement is already vertical.

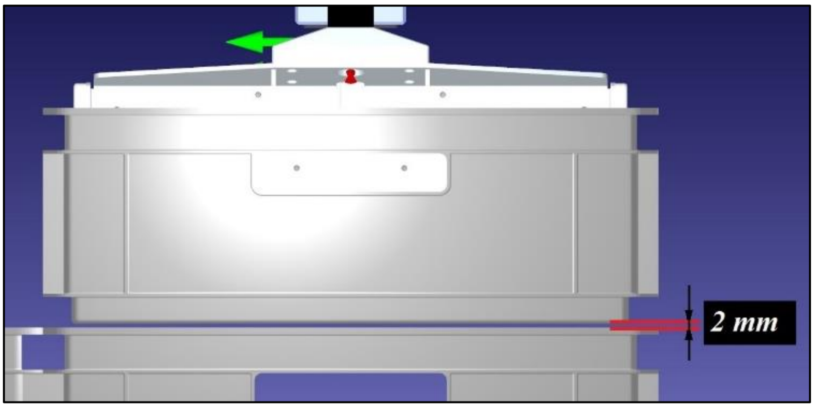


Figure 4.35. Clearance between two sets of crates.

4.3.2.1.2 Crates' Place Targets

When the *Angular Gripper* travels from the pallet approach target (cpt1) to the placing targets, the first target it meets is - cdt1, as depicted in Figure 4.36. In this instance, the system will proceed with the *Crates'* placing or wait if the *Crate's* placing area is not available for placing.

Once it's okay to proceed with the *Crates'* placing, the *Angular Gripper* will approach cdt2, and as soon as it hits this target, it changes direction and travels horizontally to target cdt3. During this last movement, which is performed at the same speed as the *Crates' Transport Conveyor,* the *Angular Gripper* will open and release the *Crates*. If not for this linear horizontal movement, the *Crates* could get caught on the *Angular Gripper's* fingers since the *Crates' Transport Conveyor* is constantly running.

All the movements performed by the robot's TCP, including the ones mentioned above, can be depicted in Table 4.5.

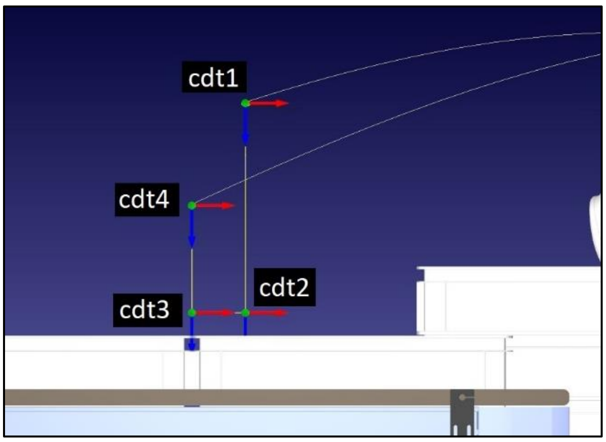


Figure 4.36. Crates' placing targets.

Table 4.5. Crates' Pick and Place targets (relative to the robot's base).

TCP move	Move Type
pick targets-cdt1	Joint
cdt1-cdt2	Linear
cdt2-cdt3	Linear
cdt3-cct4	Linear
cct4- pick targets	Joint

When the pick and place robot finishes depalletizing one pallet, it waits on target cdt4 before proceeding to depalletize another pallet.

Crate's Placing Sensors

To place a set of *2-Crates* into the *Crates' Transport Equipment,* the dropping zone needs to be available, that is, free of *Crates*. A set of three sensors with retroreflectors are used to determine if this zone is available, as depicted in Figure 4.37. These sensors are placed less than a *Crate's* length apart (*600 mm*) to detect the presence of *Crates* at all times.

Only when all three sensors aren't detecting the presence of a *Crate* is the pick and place robot able to proceed with the placing operation.

The furthest sensor (Figure 4.37' left sensor) is 100 mm away from the location where the *Crates* are placed, resulting in at least a 100 mm distance between the *Crates* placed by the robot and the *Crates* already present in the *Crates' Transport Equipment.*

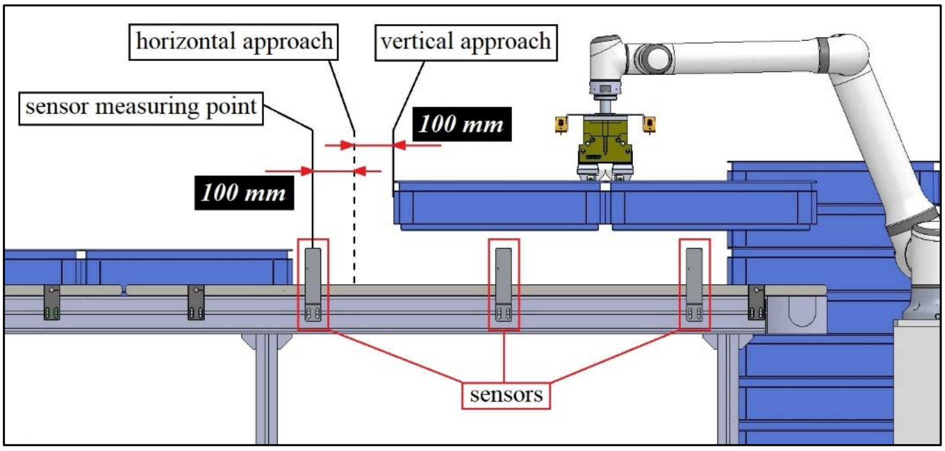


Figure 4.37. Crate's placing sensors.

4.3.2.2 Operation of the Angular Gripper

The *Angular Gripper* is attached to the pick and place robot, allowing it to pick two crates simultaneously through their handles, as depicted in Figure 4.38. This figure illustrates three different instances of the *Crate's* picking operation. Instance *a)* represents the picking approach starting point (approach target). From instance *a)* to *b)*, a 200 *mm* linear and vertical approach takes place, followed by the closing (picking) of the *Angular Gripper's* fingers from instance *b)* to *c).*

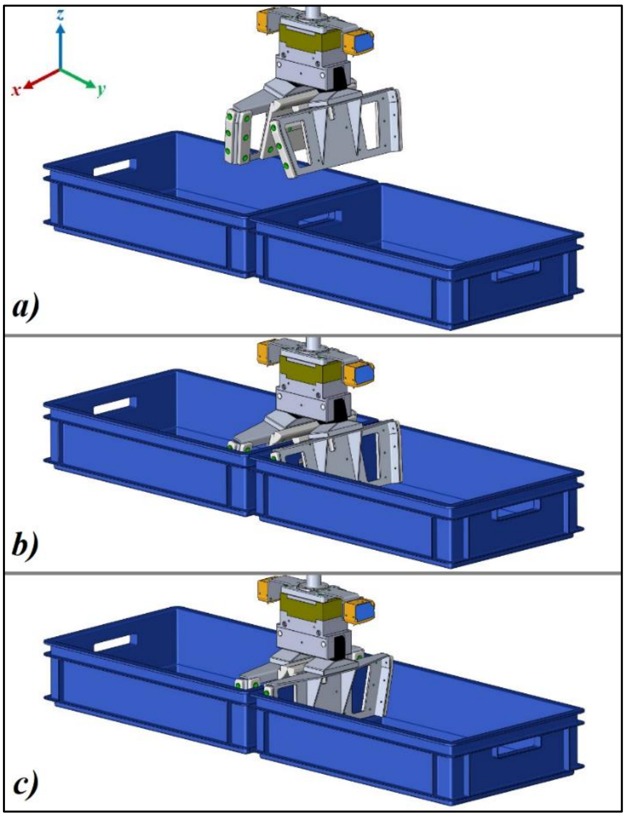


Figure 4.38. Picking Crate operation instances. a) the Angular Gripper is stationary in the approach target of the Crates and the gripper's jaws are opened; b) the Angular Gripper is stationary in picking target of the Crates, and the gripper's jaws are opened; c) the Angular Gripper is stationary in picking target of the Crates, and the gripper's jaws are closed;

To pick the *Crates,* the *Angular Gripper* features pads that directly interact with the *Crates'* surfaces during the gripping motion. These pads are meant to be replaceable and are made of nylon, an industry-standard material for applications involving contact with plastics.

Although the *Crates' Positioning* operation positioned the *Crates* with relative precision, some *Crates*, especially the ones on the top rows, may still present some deviation or rotation relative to the bottom rows of *Crates*. This scenario results in a deviation of the *Crate's* position relative to its picking target. To account for these deviations, several features were incorporated into the *Angular Gripper*, which will help correct the *Crate's* position during the picking operation.

To explain how the *Crate's* position deviation is managed, the coordinate system depicted in Figure 4.38 will be adopted.

Figure 4.39 depicts and labels all the *Angular Gripper's* pads surfaces that interact with the *Crates'* surfaces, and Table 4.6 depicts the axes directions of the *Crate's* deviation that each of the labeled surfaces is meant to correct. Pads' surfaces with similar functions are highlighted with the same colors, allowing an easier understanding of the *Angular Gripper's* operation.

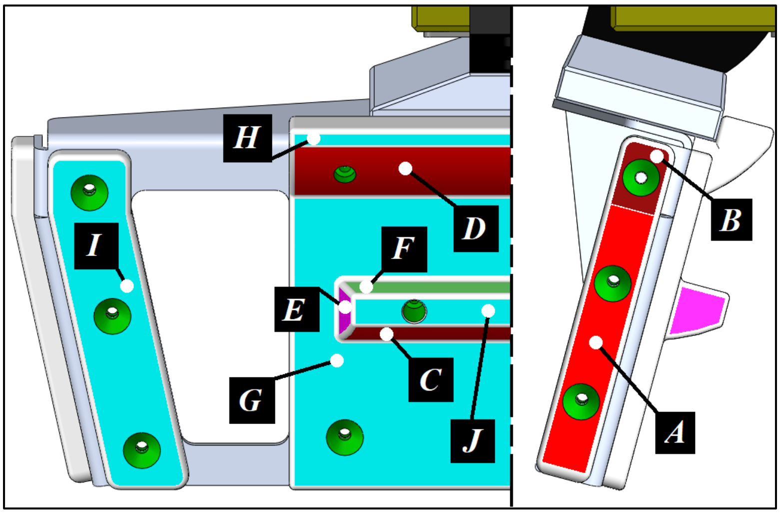


Figure 4.39. Nylon pads' working surfaces labeled. A; B; C; D; E; F; G; H; I; J.

Table 4.6. Pads' working surfaces guiding axes direction.

Guiding axes direction	Surfaces
x	*A,B,E*
y	*C,D,F,G,H,I,J*
z	*C,D,F*

In Figure 4.40, similarly to Figure 4.38, the *Angular Gripper's* approach can be depicted. Furthermore, in this figure, two close-ups (*a)* and *b)*) of the approach movement are shown, and two laser sensors, one on each side of the *Angular Gripper.*

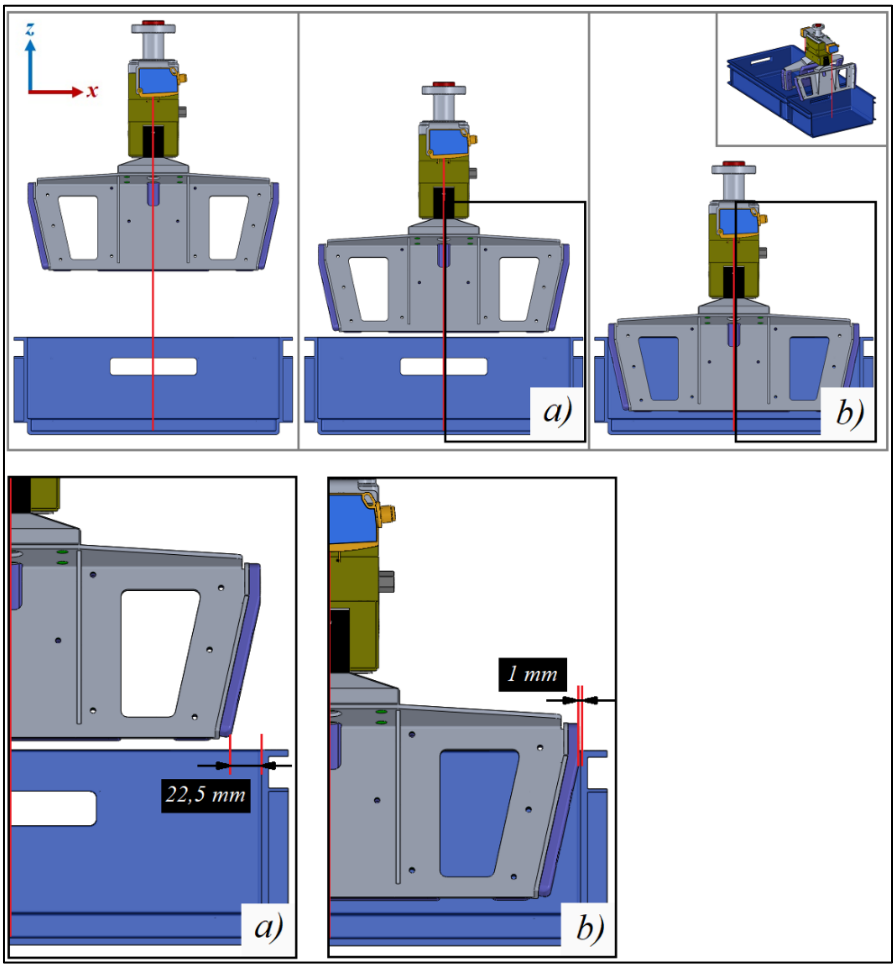


Figure 4.40. Close-ups of the Crates' position correction relative to the x axis direction. a) Angular Gripper approaching the Crates; b) Angular Gripper in the picking position of the Crates.

The laser sensors can accurately read the distance between them and the *Crates*. As a result, during the picking approach, the system can decide if it needs to adjust the picking height relative to the original picking target. This capability represents the first picking adjustment that the pick and place robot can perform in the z-axis direction.

In the instance depicted by Figure 4.40's close-up *a)*, the angular gripper is just above the *Crates,* and the lowest point of the pads' surface - *A* (see Figure 4.39) is 22,5 mm away from the side wall of the *Crate*. This distance represents the clearance between the Crate and the Angular Gripper on each side when both are perfectly aligned.

During the movement from close-up *a)* to *b)* both the *Angular Gripper's* pads' surfaces - *A* and *B* will guide the *Crates* to alignment with the *Angular Gripper*. Since the *Crates* can present some variation in width, to avoid a tight fit between the *Angular Gripper* and the *Crate*, the last is 2 mm wider than the *Angular Gripper,* allowing for a clearance of 1 mm on each side, as depicted in the close-up *b)*. The abovementioned adjustment represents the first possible adjustment that the pick and place robot can perform in the x-axis direction.

In Figure 4.41, a close-up of the angular closing operation is depicted through a cut view of the crates along Figure 4.38's x-axis. In this figure three instances of the *Angular Gripper* closing motion, can be depicted: *Angular Gripper* completely open (15°), *Angular Gripper* semi-closed (7.5°), and *Angular Gripper* completely closed (0°), respectively.

During the closing motion of the fingers, the crates are lifted 5 mm into the air. This lift is a consequence of the picking clearance, which will be explained further ahead.

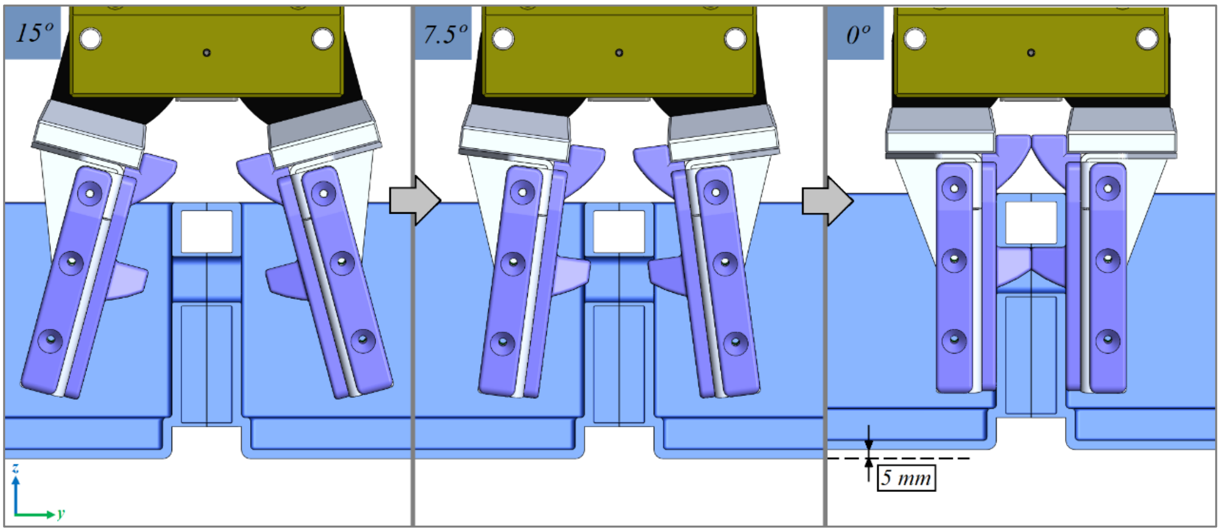


Figure 4.41. Close-up of the Angular Gripper's closing operation.

4.4 Machine Guarding

The *Machine Guarding Equipment* is responsible for covering hazardous areas of the system to prevent inadvertent contact with humans and to control hazards such as material falling from the system during handling.

Figure 4.42 represents the machine guarding of the *Packaging Workstation*, where three doors with safety locking mechanisms can be depicted. These safety locks prevent any human from entering the machine guarding enclosure while the enclosed equipment operates.

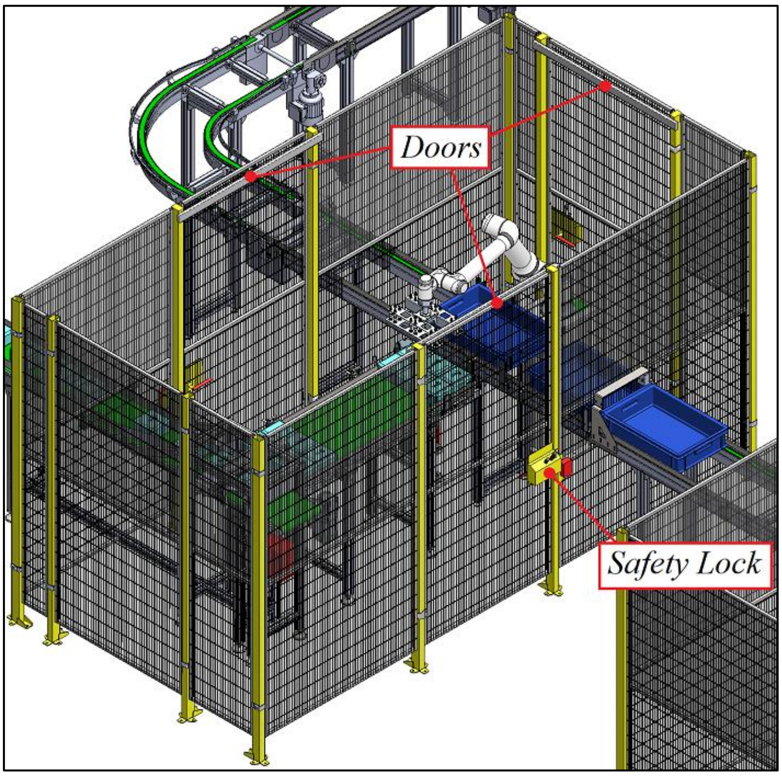


Figure 4.42. Packaging Workstation's machine guarding.

Figure 4.43 illustrates a top view from the *Packaging Workstation's* machine guarding enclosure. It depicts color-coded areas inside the enclosure that are separated by equipment and can only be accessed by a corresponding door. This machine guarding enclosure was designed so that each color-coded area has a minimum width of 500 mm, allowing workers to navigate the enclosure to perform maintenance or work with space.

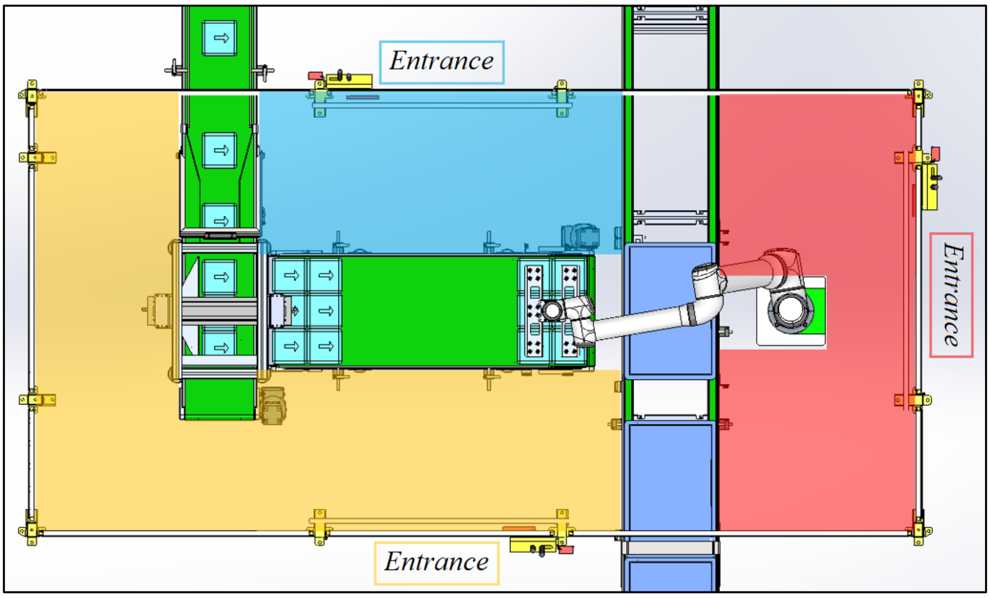


Figure 4.43. Top view of the Packaging Workstation's machine guarding.

Figure 4.44 represents the machine guarding of the *Depalletizing Workstation*, where four safety light curtains can be depicted. The safety light curtains are composed of an emitter and a receiver, being the emitter responsible for emitting light beams and the receiver for receiving them. Referring to Figure 4.44, during the system operation, these light curtains operate as follows:

1. If accidentally interrupted, the safety light curtains highlighted in green commands the *Crates' Positioning Equipment* and the *Crate's Pick and Place Robot* to stop operating.
2. During the pallet replacing operation, if the operator or any equipment interrupts the safety light curtain, highlighted in red and correspondent to the side where the pallet replacing operation is taking place, the *Crate's Pick and Place Robot* will stop operating.
3. Also, during the pallet replacing operation, the safety light curtain, highlighted in red and corresponding to the side of the enclosure where the depalletizing operation is taking place, is not active as it is constantly being interrupted by the robot arm.

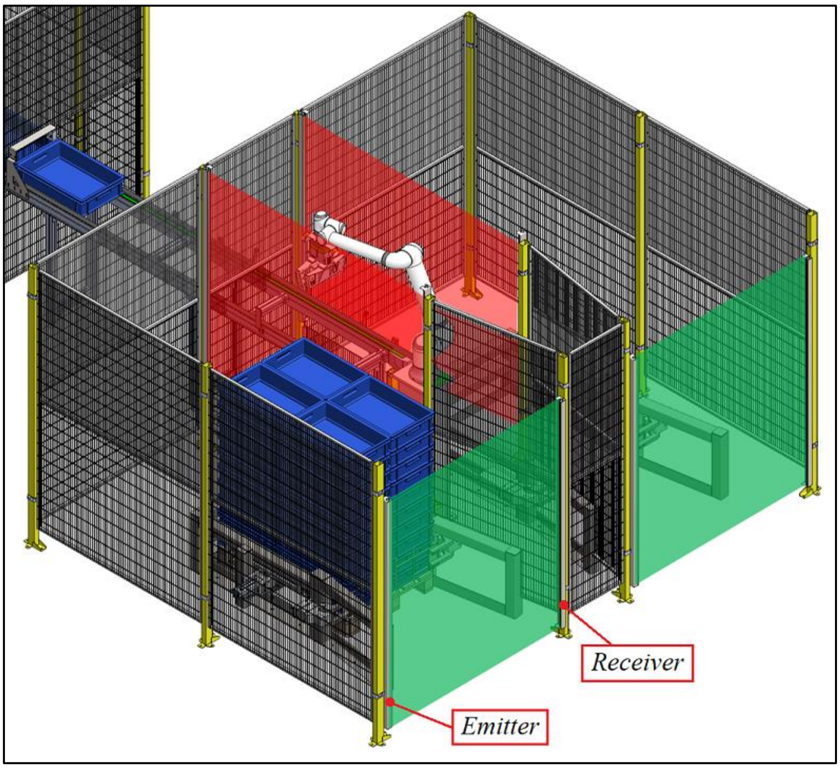


Figure 4.44. Depalletizing Workstation's machine guarding.

Figure 4.45 illustrates a cut view of the *Packaging Workstation's* machine guarding enclosure. In this figure, it can be observed that the safety light curtain, highlighted in red, isn't present all the way to the facility's floor. This safety light curtain it's complemented by a smaller panel and the side of the *U-Shaped Structure* closest to the robot arm. The combination of these pieces of equipment ensures workers can't accidentally reach the robot arm during its operation.

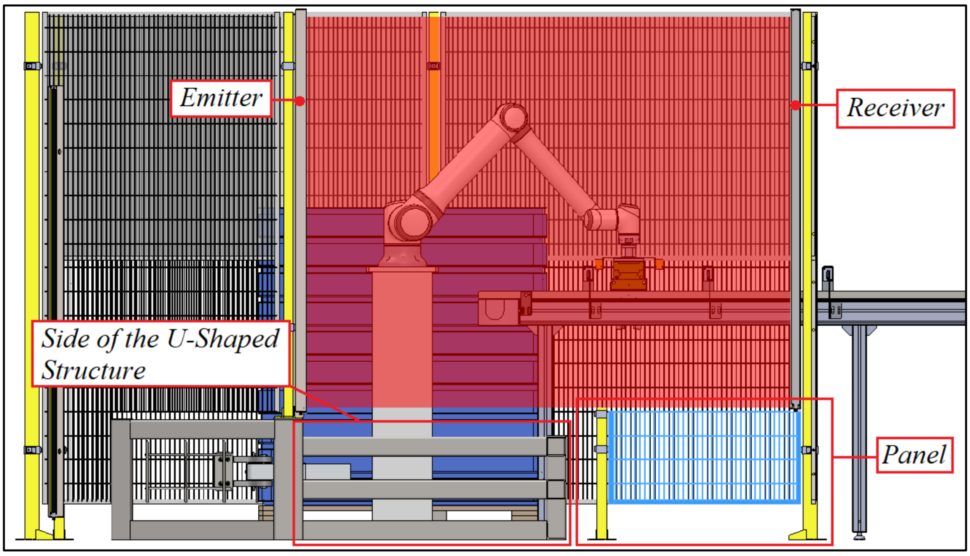


Figure 4.45. Cut-view of the Depalletizing Workstation's machine guarding.

5 Industrial Application on the Packaging and Depalletizing System

5.1 Design Scope

The design and development of the packaging and depalletizing system will be performed up to a high detail level, where equipment models and operational specifications will be determined. However, due to this dissertation's timeframe, the following tasks were excluded from the design scope of the methodology application:

1. Design of the pneumatic system;
2. Determining the operational pressure of the pneumatic equipment;
3. Performing an economic evaluation of the system;
4. Performing a failure mode and effect analysis (FMEA) on the system;
5. Producing technical drawings of the system.

Additionally, since Metal-Conser, doesn't have automation and machine guarding departments, the automation and machine guarding design presented in this project were only performed to a certain extent, where the reader can get a basic grasp on the subjects at hand.

5.2 Establish Control Data

To implement any design methodology, the first step to be taken is to clearly define control parameters. These parameters refer to system objectives, customer requirements, available space, and other significant metrics. These control parameters not only allow for a well-oriented design process but also represent the foundation of the design itself.

To be able to compare objectively both the result of the application of the proposed design methodology and Metal-Conser's initial design concept, both solutions were based on the same control data, presented ahead:

5.2.1 Customer Objectives

It is known that the customer wants to automate a portion of their packaging and depalletizing system. However, it is crucial to understand the objectives behind the system automation as it allows for a design implementation tailored to the customer's needs.

From Metal-Conser's meetings with the client, it was made clear that the system's primary objectives were reducing operating costs and improving worker safety. Considering the environment of this MHS case study, these objectives were decomposed into more detailed objectives (see Figure 5.1), which can be reached to achieve the system's primary goals.

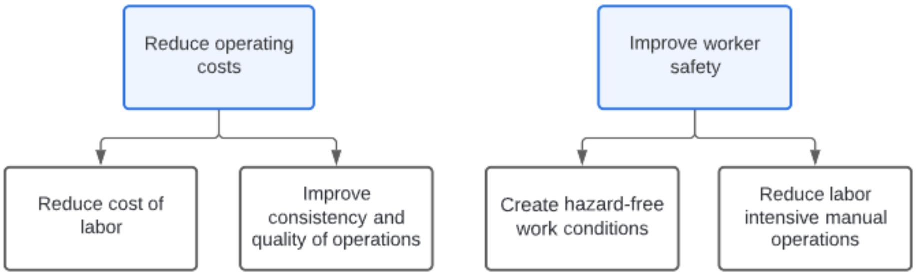


Figure 5.1. System automation objectives.

5.2.2 Customer Requirements

Not many customer requirements could be gathered in this design step. This is partially because the customer didn't provide Metal-Conser with a significant amount of information and partly because the MHS design concept wasn't selected to move forward with.

From interactions with the customer, the following system requirements were gathered:

1. Incorporate collaborative robot models - *Elite Robots* in the material handling operations of the system.
2. Ensure there's space in the system stations for manual handling in case of equipment downtime.

The *Elite Robots* models that must be employed in the system are provided by EQUINOTEC and can be depicted in Figure 5.2.

Figure 5.2. Elite Robot models.

These types of robot models are collaborative. Collaborative robots have various features that make them safer and easier to use than industrial robots. However, to take advantage of collaborative robots, they usually must pass a series of tests and simulations according to *ISO 15066* safety standards [13]. Due to a lack of resources to perform these tasks, the *Elite Robot* models will be treated as industrial robots during the development of the MHS design.

5.2.3 System Information

Since this project aims to automate only part of the packaging and depalletizing system, data relative to the pre-existing system operation was gathered and analyzed. However, some of this information is too small to have its own topic. As a result, it was collected and presented ahead:

a. **Packs' specifications**
   Each of these packs has six hot dog buns, organized in two rows of three buns resting on top of each other. The *Packs* are 88 mm tall, 155 mm long, and 152 mm wide, as depicted in Figure 5.3. Although the *Packs* have a protruding plastic bag opening, it is not considered part of the pack length since it doesn't have any significant structure.

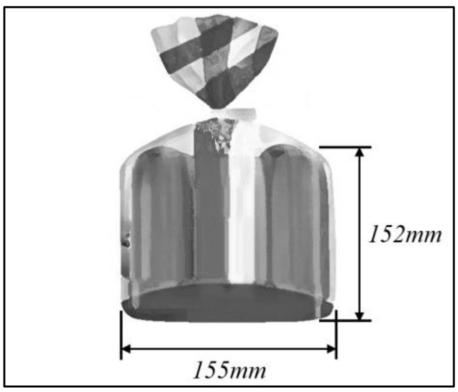


Figure 5.3. Dimensions of the hot-dog buns pack.

b. **Crates' specifications**

The crates are known to be stackable and perforated. Additionally, they have approximately a height of 134 mm, a length of 591 mm, and a width of 391 mm.

c. **Main Transport Conveyor Pack output**

This conveyor transports packs at a rate of *70 Packs per minute*, being this the input rate that the new system needs to handle.

d. **Disposition of packs inside the crate**

The packs need to be placed inside the crates in a specific orientation and configuration, forming two rows of three *Packs,* as shown in Figure 5.4.

Figure 5.4. Top view Illustration of a Crate full of packs.

e. **Specifications of pallet full of crates**

The pallets used in the customer's facilities are standardized wooden Euro Pallets (EPAL) (1200x800x144 mm). These pallets hold four stacks of ten crates, carrying a total of forty *Crates* in the configuration illustrated in Figure 5.5.

Figure 5.5. Pallet full of Crates.

f. **Pallet-jack operator**

One operator will be available full-time to handle the pallets full of *Crates*. He will do so through a hand pallet jack.

5.2.4 Available Space

Figure 5.6 represents the pre-existing packaging line layout and depicts the available space for the new automated MHS addition. In this layout, the *Main Transport Conveyor* (highlighted in green) brings the *Packs* from left to right according to the Figure 5.6 orientation.

When designing the system, it's important to consider the location of the loading and unloading of the material that the MHS processes. In this particular case, the cargo doors are located to the right of the preexisting MHS.

Dealing with an existing conveyor layout poses a constraint in the MHS design, as it results in a loss of a degree of freedom and, therefore, the overall optimal solution becomes harder to reach.

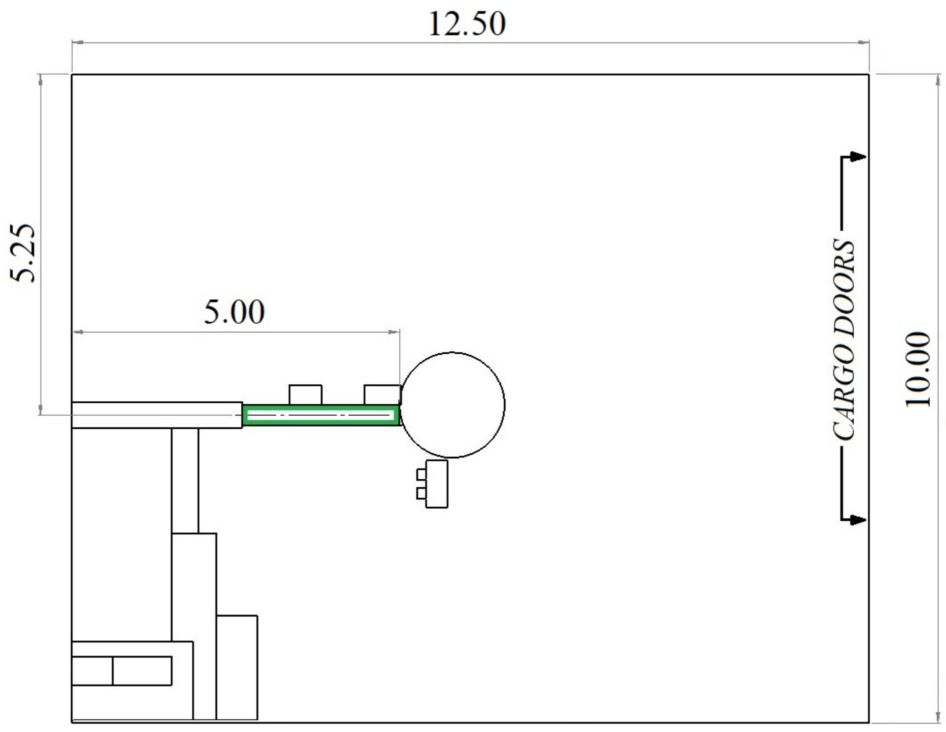


Figure 5.6. Packaging line layout. Dimensions in (m).

5.2.5 Performance Measures

The performance measures constitute a set of parameters that are meant to be determined in the design evaluation step. According to the design scope of the project, this step will be focused on the performance measures related to system output, station throughput, etc. Each of these performance measures usually has formulas that go along with it, and they should be established in this step.

Regarding this dissertation's MHS, only one performance measure was made clear by the customer:

1. **Meet the Pack output of the pre-existing line.**

   Meeting the output rate of 70 packs/minute would result in a *Crate-full-of-packs output* of around 11,67 containers/minute, according to:

$$\frac{70\,\frac{packs}{minute}}{6\,\frac{packs}{crate}} = \frac{35}{3} \approx 11{,}67\ crates/minute$$

   Considering the system would operate on a typical 8-hour shift, a total of 5600 *Crate-full-of-packs* would be outputted per shift.

5.2.6 Pre-existing Equipment Considerations

Some considerations need to be made regarding the following pre-existing equipment:

1. **Main Transport Conveyor's specifications**

   The equipment specifications for this conveyor were considered according to Table 5.1.

Table 5.1. Main Transport Conveyor technical data.

Parameters	Value
Belt Width	300 mm
Height	1000 mm
Speed (constant)	18 m/min
Belt material	Food grade PVC
Belt surface finish	Smooth finish

To make the considerations mentioned above, the following factors were considered:

- Belt Width: The *Main Transport Conveyor* width was considered based on the pre-existing packaging line layout (Figure 5.6), where an approximate width of 300 mm can be depicted.
- Speed: On a previous visit to the client's facility, the Metal-Conser team had the opportunity to watch the packaging line in operation. The team visit recount considered that *Main Transport Conveyor* was working at around 0.3 m/s (18 m/min).
- Belt material and surface finish: Although the hot-dog buns are inside a plastic wrapper and don't touch the conveyor belt surface directly, the belt material was considered to be food-grade PVC, with a smooth finish.

From the conveyor speed and knowing that the packs have an output of 70 units/min, it was determined that at around every 257 mm, there's a pack in the conveyor belt (see Figure 5.7).

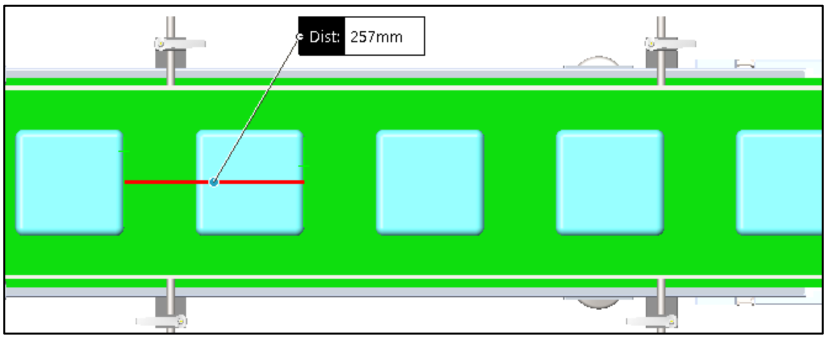


Figure 5.7. Distance between packs in the Main Transport Conveyor.

2. Crates specifications

Although the *Crates'* approximate general dimensions (591x391x134 mm) were given, no crate model was found with these exact characteristics after extensive online research. Furthermore, no *Crate* model or reference was provided to the Metal-Conser team.

Considering the equipment selection *Standardization Principle*, a perforated euro-norm 600x400x140 mm was selected to represent the Crate used in the customer's facilities adequately. These *Crate* models are usually perforated on both the sides and bottom and feature handgrips, as depicted in Figure 5.8. This figure's *Crate* weighs 1.33 Kg which was considered the *Crate's* weight during the project development.

To model the system in CAD software, a 3D model of the *Crate* was created through CAD software, resulting in the model depicted in Figure 5.9. This model features a slightly different design but keeps the same euro-norm dimensions. Additionally, although perforations can not be seen on its surfaces, this 3D *Crate* model was considered perforated during the system's design.

Figure 5.8. Euro-norm perforated crate (600x400x140mm)[1].

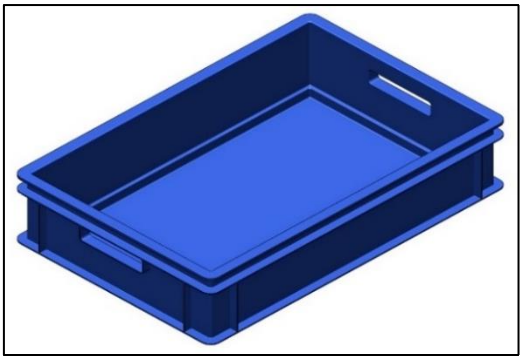


Figure 5.9. Crate modeled with CAD software (600x400x140mm).

5.3 Functional Decomposition of Objectives

This is a valuable step in the design process since identifying material handling functions will later help to determine categories of equipment suitable to perform them. Furthermore, these functions will lay the foundation for every possible design variation.

The major functions the new MH system design needs to perform are the same as the previously installed one:

- Package packs of hot-dog buns.
- Depalletize pallets full of crates.

Considering the major functions identified and the requirements established in the control data steps, the sub-functions performed and required to be performed in the customer's facility were identified as depicted in Figure 5.10.

[1] Avaible at: https://www.bekuplast.com/en/products/euro-norm-special-containers/perforated-containers-156/1301-050000-80/

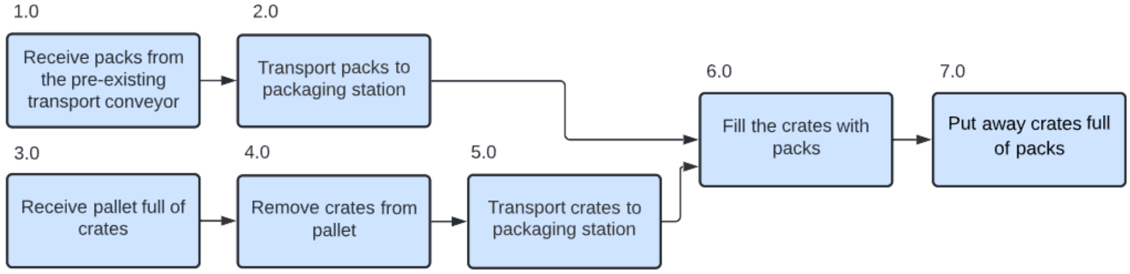


Figure 5.10. Block diagram of the system's major functions.

Depending on the MHS complexity, these sub-functions can be decomposed to a higher degree of detail. However, in this case, study instance, since a completely new system design is being proposed, these sub-functions will greatly depend on the design of the sub-systems performed in the upcoming design steps.

5.4 Equipment Selection

5.4.1 Determination of Candidate Equipment Classes

With the major functions of the MH system determined in the previous design step, the classes of equipment suitable to perform them can be identified. This case study's candidate equipment classes were selected, as depicted in Table 5.2.

Table 5.2. Selection of candidate equipment in the preliminary design phases of the packaging system.

Functions	Candidate classes
1. Receive *Packs* from the *Main Transport Conveyor*	Positioning Equipment
2. Transport *Packs* to the packaging station	Transport Equipment
3. Receive pallet full of *Crates*	Positioning Equipment
4. Remove *Crates* from pallet	Positioning Equipment
5. Transport *Crates* to the packaging station	Transport Equipment
6. Fill the *Crates* with *Packs*	Positioning Equipment
7. Put away *Crates* full of *Packs*	Transport Equipment

5.4.2 Design of the Sub-systems

Some of the classes of MH equipment identified in the previous design step are systems in their own right and include several components. Furthermore, in order to make equipment of different classes work together, some MH systems require the design of custom subsystems.

In this design stage, these sub-systems are identified and developed. This development implies functional decomposition of the sub-systems and determination of the required classes of equipment to perform these functions.

Based on the control data, some of the equipment used in this MH system is already specified, which presents a constraint in design freedom as the design path will derive from this particular equipment.

Considering Metal-Conser's proposed design concept, Figure 5.11's block diagram was made to depict the initial systems and subsystems proposed by the company as well as the functions and sub-functions these systems support.

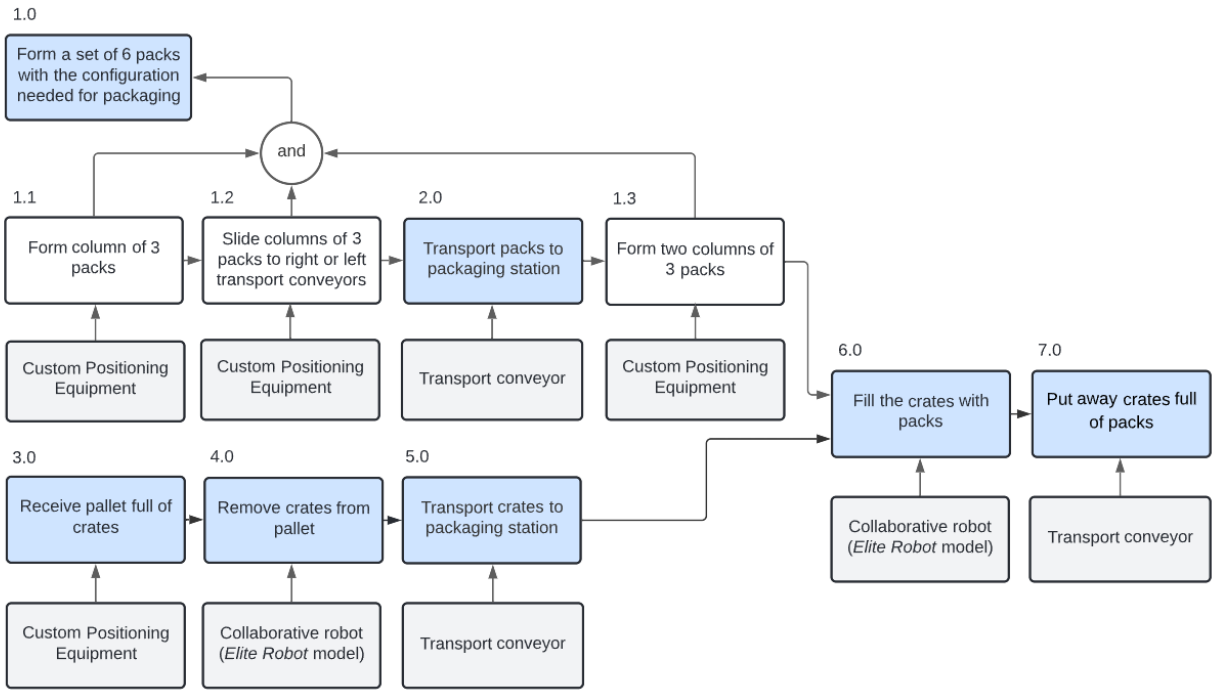


Figure 5.11. Block diagram of the functions and sub-functions of the system and the type of equipment selected to support those functions according to Metal Conser 's design concept.

The main difference between Figure 5.10 and Figure 5.11 diagrams is the addition of a new function - *1.0 Form a set of 6-Packs with the configuration needed for packaging* and its corresponding sub-functions. The addition of this function resulted from the decision to place all 6 *Packs* inside a *Crate* simultaneously. Consequently, each set of 6 Packs must be in the packaging configuration before being picked.

As mentioned previously, to perform an adequate comparison between Metal-Conser's design concept and the design developed in this dissertation, the remaining steps of the design methodology application were based on the subsystem concepts proposed by Metal-Conser.

With every design iteration performed during the *Equipment Selection* step, the MH system became more complex as the selection and modeling of equipment achieved higher detail levels. These iterations were performed until the design detail objective proposed in the design scope was reached, resulting in the systems and sub-systems presented in Table 5.3.

Instead of assigning each function the name of the equipment model selected to perform it, an equipment designation was given. This designation is meant to be more in line with the equipment type of operation, allowing an easier understanding of the selected equipment functions.

Table 5.3. Functional decomposition and selection of equipment for the MHS.

Detailed Design	
Functions and sub-functions	**Selected equipment**
1. Form a set of 6 *Packs* with the configuration needed for packaging	
1.1. Form column of 3 *Packs*	*Column Forming Equipment*
1.1.1. Center the *Packs* on the *Main Transport Conveyor's* belt	*Guiding Rails*
1.1.2. Stop the *Packs* coming on the *Main Transport Conveyor*	*Packs' End Stop*
1.1.3. Ensure the *Packs* don't crash into the *3-Pack-Columns*	*Angular Barrier*
1.1.4. Detect the presence of each *Pack*	*3-Pack-Column Sensors*
1.2. Transfer the *3-Pack-Column* to the *Secondary Transport Conveyor*	*Column Sliding Barrier*
1.3. Form two *3-Pack-Columns*	*Two-Columns Forming Equipment*
1.3.1. Stop two *3-Pack-Columns* side by side	*Columns' End Stop*
1.3.2. Detect the presence of each of *3-Pack-Column*	*Two-Column Sensor*
2. Transport *Packs* to the packaging station	*Secondary Transport Conveyor*
3. Receive pallet full of *Crates*	
3.1. Guide the pallet during the unloading area approach	*U-Shaped Structure*
4. Correct the position of the *Crate's* stacks	
4.1. Position the *Crates'* stacks against the reference surface - *C*	*Guided Actuator*
4.2. Position the *Crates'* stacks against the reference surface - *B*	*Clamps*

Table 5.4. Continuation of Table 5.3 (Functional decomposition and selection of equipment for the MHS.).

Detailed Design	
Functions and sub-functions	**Selected equipment**
5. Correct the picking position error	
5.1. Correct the picking position error in the z-axis direction.	*Angular Gripper's Laser Sensors; Angular Gripper's Pads*
5.2. Correct the picking position error in the x-axis direction.	*Angular Gripper' Pads*
5.3. Correct the picking position error in the y-axis direction.	*Angular Gripper' Pads*
6. Remove *Crate* from pallet	
6.1. Pick *Crate* from *Crate's* stack	*Collaborative Robot; Angular Gripper*
6.2. Ensure the presence of the picked *Crates* during the picking operation	*Angular Gripper Laser Sensors*
6.3. Ensure there are no *Crates* on the *Crate's* placing zone	*Crate's Placing Sensors*
6.4. Place *Crate* on the *Crates'* transport conveyor	*Collaborative Robot; Angular Gripper*
7. Move *Crates* to the packaging station	*Crate's Transport Equipment*
8. Make *Crates* available one at a time in the packaging station	
8.1. Detect the presence of *Crates*	*Crates' Sensors*
8.2. Stop first and second *Crates* individually	*Stop-Gates*
9. Fill the crates with *Packs*	
9.1. Pick the set of six *Packs*	*Collaborative Robot; Vacuum Gripper*
9.2. Drop six packs inside each *Crate*	*Collaborative Robot; Vacuum Gripper*
10. Put away *Crates* full of *Packs*	*Crate's Transport Equipment*
11. Ensure system compliance with safety standards	*Machine Guards;*

5.4.3 Identification And Prioritization of Key Metrics

Once a system concept has been created, the identification and prioritization of the system's key metrics should be performed. These key metrics can constitute equipment choices, performance measures, and system requirements, which will be later evaluated to determine if they meet the project engineer's expectations.

To identify and prioritize the system's key metrics, the sub-systems and candidate equipment classes determined in the previous design steps were considered, and the following criteria were established:

1. **Requirements.** The equipment requirements and system performance measures should be a priority during the equipment selection process as the system design derives from them.
2. **The complexity of the equipment.** Usually, the more complex a system is, the more time it will be spent developing it. Furthermore, complex systems have many parts or machines dependent on each other.
3. **Common equipment application.** Usually, if a piece of equipment is being used on an uncommon application, there's less certainty that it will operate according to expectations.
4. **Equipment cost relative to the system.** If the cost of an equipment is very high relative to the overall projected system cost, it might be wise to prioritize the selection of that equipment.

Depending on the system application, these criteria can vary in number and order. As a result of its application, the key metrics for the initial design concept were identified and prioritized, as depicted in Table 5.5.

Table 5.5. Key metrics prioritization and their effects on the system design.

Key metrics (prioritized)	Influence on the system's design
Collaborative Robot's Payload Capacity	In conjunction with the grippers' weight, it allows to determine how many units (if any) of *Packs* and *Crates* can be handled simultaneously and, consequently, the number of robots needed.
Mechanical Gripper's Weight	In combination with the robot's payload capacity allows to determine how many units (if any) of *Packs* and *Crates* can be handled simultaneously and, consequently, the number of robots needed.
Vacuum Gripper's Weight	In conjunction with the robot, payload capacity allows to determine how many units (if any) of *Packs* and *Crates* can be handled simultaneously and, consequently, the number of robots needed.
Collaborative Robot's Reach	Allows to determine the system's layout for the pick and place operation. Allows to determine if one robot can reach the necessary *Crates* in a pallet during the pick and place operation.
Pick And Place Cycle Times	Allows to determine how many pick and place robots are required based on their cycle times and the required packaging rate.

5.4.4 Evaluation of the Key Metrics

Once the key metrics for the initial design concept are identified and prioritized, the key metrics can be evaluated. These evaluations can range from equipment selection to performance-related calculations depending on the key metric. The goal of this step is to try and obtain a candidate or approximate value for the key metrics in question.

Considering this information, a presentation of the evaluation performed on each key metric during the preliminary design stage, as well as the conclusions it allowed to achieve, is made ahead:

5.4.4.1 Collaborative Robot's Payload Capacity

The payload capacity of a robot is present on its technical datasheet. Since, per customer requirement, this design has to use one of three *Elite Robot* model variants, the payload capacities available to this project are shown in Table 5.6.

Table 5.6. Elite Robots payload capacities[2].

Robot model	Payload capacity
EC63 / EC63M	3 Kg
EC66 / EC66M	6 Kg
EC612 / EC612M	12 Kg

The obtained payload capacity values allowed to conclude that the larger payload capacity seems adequate for the *Pack's* application but not ideal for the *Crates'* application. Even for the larger available payload capacity, the *Crates* are considered relatively heavy for the application.

5.4.4.2 Mechanical Gripper's Weight

Since no gripper model has been selected yet, to determine the Mechanical Gripper's Weight, several gripper model candidates have to be considered.

When choosing a gripper candidate, the workpiece weight is the most critical parameter to consider. The workpiece weight is the product of the number of units to handle simultaneously times the single unit weight. Following this parameter, permissible finger length,

---

[2] Avaible at: https://www.eliterobots.pt/assets/documents/Desdobravel_ELITE-ROBOTS-10.2021_PT_web.pdf

closing/opening force, stroke per jaw, etc., represent other important factors to consider when selecting a mechanical gripper.

Four gripper candidates were selected based on the abovementioned factors, and their weight is presented in Table 5.7. Each candidate can handle at least two *Crates* weighing 1.33 Kg each.

Table 5.7. Mechanical gripper models and respective weights[3].

Gripper type	Gripper model	Weight [4]	Workpiece weight
Parallel	*PGN-plus-P 200-1*	5.4 Kg	19 Kg
Parallel	*PGN-plus-P 160-1*	3.8 Kg	12.5 Kg
Angular	*PWG-plus 160-KVZ*	2.92 Kg	7.72 Kg
Angular	*PWG-plus 160*	2.12 Kg	3.86 Kg

From the obtained candidate gripper's weights, the following conclusions were reached:

- Considering the pick and place operation of one *Crate* and a robot payload capacity of 12 Kg, the maximum combined weight of the gripper's fingers plus any support equipment can range from 5.27 Kg to 8.55 Kg, considering the heavier and lighter candidate grippers, respectively.
- Considering the previous scenario, but for the pick and place operation of two *Crates*, the maximum combined weight of the gripper fingers, plus any support equipment, can range from 3.94 Kg to 7.22 Kg, considering the heavier and lighter candidate grippers, respectively.

5.4.4.3 Vacuum Gripper's Weight

Since no vacuum gripper model has been selected yet, the gripper's selection or modeling must be performed to obtain an approximate weight.

Due to the simplicity to model and the opportunity to save on cost, it was decided that the vacuum gripper would be custom-made and modeled through CAD software (SolidWorks). Doing so allowed to better manage the weight of the equipment by optimizing the gripper design and its material composition.

The weight properties of the achieved vacuum gripper design are depicted in Table 5.8.

[3] Avaiable at: https://schunk.com/de/en/gripping-systems/c/PUB_8293
[4] Not including finger/jaw weight.

Table 5.8. Vacuum gripper weight properties.

Equipment and components	Weight
Vacuum Gripper (total)	3.432 Kg[5]
Aluminum structure	1.512 Kg
Suction grippers	1.920 Kg

Considering the pick and place operation of a set of 6 *Packs* and a robot payload capacity of 12 Kg, the obtained vacuum gripper weight allowed to conclude that the remaining gripper operation support equipment can weigh up to approximately 6.588 kg.

5.4.4.4 Collaborative Robot's Reach

The robot payload reach of a robot is present on its technical datasheet. The obtained reach values for the three different *Elite Robot* models are shown in Table 5.9.

Table 5.9. Elite Robot models reach[6].

Robot model	Reach
EC63 / EC63M	624 mm
EC66 / EC66M	914 mm
EC612 / EC612M	1304 mm

From the obtained values, the following conclusions were reached:

1. Considering the use of the *EC612* robot, its reach was deemed adequate for the *Crates'* Pick and Place application. However, the room margin to spare is minimal.
2. Considering the use of the *EC612* robot, its reach was deemed adequate for the *Packs'* Pick and Place application.

5.4.4.5 Pick And Place Cycle Times

To obtain an approximate value for both pick and place operations cycle duration, the software RoboDK was employed.

Founded in January 2015 by Albert Nubiola, *RoboDK* is a simulation tool for industrial robots. This software was created by *RoboDK*, a spin-off company from one of the most prestigious robotics labs in Canada, the CoRo laboratory at ETS University in Montreal, Canada [14].

[5] Not including fasteners or supporting equipment for the vacuum operation.

[6] Avaible at: https://www.eliterobots.pt/assets/documents/Desdobravel_ELITE-ROBOTS-10.2021_PT_web.pdf

Although RoboDK allows to perform trajectory planning and simulation, currently, it isn't able to output cycle times. To obtain the pick and place cycle times, a code for each pick and place program was generated with RoboDK and sent to EQUINOTEC representatives, who test ran the code on an actual robot model, with the parameters shown in Table 5.10. These parameters were set by the EQUINOTEC representatives, whose empirical knowledge led to the considered values.

Table 5.10. Robots pick and place testing parameters.

Parameter	Value
Speed	100%
Acceleration	50%
Deceleration	50%

5.4.4.5.1 Crates' Pick and Place Path Planning and Cycle Time

To obtain an approximate pick and place cycle time, a path trajectory similar to the one presented in *Crates Pick and Place Trajectory Planning* was used (see Figure 5.12).

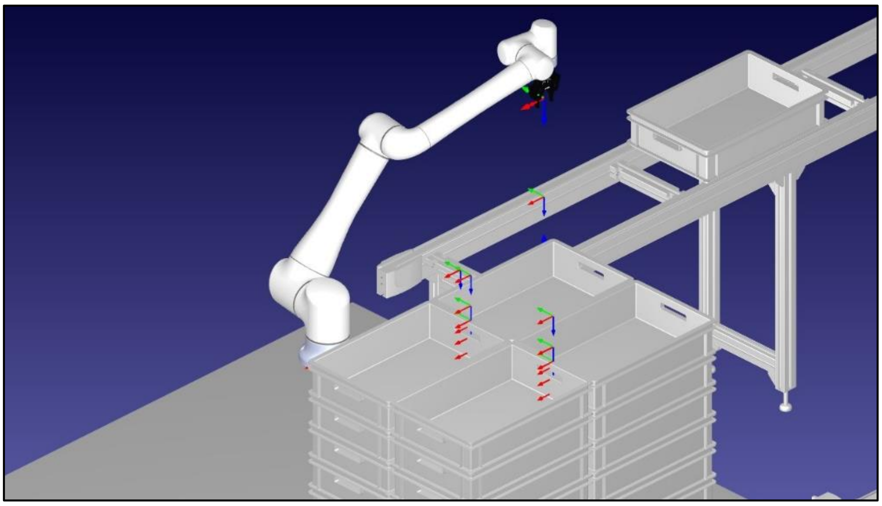


Figure 5.12. Crates pick and place evaluation setup.

No robot tool was used for this step as it had not been selected yet. Furthermore, for a depalletizing operation, every pick and place cycle has a different duration since the further away a crate is from the base of the robot, the longer its pick and place duration is.

For the purpose of the key metric evaluation goal, it was considered adequate only to obtain the cycle time for the top and bottom pick targets furthest from the robot base. Furthermore, for both the picking and placing test run parameters, a duration of 250 milliseconds was set.

The obtained result from the test run for the cycle time relative to the top pick position furthest from the robot base is around 3.67 seconds, as shown in Figure 5.13. For the bottom pick position furthest from the robot base, the cycle time achieved was around 4.97 seconds, as depicted in Figure 5.14.

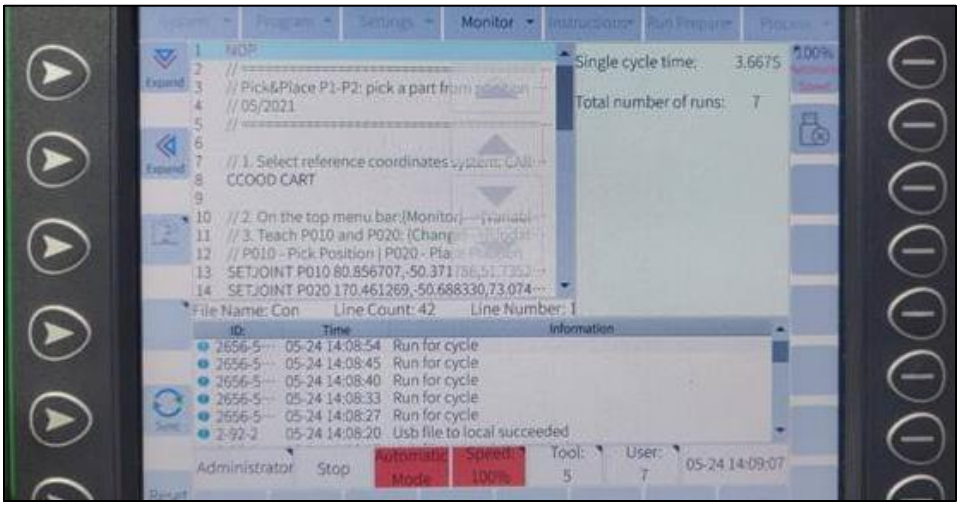


Figure 5.13. Test run cycle time relative to the top pick position furthest from the robot base.

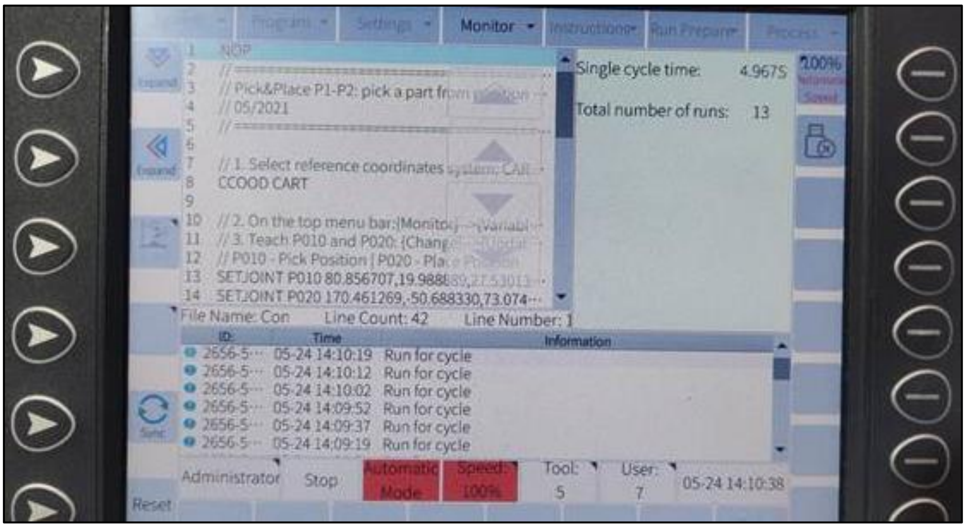


Figure 5.14. Test run cycle time relative to the bottom pick position furthest from the robot base.

Based on the test run results mentioned above, an approximate pick and place cycle time was put together, according to Table 5.11. Although the EQUINOTEC team considered 250 milliseconds for both the gripper's picking and placing duration, in order to have a higher safety margin, higher picking and placing durations were considered in this MHS application.

Additionally, to obtain the duration of the robot movement between pick and place operations, for the bottom pick position furthest from the robot base, 250 milliseconds were subtracted from the cycle time result of the test run.

Table 5.11. Crates' pick and place cycle approximate cycle duration considering the test run results.

Parameters	Duration
Crates' pick and place cycle duration (total)	8.97 s
Gripper picking duration	3.00 s
Gripper placing duration	1.50 s
Duration of the robot movement between pick and place operations for the bottom pick position furthest from the robot base.	4.47 s

Knowing that the time it takes to form a batch of 6 *Packs* is around 5.14 seconds, the following conclusions were reached:

- Handling one *Crate* at-a-time by the pick and place robot requires the system to use at least two robots for the *Crates*' pick and place operation.
- Handling two Crates at-a-time by the pick and place robot requires the system to use at least one robot for the *Crates*' pick and place operation.

Considering the information above and that the robot has the payload capacity to handle two *Crates* simultaneously, a decision was made to use only one robot for the *Crates*' pick and place operation, departing from the two robots used in Metal-Conser's design concept. This decision intends to take the most advantage of the equipment while reducing the number of equipment needed for the MHS and, in turn, reducing the up-front cost of the MHS.

5.4.4.5.2 Packs' Pick and Place Path Planning and Cycle Time

To obtain an approximate *Packs'* pick and place cycle time, the setup in Figure 5.15 was used. This setup features the robot between the packs' picking station and packs' dropping station as it was thought to be the optimal robot placement for a faster pick and place cycle time.

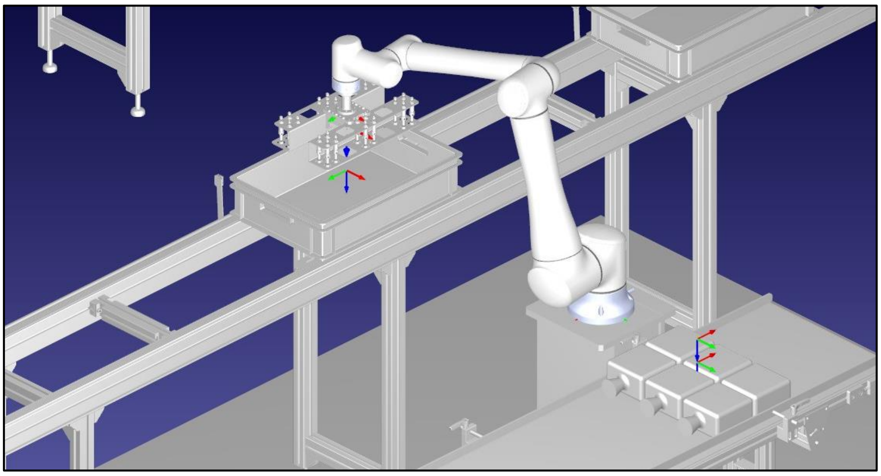


Figure 5.15. Packs' pick and place evaluation setup (robot between picking and dropping station).

The programmed tool path is straightforward, composed of only two sets of approach pick/place targets, which was enough to accomplish this key metric evaluation goal. Furthermore, for both the picking and placing test run parameters, a duration of 250 milliseconds was set.

The obtained cycle time from the test run was approximately 4 seconds, as shown in Figure 5.16.

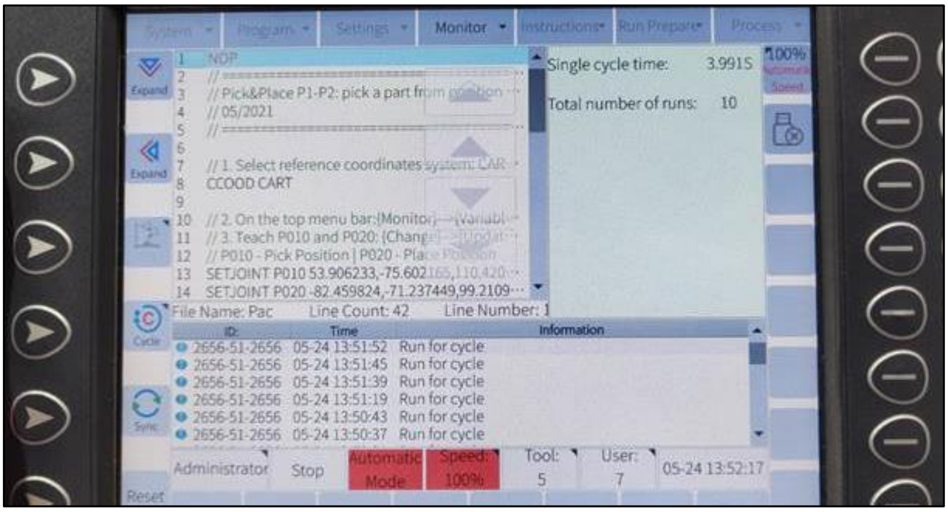


Figure 5.16. Packs' pick and place test run cycle time (robot between picking and dropping station).

Although this test run achieved a good cycle time for the application in question, after discussions with EQUINOTEC representatives, it was determined that a better cycle time result could be achieved if the pick and place stations were placed in the setup depicted in Figure 5.17.

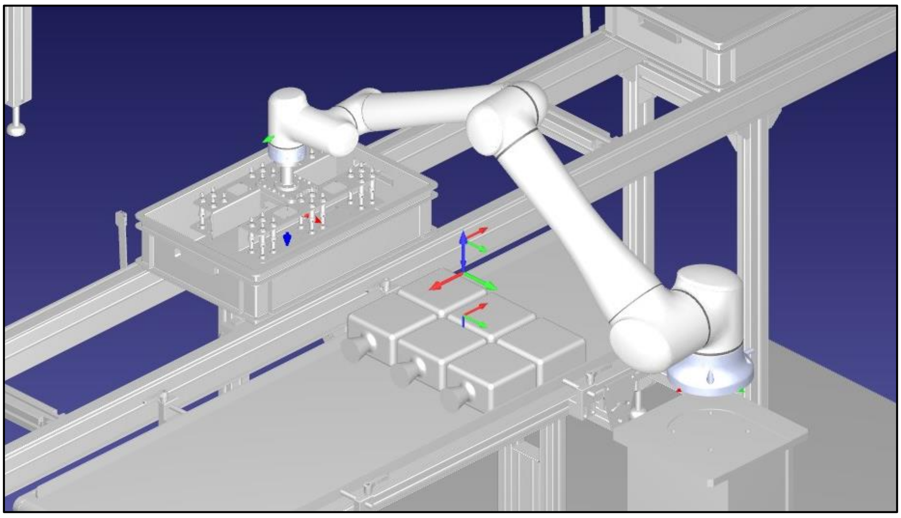


Figure 5.17. Packs' pick and place evaluation setup (picking and dropping station side by side).

Since the robot's base joint is the robot's slowest moving joint, avoiding the previous setup's 180-degree base joint rotation allowed for a faster cycle time of approximately 2.82 seconds (see Figure 5.18). This new cycle time represents a time saving of 1.17 seconds (29,3 % shorter duration).

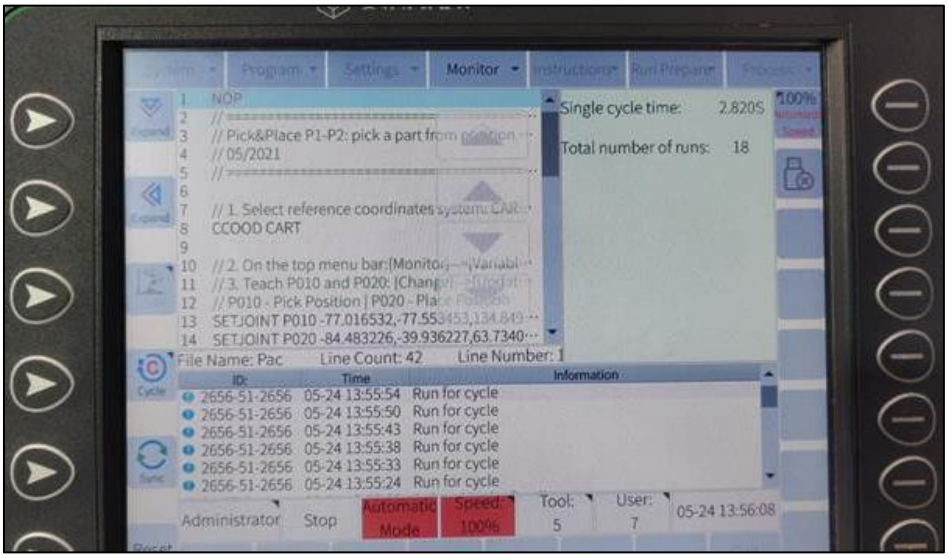


Figure 5.18. Packs' pick and place test run cycle time (picking and dropping station side by side).

Although the EQUINOTEC team considered 200 milliseconds for both the gripper's picking and placing duration in the test run, in order to provide a safety margin, higher duration values were considered in this MHS application, as depicted in Table 5.12. This table also depicts the duration of the robot movement between pick and place operations, which was obtained by subtracting the 200 milliseconds from the cycle time achieved in the last test run.

Table 5.12. Packs' pick and place approximate cycle duration considering the test run results.

Parameters	Duration
Packs' pick and place cycle duration (total)	2.67 s
Vacuum gripper picking/dropping duration	0.25 s
Duration of the robot movement between pick and place operations	2.42 s

Knowing that the time it takes to form a batch of 6 *Packs* is approximately 5.14 seconds, it was concluded the only one robot is needed to perform the *Packs' pick and place operation.* Considering this information, a decision was made to use only one robot in the MHS for this operation, departing from the two robots used in Metal-Conser's design concept. This decision intends to take the most advantage of the equipment while reducing the number of equipment required for the MHS and, in turn, reducing the up-front cost of the MHS.

5.4.5 Selection/Modeling of the Remaining Equipment

The equipment not selected during the Evaluation of the Key Metrics step is meant to be chosen in this step. The selection process consists of selecting an off-the-shelf part or equipment or modeling a part with CAD software.

This chapter will focus on the equipment's technical data and the calculations made to validate its selection since, in the Proposed Design Solution chapter, both how the equipment operates and why it operates as it does have already been explained.

To provide a coherent presentation of the selection process, each equipment selection process will be presented within the context of its purpose in the system. Therefore, this system's sub-systems will be approached as a whole, followed by an equipment decomposition.

5.4.5.1 Column Forming Equipment

This equipment is decomposed in Table 25, and the visual representation is shown in Figure 5.19.

Table 5.13. Column forming equipment decomposition.

Equipment name	Nº of units	Sub-systems names	Nº of units
Column Forming Equipment	1	*Main Transport Conveyor*	1
		Packs' End Stop	1
		Tilting Barrier	1
		Guiding rails (Left and Right)	2 (symmetric)
		3-Pack-Column Sensor	3

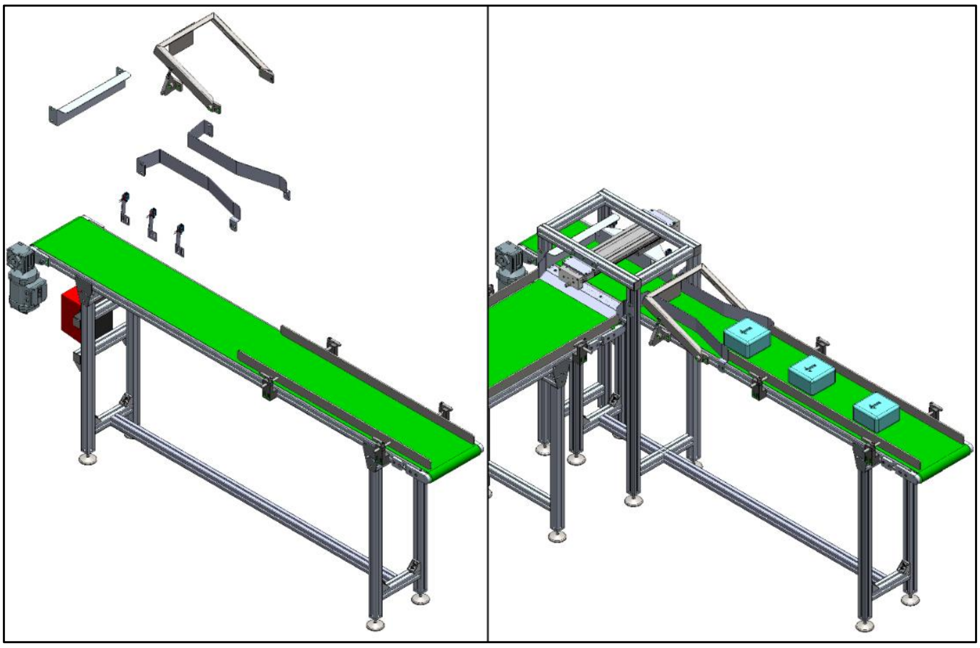
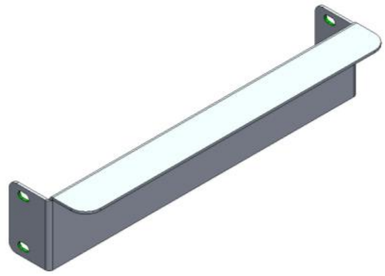
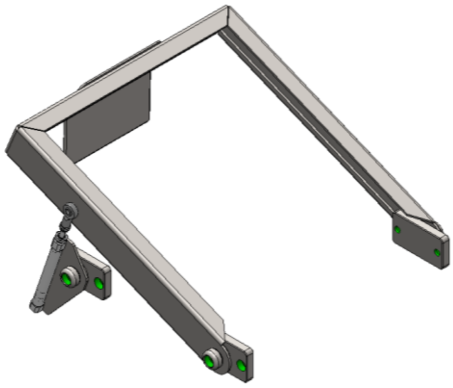
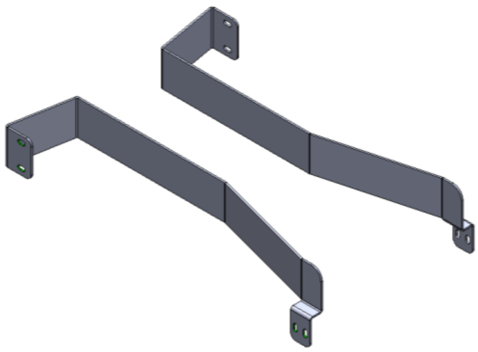


Figure 5.19. Column Forming Equipment decomposition.

Relatively to the custom-made parts present in this equipment, they have the following specifications (see Table 5.14):

Table 5.14. Column Forming Equipment custom-made parts specifications.

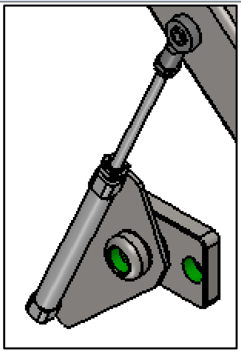
Equipment	General Information	Illustration
Packs' End Stop	Material: *304 stainless steel.* Fabrication Processes: Laser cutting; Metal bending.	
Tilting Barrier	Material: *304 stainless steel* (sheet metal and machined parts). Fabrication Processes: Laser cutting; Metal bending; Machining.	
Guiding Rails	Material: *304 stainless steel.* Fabrication Processes: Laser cutting; Metal bending.	

Relatively to the off-the-shelf selected equipment, both their most relevant specifications as well as the calculations performed to validate their selection are depicted ahead.

Round Cylinder (Tilting Barrier)

The *Tilting Barrier Equipment* features a Round Cylinder responsible for the equipment's angular movement. This cylinder was selected from *Festo* and has the following technical data (see Table 5.15):

Table 5.15. Round Cylinder (DSNU-S-12-80-P-A) technical data[7].

Parameters	Value	Illustration
Stroke	80 mm	
Piston diameter	12 mm	
Cushioning	Elastic cushioning	
Theoretical force (at 6 bar), return stroke	50.9 N	
Theoretical force (at 6 bar), advance stroke	67.9 N	
Mode of operation	Double-acting	

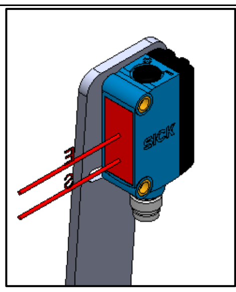
During the selection process of this cylinder, the cylinder force and stroke were considered the most important selection criteria. For simplification purposes, the force that the cylinder needs to exert can be considered to be at least equal to the weight of the equipment that it is pushing upwards. *SolidWorks's Mass Properties* feature determined that the weight of the equipment in question is approximately 24.6 N.

From the cylinder technical data, the cylinder's theoretical force is 67.9 N during the advancing stroke (where the cylinder needs to exert the most force). This value is more than double the required force (24.6 N).

3-Pack-Column Sensor

The sensors selected are from *SICK* and have the following technical data (see Table 5.16):

Table 5.16. 3-Pack-Column Sensor (GTE6-P4211) technical data[8].

Parameters	Value	Illustration
Type of device	Photocells	
Detection range max.	≤ 300 mm	
Light type	Visible red light	
Spot size (distance)	Ø7 mm (90 mm)	

[7] Available at: https://www.festo.com/media/pim/046/D15000100152046.PDF
[8] Available at: https://cdn.sick.com/media/pdf/7/97/797/dataSheet_GTE6-P4211_1050710_en.pdf

These sensors are photoelectric sensors. They emit a light beam that bounces back to the sensor when interrupted by an object. The amount of light the sensor receives is then converted into an electrical output communicating the object's distance from the sensor with the system.

During the sensor selection process for this application, the following main factors were taken into consideration:

a. **No space for retroreflectors**. Some photoelectric sensors use retroreflectors to bounce the light beam back. However, they could not be implemented in this environment since the *Secondary Flat Conveyor Belt* is directly in front of the sensor's location.
b. **The distance from the *Pack's* surface to the sensor**. This distance will determine the type of sensor to use, as it needs to be within the sensor's detecting range.

As depicted in Figure 5.20, the distance between the sensor and the pack that the first must detect is around 107.15 mm.

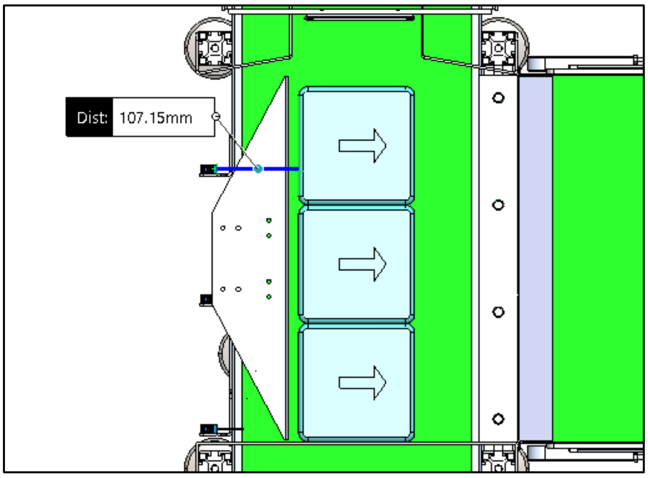


Figure 5.20. Distance from the pack's surface to the sensor's position.

Considering the information above, the sensor model (*GTE6-P4211*) was selected. This model is a photoelectric proximity sensor that detects an object at a pre-established distance range from the sensor without needing retroreflectors. Furthermore, it has a range of detection up to 300 mm, which is adequate for the application.

5.4.5.2 Two-Columns Forming Equipment

This equipment is decomposed in Table 29, and the visual representation is shown in Figure 5.21.

Table 5.17. Two-Columns Forming Equipment decomposition.

Equipment name	Nº of units	Sub-systems names	Nº of units
Two-Columns Forming Equipment	1	*Secondary Transport Conveyor*	1
		Column Sliding Barrier	1
		Conveyor Transitioning Step-Down	1
		Columns' End Stop	1
		Two-Column's Sensors	2

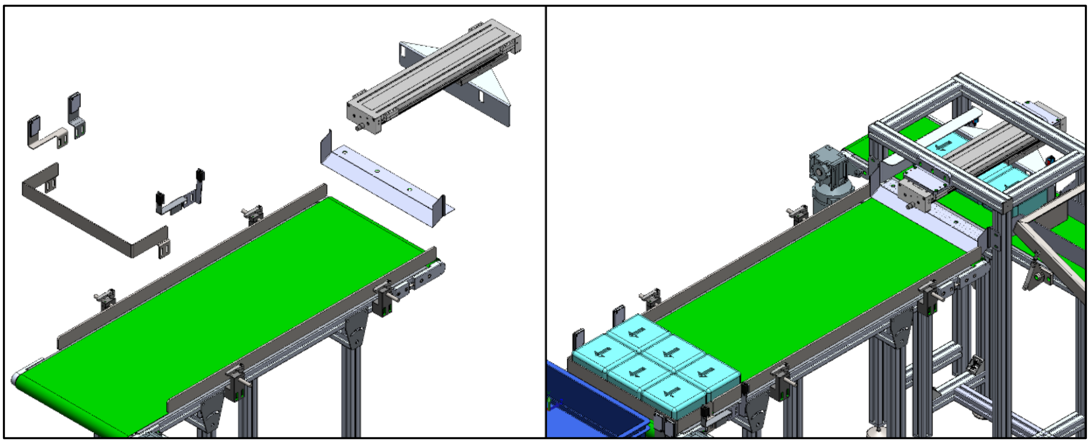
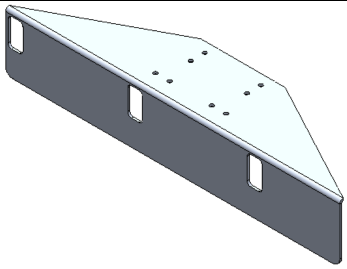
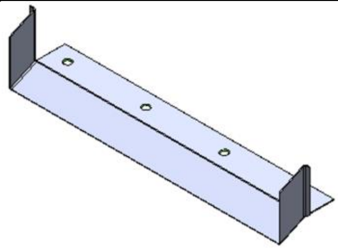
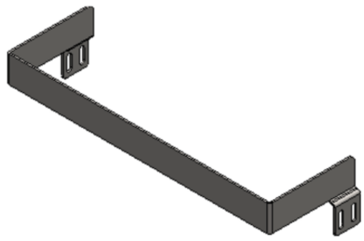


Figure 5.21. *Two-Columns Forming Equipment* decomposition.

Relatively to the custom-made parts present in this equipment, they have the following specifications (see Table 5.18):

Table 5.18. Column Forming Equipment custom-made parts specifications.

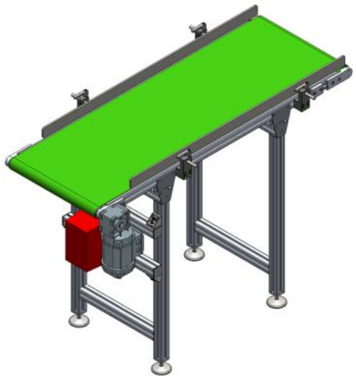
Equipment	General Information	Illustration
Column Sliding Barrier	Material: *304 stainless steel.* Fabrication Processes: Laser cutting; Metal bending. Features: Rectangular cut-outs for the sensor light beam to pass through.	
Conveyor Transitioning Step-Down	Material: *304 stainless steel.* Fabrication Processes: Laser cutting; Metal bending; Countersinking.	
Columns' End Stop	Material: *304 stainless steel.* Fabrication Processes: Laser cutting; Metal bending.	

Relatively to the off-the-shelf selected equipment, both their most relevant specifications as well as the calculations performed to validate their selection are depicted ahead:

Secondary Transport Conveyor

The *Secondary Transport Conveyor* selected for this MH system design is from Metal-Conser. Metal-Conser can fabricate and customize several types of transport conveyors, being the one selected one of them. Doing so allows Metal-Conser to make savings as they don't need to outsource the equipment. Considering this information, the Secondary Flat Belt Conveyor was configured according to Table 5.19's technical data.

Table 5.19. Secondary Transport Conveyor's technical data.

Parameters	Value	Illustration
Belt Width	480 mm	
Belt length	1369 mm	
Height	970 mm	
Speed (constant)	8 m/s	
Belt material	Food grade PVC	
Belt surface finish	Smooth	

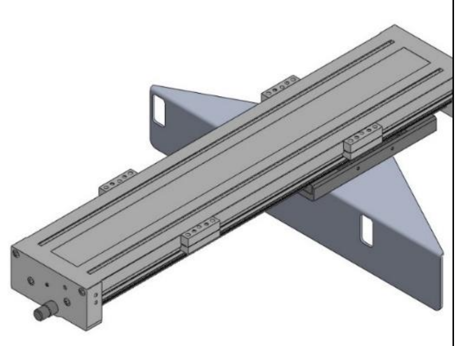
During the configuration process of the *Secondary Transport Conveyor* parameters, the following factors were taken into consideration:

- **3-Pack-Column's width**: To accommodate the 465 mm width of the *3-Pack-Column*, a 480 mm wide conveyor belt was chosen. The side rails can be adjusted to make the gap between the rails and the packs smaller or bigger. In the current configuration, the present gap is 10 mm on each side of the *3-Pack-Columns*.
- **Storage buffer and space for manual handling**: To create some storage buffer, the belt length was configured to be 1369 mm, allowing for eight 3-Pack-Column s (four sets of 6 *Packs*) on top of the conveyor belt at the same time. Furthermore, this length allows a worker to manually handle the packs comfortably in the case of equipment downtime.

Column Sliding Barrier

The *Column Sliding Barrier's* movement is powered by a guided linear drive from *Festo* with the following technical data (see Table 5.20).

Table 5.20. Heavy-duty guide DGC-HD technical data[9].

Parameters	Value	Illustration
Piston diameter	18 mm	
Stroke	320 mm	
Max. speed	3 m/s	
Mode of operation	Double-acting	
Theoretical force (at 6 bar), return/advance stroke	153 N	
Cushioning	Shock absorber	

During this equipment selection process, the main factors taken into consideration were:

a. **Stroke length.** When ordering the equipment, the piston's stroke is configurable, allowing one to choose a pneumatic-guided linear drive with a stroke matching the system's needs.

The necessary stoke length corresponds to the distance the barrier needs to travel to push the *3-Pack-Column* to the *Secondary Flat Belt Conveyor* while clearing the *Main Flat Belt Conveyor* and the *Conveyor Transitioning Step-Down.* This distance results in a stroke of 320 mm, as depicted in Figure 5.22.

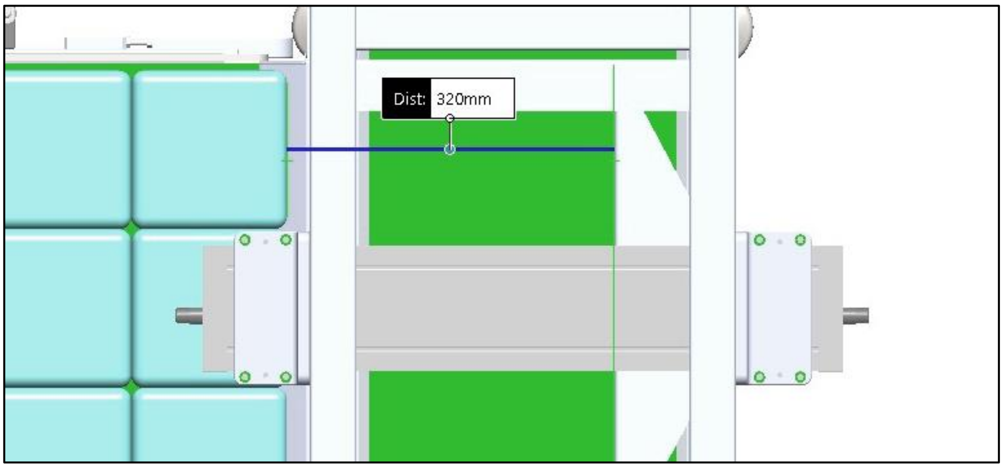


Figure 5.22. Sliding Barrier stroke length.

[9]Available at: https://www.festo.com/cat/en-gb_gb/data/doc_ENGB/PDF/EN/DGC-HD_EN.PDF

b. **Advance force required to push the Packs.** For simplification purposes, it was considered that the force necessary to push the *3-Pack-Column* is equivalent to their weight. Knowing the weight of each *Pack* to be 330 grams, the weight of the column can be determined by the following equation:

$$W = mg \tag{5.1}$$

Where:

$W = weight\ (kgf)$

$m = mass\ (kg)$

$g = acelaration\ of\ gravity = 9.81\ m/s^2$

Inserting the values in question results in:

$$(3 * 0.330)\ kg\ * 9.81 \frac{m}{s^2} \approx 9.72N$$

The guided linear drive technical data shows that the theoretical stroke force is 153 N*,* which is superior to the force necessary to push the *3-Pack-Column*.

Columns' Sensors

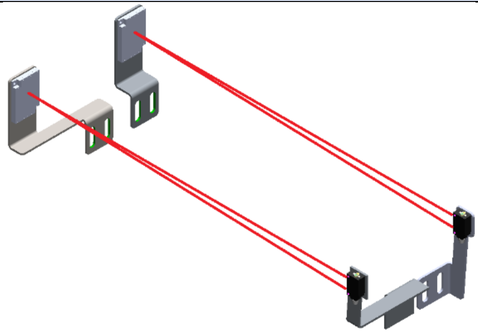
The *Columns' Sensors* are used to detect the presence of each *3-Pack-Column* and are mounted on custom sheet metal brackets at the end of the *Secondary Transport Conveyor*.

Similarly, to the *Packs' Sensors,* these sensors are photoelectric, however, they use retroreflectors to reflect the emitted light beam.

The reason behind selecting this type of photoelectric sensor is due to its everyday use in the industry and low price point.

Since the retroreflectors are positioned around 480 mm apart (conveyor belt width), the selected sensor model is from *Omron*, with a sensing distance between 100 mm and 4000 mm, as seen in Table 5.21.

Table 5.21. Columns' Sensors (E3Z-R61) technical data[10].

Parameters	Value	Illustration
Sensing method	Retro-reflective	
Detection range max.	4000 mm	
Detection range min.	100 mm	
Light type	Polarized red light	

5.4.5.3 Packs' Pick and Place Equipment

This equipment is decomposed in Table 34, and the visual representation is shown in Figure 5.23.

Table 5.22. Packs' Pick and Place Equipment decomposition.

Equipment name	Nº of units	Sub-systems names	Nº of units
Packs' Pick and Place Equipment	1	*Packs' Robot*	1
		Vacuum Gripper	1
		Packs' Robot Base	1

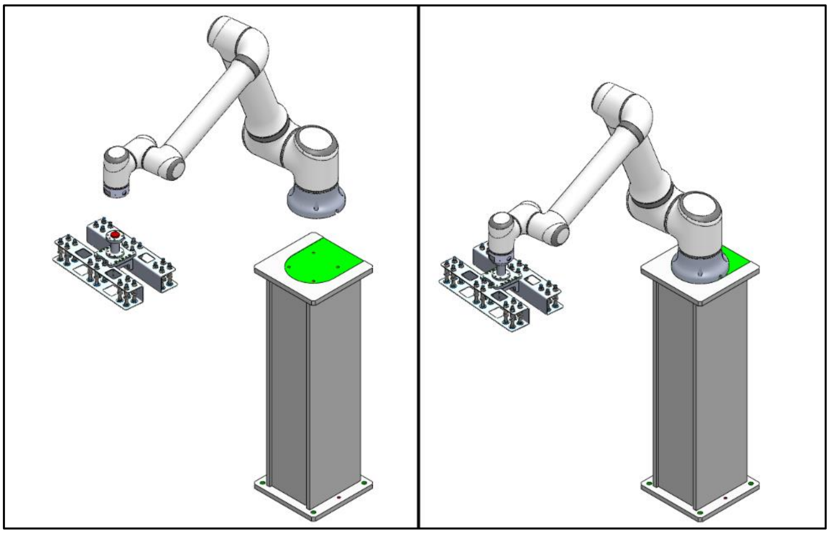


Figure 5.23. Packs' pick and place equipment decomposition.

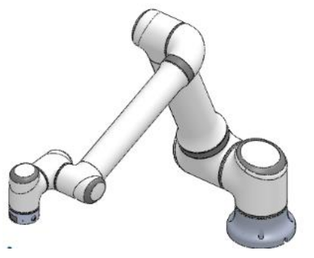
The reasoning behind each equipment selection, as well as the equipment parameters behind it, will be explained ahead:

[10] Available at: https://assets.omron.eu/downloads/datasheet/pt/v1/e701_e3z_datasheet_pt.pdf

Packs’ Robot

The selection process behind the Packs' Robot has been explained primarily in the Evaluation of the Key Metrics step. The *Elite Robot* model - EC612, depicted in Table 5.23, was selected due to its larger reach and payload capacity over the other *Elite Robot* models.

Table 5.23. Elite Robot model - EC612 technical data[11].

Parameters	Value	Illustration
Weight	33.5 Kgf	
Payload	12 Kg	
Reach	1304 mm	
Footprint	Ø200 mm	
Accuracy	+/-0.03 mm	

Vacuum Gripper

The Vacuum gripper equipment is mainly composed of suction grippers and a supporting structure (see Figure 5.24). The supporting structure is custom-made, and *1060 aluminum* was selected as the part's material composition to make the tool lightweight.

To stabilize the packs during the picking operation, the surfaces highlighted in Figure 5.25 were modeled. In this figure, it is also possible to see square cut-outs in the sheet metal surfaces performed to reduce the tool weight.

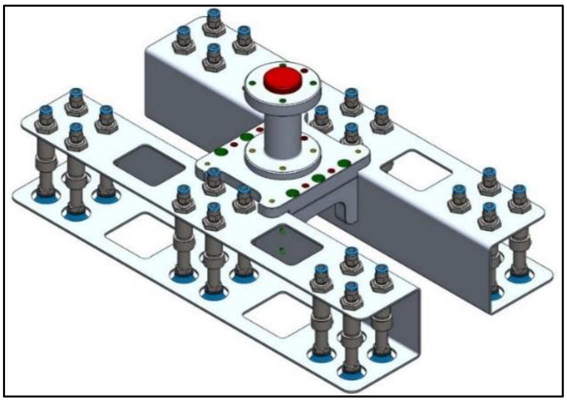


Figure 5.24. *Vacuum gripper.*

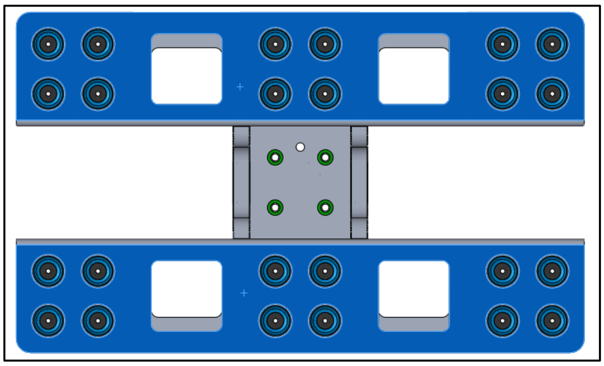


Figure 5.25. Highlighted contact surface between *Packs* and *Vacuum Gripper.*

[11] Available at: https://www.eliterobots.pt/assets/documents/Desdobravel_ELITE-ROBOTS-10.2021_PT_web.pdf

Since the material being picked is a relatively lightweight plastic pack, the priority when selecting the type and number of suction grippers was the suction cup shape and the number of suction grippers needed per *Pack*.

Because large suction cups tend to leave a deformation mark on plastic bags such as the ones that constitute the packs, using more and smaller suction cups is more suitable for this application than using fewer and bigger ones. As a result, it was decided to use four small suction grippers per *Pack*. These suction grippers were selected from *Festo* with the model configuration depicted in Table 5.24.

Table 5.24. Suction gripper - 189173_ESG-20-EU-HCL-QS technical data[12].

Parameters	Value	Illustration
Weight	80 gf	
Suction cup diameter	20 mm	
Holding force (at 0.7 bar)	17 N	
Suction cup shape	Extra deep round	
Suction cup material	VMQ (silicone)	

Since the selection process for this equipment started with selecting the suction cup size, the next step was determining if the suction gripper holding force would fit the operation requirements. From the previously determined *3-Pack-Column* weight, it's known that a *Pack* weighs around 3.24 N.

Since four suction grippers will hold each pack, each providing a holding force of *17N*, the theoretical holding force provided to each *Pack* is 68 N. This value is significantly larger than the required 3.24 N, validating the equipment selection.

Packs' Robot Base

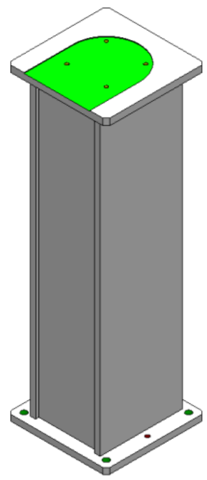
The *Pack's Robot Base* is also a custom-made part, and it results from an adaptation of a robot base that is constantly used by the team at Metal-Conser in similar applications. This equipment is mainly composed of 20 mm thick plate steel, providing the required rigidity for the robot operation. All the steel plate parts that make this structure are welded together and fastened with bolts to both the robot's base and facility floor.

[12] Available at: https://www.festo.com/cat/en-au_au/data/doc_engb/PDF/EN/ESG_EN.PDF

When deciding the robot's height base, the robot's operation movement was considered to avoid hitting the surrounding equipment. Furthermore, to facilitate the positioning of the robot's base on the top plate, a 2 mm recess was machined.

Considering the information above, the Pack's Robot Base configuration is displayed in Table 5.25.

Table 5.25. Pack's Robot Base parameters.

Parameters	Value	Illustration
Weight	936 mm	
Width	300 mm	
Material	Steel	

5.4.5.4 Crates' Pick and Place Equipment

Similarly, to the *Packs' Pick and Place Equipment,* the *Crates' Pick and Place Equipment* is made of a series of parts and machines, of which some are off-the-shelf, and others are custom-made. This equipment is decomposed in Table 38, and the visual representation is shown in Figure 5.26.

Table 5.26. Crates' pick and place equipment decomposition.

Equipment name	Nº of units	Sub-systems names	Nº of units
Crates' Pick and Place Equipment	1	*Collaborative Robot*	1
		Angular Gripper	1
		Crates' Robot Base	1
		Crates' Placing Sensors	1
		Gripper' Sensors	2

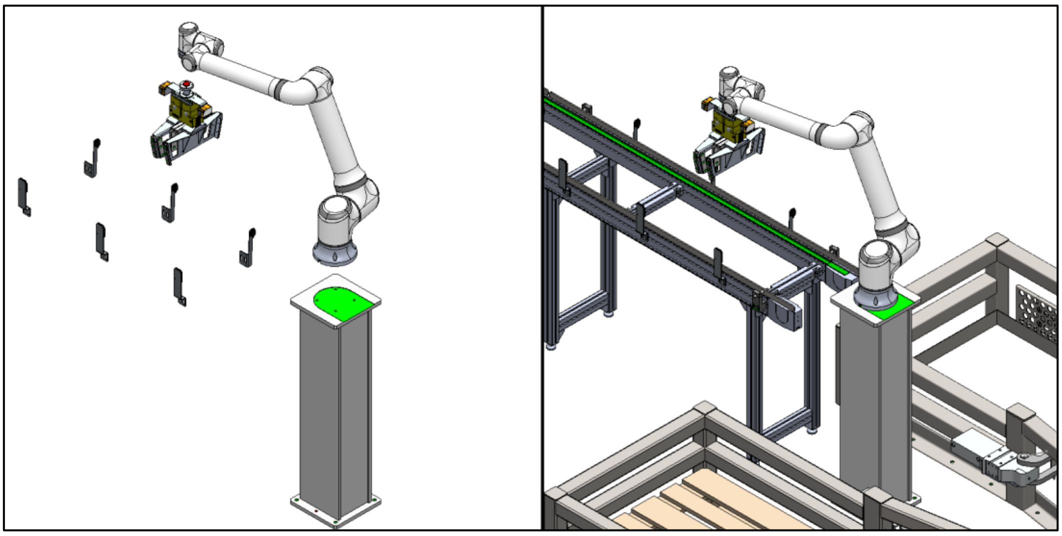


Figure 5.26. Crates' Pick and Place Equipment decomposition.

Before proceeding with the equipment selection process, to avoid repetitiveness in the selection process, the last won't be shown for the following equipment:

a. *Crates' Placing Sensors:* These sensors are the same as the ones on *Two-Columns Forming Equipment.*
b. *Crates' Robot Base:* This equipment is very similar to the *Packs' Robot Base,* differing only in height (the *Crates' Robot Base* is 1135.75 mm tall).
c. *Collaborative Robot:* The selected robot model is the same as the one used in the *Packs' Pick and Place Equipment* (EC612), and its selection process has been explained in the *Key Metrics Evaluation* step.

The remaining equipment's selection process and parameters behind it will be explained ahead:

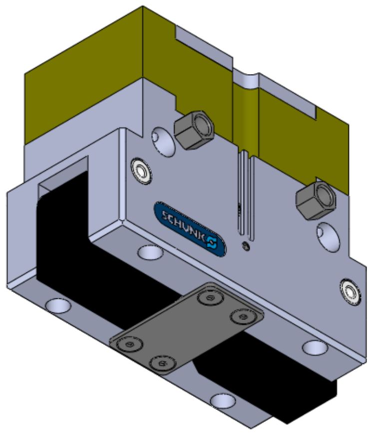
Angular Gripper

As discussed in the *Evaluation of* the Key Metrics step, there were two types of gripper candidates: angular and parallel grippers. During the selection process between these gripper types, the following main parameters were taken into account:

1. Opening clearance: This parameter corresponds to the maximum distance between the gripper's fingers when opened;
2. Weight;
3. Maximum permissible finger length;

Considering the factors mentioned above, the angular gripper model - *PWG-plus 160-KVZ* from *Schunk* was selected. This model has the following technical data (Table 5.27):

Table 5.27. Angular gripper - PWG-plus 160-KVZ technical data[13].

Parameters	Value	Illustration
Closing force (with finger lengths of 0 mm)	6250 N	
Opening angle per jaw	15°	
Closed angle per jaw up to	3°	
Closing moment	200 Nm	
Weight	2.92 Kg	
Closing time	0.32 s	
Opening time	0.26 s	
Max. permissible finger length	200 mm	
Max. permissible mass moment of inertia per chuck jaw	560.7 $Kgcm^2$	

With the gripper model selected, the next task was to model its fingers. These were modeled with CAD software (*SolidWorks*), and feature machined steel and nylon parts, as well as sheet metal bent parts, as depicted in Figure 5.27. The nylon parts are referred to as nylon pads and are modeled in nylon as it is a suitable material to press against the plastic crate surfaces.

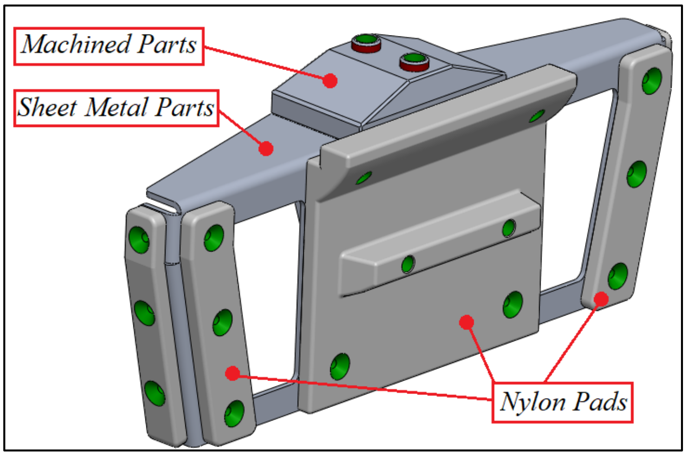


Figure 5.27. Angular Gripper's finger.

[13] Available at: https://schunk.com/de/en/gripping-systems/angular/radial-gripper/pwg-plus/pwg-plus-160-kvz/p/000000000000311665#technical_data

To validate the use of the fingers in combination with the angular gripper for the *Crates'* Pick and Place application, the following parameters were considered:

1. Mass moment of inertia per chuck jaw: *SolidWorks's Mass Proprieties* feature obtained a mass moment of inertia per chuck jaw of 93.4 $Kgcm^2$.
2. Finger length: The gripper's fingers measure around 194 mm in length (see Figure 5.28).

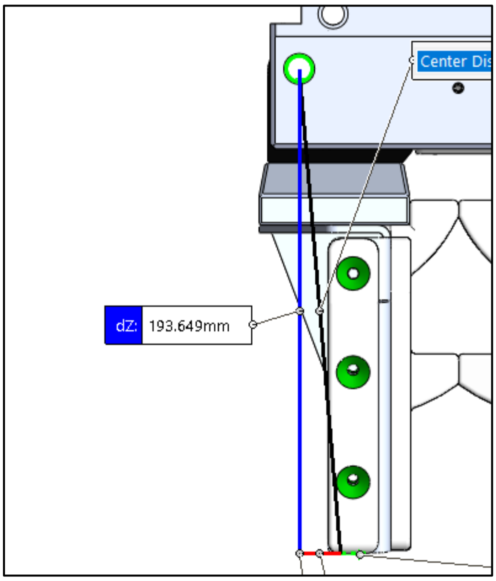


Figure 5.28. Finger length.

All the parameters mentioned above are within the gripper limits (see Table 5.27), validating this equipment selection.

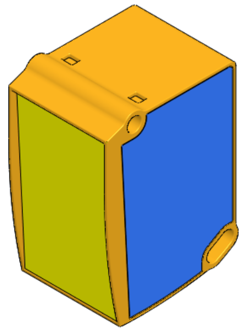
Gripper' Sensors

During the selection process of the *Gripper' Sensors*, the main factors that were taken into consideration are:

1. The requirement to be capable of measuring distances;
2. Being compact and lightweight.

Considering the factors above, the model - *DS35-B15821* from *SICK* was selected as the *Gripper's Sensor*. Table 5.27 depicts the equipment technical data.

Table 5.28. Gripper's Sensors (DS35-B15821) technical data[14].

Parameters	Value	Illustration
Type of device	Photocells	
Detection range max.	50 mm<x<12,000 mm	
Light type	Laser, infrared	
Repeatability	≥ 0.5 mm	

5.4.5.5 Crates' Transport Equipment

The *Crates' Transport Equipment* can be decomposed into three flat top conveyor segments, as shown in Table 5.29 and Figure 5.29.

Table 5.29. Crates' transport equipment decomposition.

Equipment name	Nº of units	Sub-systems names	Nº of units
Crates' Transport Equipment	1	*4-Meter Chain Conveyor*	1
		1,5-Meter Chain Conveyor	1
		90º Curve-Chain Conveyor	1

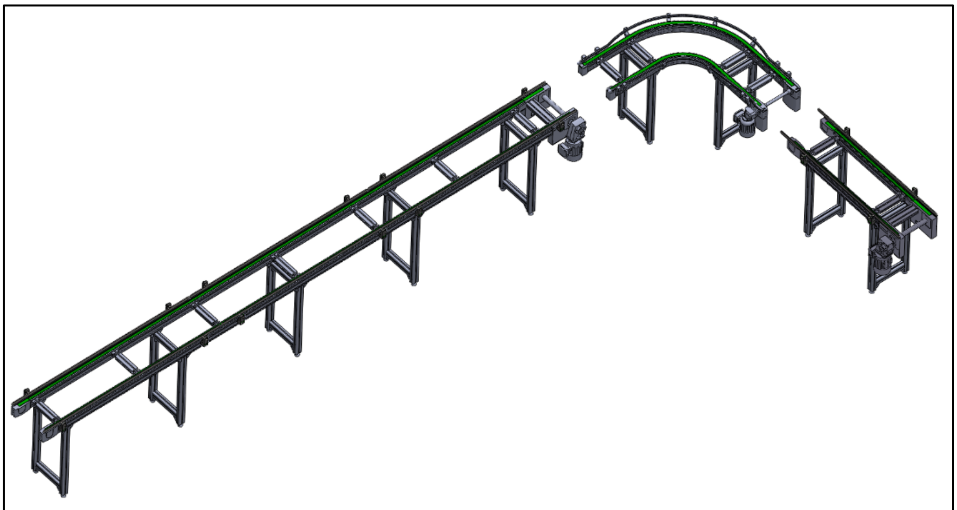


Figure 5.29. Crates' Transport Equipment decomposition.

[14] Available at: https://cdn.sick.com/media/pdf/8/58/058/dataSheet_DS35-B15821_1057656_en.pdf

The selected conveyor segments are from *Rexroth's TS 2plus Transfer System* lineup and were selected based on their ability to work with the accumulation of workpieces. These conveyor segments can be configured for various parameters such as track width, conveyor speed, motor mount, and others, being the selected configuration depicted in Table 5.30.

Table 5.30. TS 2plus Transfer System segments technical data[15].

Parameters	Value
Track Width	400 mm
Height	996 mm
Speed (constant)	18 m/min
Chain material	Polyamide
Max. section load in accumulation operation	60 Kg

The track width was selected based on the *Crates* width (*400 mm*), and the speed was set based on:

1. The time it takes for a set of 6 *Packs* to be ready to be placed inside a *Crate.*
2. The distance between the *Stop Gates* responsible for stopping the *Crates.*

Knowing that it takes around 5,14 seconds for a set of 6 *Packs* to be ready to be placed inside a *Crate* and that the distance between the *Crates' Stop Gates* is 778 mm (see Figure 5.30), the minimum velocity needed for the conveyor segments can be determined through the following equation:

$$s = \frac{d}{t} \tag{5.2}$$

Where:

$s = speed\ (m/s)$

$d = distance\ (m)$

$t = time\ (s)$

When applied to this case:

$$\frac{0.778\ m}{5.14\ s} * 60\ s \approx 9.07\ m/min$$

[15] Available at: https://www.boschrexroth.com/en/xc/myrexroth/document-library?p_p_id=20&p_p_lifecycle=0&p_p_mode=view&p_p_state=maximized&_20_struts_action=%2Fdocument_library%2Fview_file_entry&_20_redirect=./&_20_fileEntryId=29892683

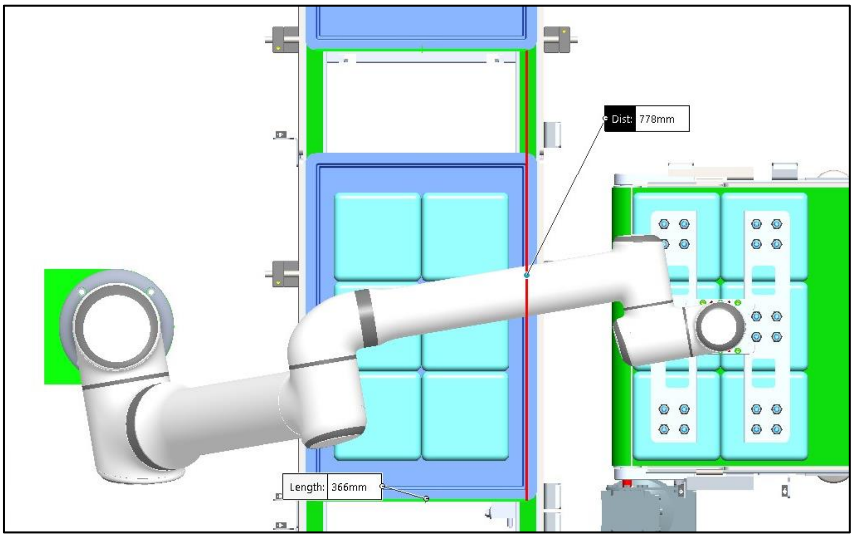


Figure 5.30. Crates transport distance between stop gates.

From the available configurable speeds, 18 m/min was selected for the system.

Although the conveyor track width is the same as the *Crate's* width, the considered *Crate* shape doesn't allow for an optimal chain-*Crate* contact surface, as the bottom of the *Crate* is narrower than its overall width. If not well centered, this could cause the Crate to lose traction on either side. Maintaining the crates centered can be addressed by adjusting the guide rails present in the system (see Figure 5.31).

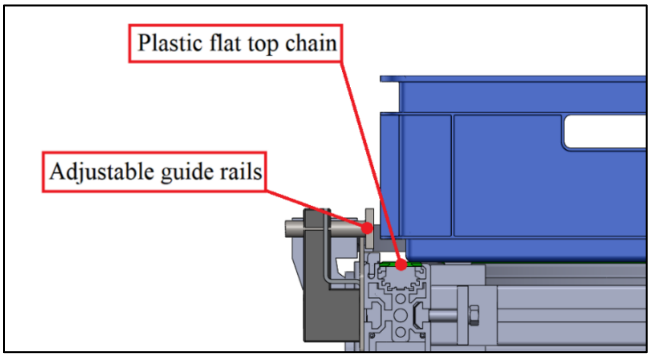


Figure 5.31. Contact between flat top chain and Crate.

5.4.5.6 Crates' Indexing Equipment

The *Crates' Indexing Equipment* is responsible for making one crate available at-a-time for the *Pack's Pick and Place Operation*. This equipment can be decomposed, as shown in Table 5.31 and Figure 5.32.

Table 5.31. Crates' Indexing Equipment decomposition.

Equipment name	Nº of units	Sub-systems names	Nº of units
Crates' Indexing Equipment	1	*Crates' Transport Equipment*	1
		Stop Gates	2
		Crates' Indexing Sensors	3

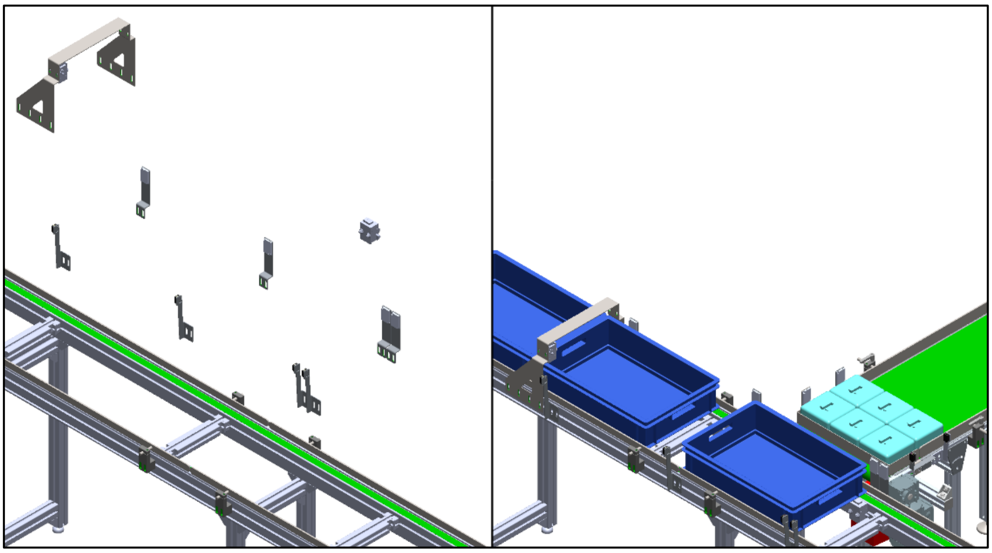


Figure 5.32. Crates' Indexing Equipment decomposition.

The *Crates' Transport Equipment* has already been presented, and the selection process behind the *Crates' Indexing Sensors* is the same as the one on *Two-Columns Forming Equipment*. Therefore, the Stop Gates is the equipment whose selection process remains to be explained.

The *Stop Gates* are responsible for stopping *Crates* at the *Packaging Station*. The first *Stop Gate* is mounted on a metal sheet bracket, as shown in Figure 5.33, and the second *Stop Gate* is mounted inside the transport conveyor rails.

The selected *Stop Gate* model for this application is the model - *VE 2/M* from *Rexroth.* This model's selection is a natural decision due to being an accessory to the selected *Crates' Transport Equipment - TS 2plus Transfer System*.

The parameters necessary to validate the use of this *Stop Gate* model can be found in Table 5.32.

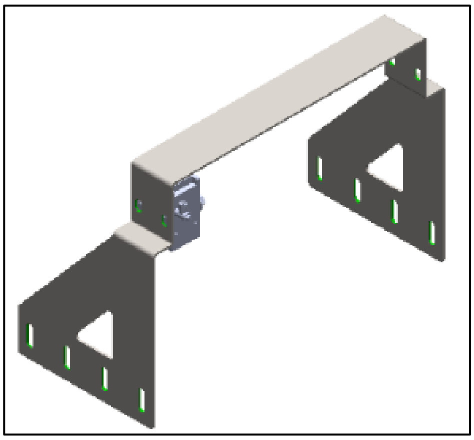


Figure 5.33. Stop_gate_1.

Table 5.32. VE 2/M Stop Gate technical data[16].

Parameters	Value
Max. total weight of workpiece	200 Kgf
Permissible accumulation load (for workpieces traveling at 18 m/min)	50 Kgf

Knowing that the weight of a single *Crate* is 1.3 Kg, the workpiece is well under the maximum total weight that the stop gate can support. Furthermore, since *Crates' Transport Equipment* has the length to accumulate up to 6 *Crates* behind the first *Stop Gate*, the accumulation load (for workpieces traveling at 18 m/min) is 7.8 Kg. This result is also well under the permissible accumulation load of 50 Kg, making this equipment suitable for operation.

5.4.5.7 Crates' Positioning Equipment

This equipment is responsible for guiding the unloading of the pallet full of crates into position and partially correcting the position of the crate stack for the crate picking operation. There are two units of this equipment in the system, a right version, and a left version. These versions mirror each other, being the difference between them is the *U-Shaped-Structure*. Besides this structure, two more pieces of equipment make up the *Crates' Positioning Equipment*, as seen in Table 5.33 and Figure 5.34.

Table 5.33. Crate positioning equipment.

Equipment name	Nº of units	Sub-systems names	Nº of units
Crate Positioning Equipment	2 (symmetrical)	*U-Shaped Structure*	1
		Positioning Guided Actuator	1
		Positioning Clamps	2

[16] Available at:

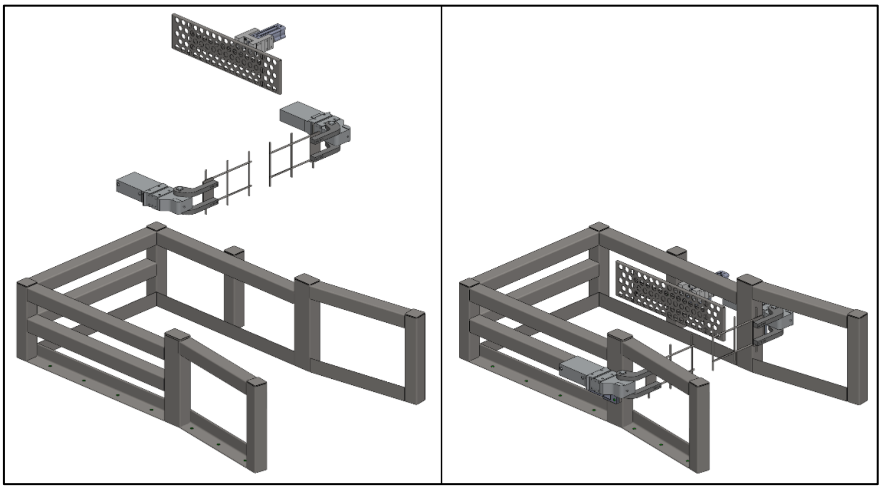


Figure 5.34. Crate positioning equipment.

The selection process behind each piece of equipment will be explained ahead:

U-Shaped Structure

This equipment was modeled with CAD software (*SolidWorks*) and had two primary purposes:

1. Holding the *Guided Actuator* and the *Clamps*;
2. Facilitate the unloading of the *Crates'* pallets.

The structure of this equipment is made primarily of steel tubing, and it's meant to be bolted to the customer's facility floor. The general dimensions of the equipment can be seen in Figure 5.35.

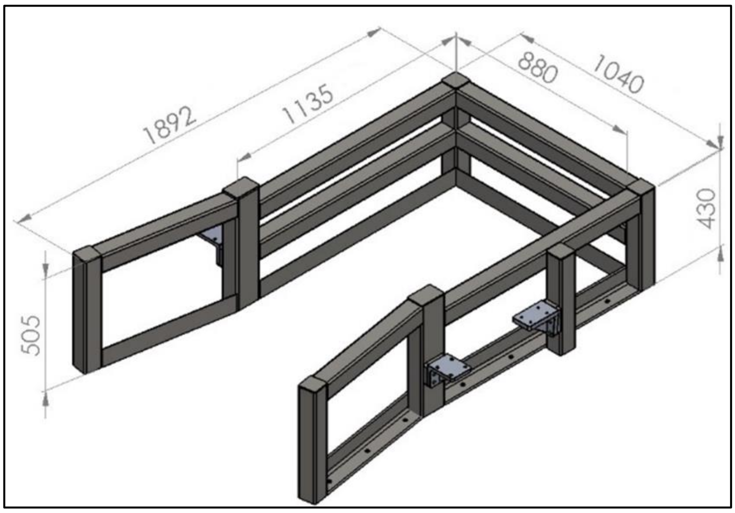


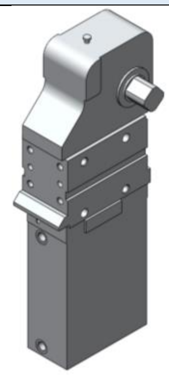
Figure 5.35. U-Shaped Structure general dimensions (in mm).

Clamps

The *Clamps* are formed by a pneumatic clamp and a custom clamp arm. The custom arm is comprised of two of-the-self clamp arms with a custom-made attachment.

Relatively to the pneumatic clamp, the selected model is - *82M-3E230080K9* from *Destaco*, with the following technical data (see Table 5.34):

Table 5.34. Clamp model 82M-3E230080K9 technical data[17].

Parameters	Value	Illustration
Max Holding Torque	3000 Nm	
Max Clamping Torque at 5bar	850 Nm	
Movement range	135 degrees	

The custom arm is composed of a CAD modeled part attached to two off-the-self *Destaco* arms (model - *8s801_45_204*), which combined measure around 482.5 mm in length, as depicted in Figure 5.36.

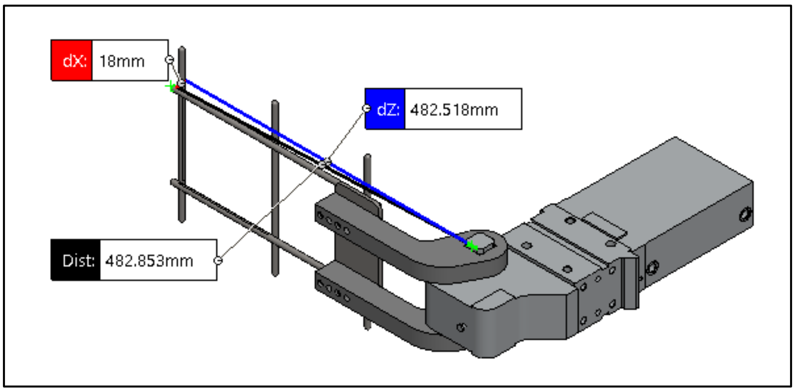


Figure 5.36. Clamp arm length.

[17] Available at: https://www.destaco.com/content/destaco/language-masters/en/clamping/Pneumatic/pneumatic-power-clamps/pneumatic-power-clamps-82m-3e-arms/jcr:content/root/container/vws_tabs_copy_copy_c/tabItems/item_1625664116752/content/destacoresource_copy.pdf?pdfPath=/content/dam/destaco-assets/documents/pdf/catalogs/PC-PPC-TCC-2_82M-3_US-2845.pdf

To determine if this equipment was suitable for the system, the following parameters were determined:

1. Clamp arm weight (tooling weight);
2. Maximum clamping torque exerted during the clamping operation.

From *SolidWorks's Mass Properties* feature, it was determined that the clamp arm had a weight close to 5.4 Kg, and it was determined that the distance from the clamp arm pivot point to its center of mass is approximately 110 mm (see Figure 5.37).

Table 5.35 is part of the clamp's model technical data and depicts the maximum tooling weight according to the distance from the pivot point to the center of mass. From this table, it is possible to conclude that for a distance from the pivot point to the center of mass of 110 mm, the maximum tooling weight is more than 10 Kg, validating the tooling weight parameter.

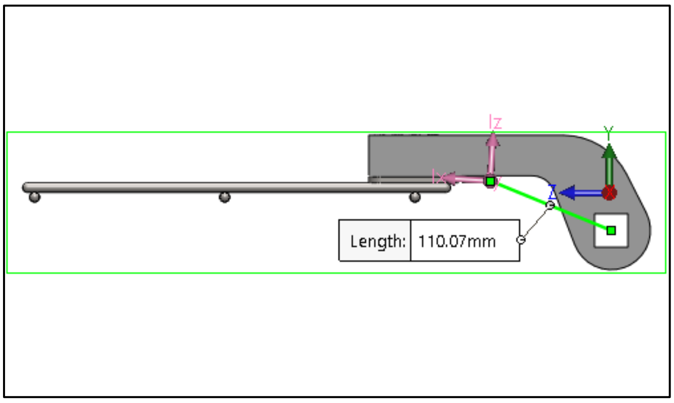
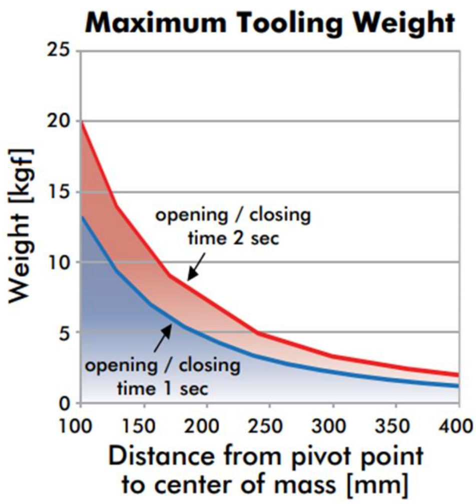


Figure 5.37. Clamp arm distance from pivot point to center of mass.

Table 5.35. Maximum tooling weight according to the distance from pivot point to center of mass.



Relative to the maximum clamping torque exerted during the clamping operation, a static friction coefficient of 0.4 was considered between the *Crates* and pallet's surfaces [15]. Furthermore, to determine the force needed to move the *Crates'* stacks, a scenario similar to the one depicted in Figure 5.38 was considered. In this scenario, one *Clamp* pushes three stacks of *Crates* instead of two.

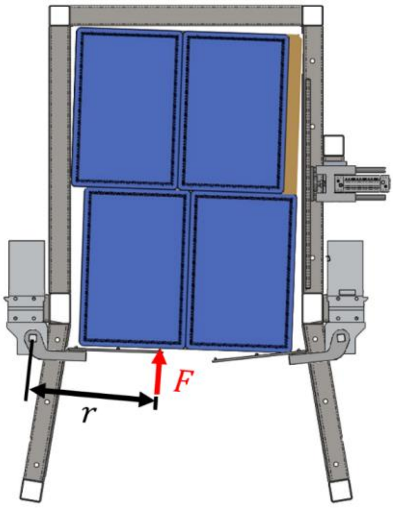


Figure 5.38. Illustration of a Clamp pushing three Crates' stacks.

To perform these calculations, the equation (5.1) and the following equations were used:

$$f_{friction} = \mu N \tag{5.3}$$

Where:

$f_{friction} = Friction\ force\ (N)$

$\mu = coeficient\ of\ friction$

$N = Normal\ force\ (N)$

$$N = mg \tag{5.4}$$

Where:

$N = Normal\ force\ (N)$

$\mu = coeficient\ of\ friction$

$g = acelaration\ of\ gravity = 9.81\ m/s^2$

Applying the values in question to these equations results in:

$$1.33\ kg * 3 * 10\ units = 39.9\ kg$$

$$N = 39.9 * 9.8 \frac{m}{s^2} = 391.4\ N$$

$$f_{friction} = 391.4 * 0.4 = 156.6\ N$$

Considering the force determined above, the maximum clamping torque exerted during the clamping operation was determined considering the arm clamp was pushing the *Crates* with the end of their arms. The calculations were performed as follows:

$$\tau = Frsin(\theta) \tag{5.5}$$

Where:
$\tau = torque\ (Nm)$
$F = force\ (N)$
$r = lenght\ of\ the\ moment\ arm$
$\theta = angle\ between\ force\ vector\ and\ moment\ arm$

Applying the values in question to these equations results in:

$$156.6\ N * 0.4828\ m * \sin\,(90°) = 75.6\ \mathrm{Nm}$$

Table 46 shows that the equipment's maximum clamping torque is 850Nm (at 5bar), which is superior to the needed 75.6 Nm clamping torque, validating the equipment selection.

Guided Actuator

The *Guided Actuator* is formed by a cylinder with a guiding unit and a custom-made barrier modeled with CAD software (*SolidWorks*), as depicted in Figure 5.39.

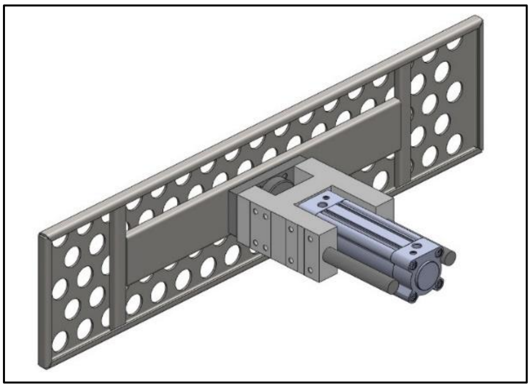


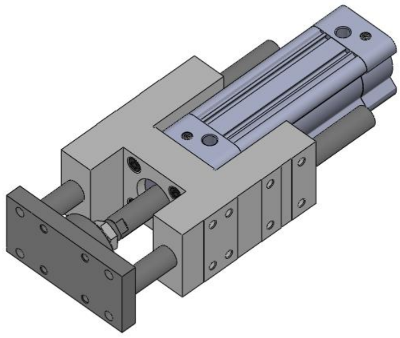
Figure 5.39. Guided Actuator.

The custom-made barrier was modeled in *304 stainless steel*, composed of several C-channel segments and a perforated sheet metal bent front surface that interacts directly with the *Crate's* surfaces.

The cylinder model selected is - *DSBC-50-100-PPVA-N3,* and the guiding unit model is - *FENG-50-100-KF,* both from *Festo*. When assembled together, this equipment can handle larger torque values than the cylinder by itself.

Table 5.36 depicts the equipment's technical data relevant to the selection process.

Table 5.36. Guiding unit - FENG-50-100-KF plus cylinder - DSBC-50-100-PPVA-N3 assembly technical data[18].

Parameters	Value	Illustration
Piston diameter	50 mm	
Stroke	100 mm	
Theoretical force (at 6 bar), advance stroke	1178 N	
Max. static torque Mz	89 Nm	
Cushioning stroke	22 mm	

To determine if this equipment was suitable for the system, the following parameters had to be determined:

1. The maximum force exerted by the *Guided Actuator* during operation;
2. The maximum static torque Mz exerted by the *Guided Actuator* during operation;

From the *Clamps*' selection process, it's known that the needed force to push three stacks of *Crates* is around 156.5 N. To move four stacks of *Crates,* the *Guided Actuator* needs to exert 208.6 N, which is significantly lower than the theoretical force of 1178 N (see Table 5.36).

To obtain the maximum static torque Mz. that the assembly might need to exert on the crate stacks, the following scenario was considered:

1. The *Guided Actuator's* barrier pushes the *Crates'* stacks with the largest momentum arm (400 mm - half of the barrier's width).
2. The *Guided Actuator's* barrier pushes three *Crates'* stacks instead of two.

Considering the scenario mentioned above, the maximum static torque Mz. exerted by the guided actuator is 62.62 Nm, according to the equation (5.5). This value is inferior to the maximum static torque Mz that equipment can exert (see Table 5.36), validating the equipment selection.

[18] Available at: https://www.festo.com/cat/en-gb_gb/data/doc_ENUS/PDF/US/FEN-FENG_ENUS.PDF

5.4.5.8 Machine Guarding Equipment

The *Machine Guarding Equipment* was selected according to the *ISO 13857* norm, which establishes values for safety distances in both industrial and non-industrial applications to prevent machinery hazard zones from being reached [16].

The selection process for this equipment started with the selection of the panel type, being the remaining equipment selected around it. The selected panel type is the *ST20* from *Troax*, with a mesh size of 20×100mm, a standard height of 2,050 mm, and with up to eight different widths. This selection was followed by the selection of the posts and doors, being the last single-hinged and equipped with *Troax's Safe Locks*, which can be fitted with a vast range of safety switches.

Since there's only one worker available for the pallet replacing operation, the faster this operation could be performed, the more time the operator had to dedicate to other tasks. This factor was the main reason behind the selection of safety light curtains instead of gates in both entrances of the *Depalletizing Workstation*, as operating safety light curtains was considered faster and less demanding than operating gates. The selected safety light curtains model is - *SLC240COM*, from *Schmersal*, with the following technical data:

Table 5.37. Safety light curtains model SLC240COM technical data[19].

Parameters	Value	Illustration
Safety Standards	EN ISO 13849-1; EN IEC 62061	
Reaction time, maximum	20 ms	
Protection filed height	330 mm-1930 mm	
Resolution	14 mm	

[19] Available at: https://products.schmersal.com/pt_PT/slc240com-er-0650-30-12.html

5.4.6 Operational Parameters

Equipment parameters not intended to be altered, such as the transport conveyors' speeds, determined in the Equipment Selection step, won't be presented in this subchapter.

Packs' Pick and Place Cycle Duration

Since the *pick and place* test runs performed in the Key Metrics Evaluation step resulted in a *cycle duration* of approximately 2.82 seconds*,* the operational cycle duration should not be lower than this value. Furthermore, it has been determined that a set of six-packs needs to be picked on average every 5.14 seconds, and as a result, this pick and place operation can't take longer than that.

To set this operational parameter, the following factors were taken into account:

a. The longer the cycle duration is, the slower the acceleration and deceleration can be (for the same moving speed). The slower the acceleration and deceleration, the lower the probability of the packs detaching from the gripper while being handled.
b. In case of an operation delay on other parts of the system, the closer the cycle duration to the system's needs (5.14 seconds), the larger the probability of failing to meet those needs.
c. The vacuum gripper will create a vacuum during the robot returning movement to the pick station, saving time for the overall operation.
d. The vacuum gripper will remain in the pick target for a number of milliseconds to ensure a proper pick and place of the packs. This reassurance shouldn't be needed in a real-world application but will be considered in this dissertation.

Considering these factors, the operational parameters were set according to Table 5.38.

Table 5.38. Packs' pick and place cycle duration.

Parameters	Duration
Packs' pick and place cycle duration (total)	4.00 s
Vacuum gripper picking/dropping duration	0.25 s
Robot movement between pick and place operations duration	3.50 s

Crates' Pick and Place Cycle Duration

The *Crate's* pick and place operation has multiple paths to travel due to its several picking positions. This factor results in different cycle times for different picking positions, being that the picking targets nearest to the robot base would result in shorter pick and place cycle times.

Since data was only obtained for the top and bottom furthest picking targets, there's no way to determine how the cycle times duration evolves through the several *Crate's* stack layers. As a result, a correlation between the picking target position relative to the robot's base and the pick and place cycle duration cannot be obtained.

Due to the abovementioned factors, the *Crate's* pick and place cycle duration will be considered the same for all picking positions. Although this consideration won't correctly represent a real-world application, it still represents a valid approximation since the considered cycle duration is greater than the longest cycle duration obtained in the key metrics evaluation results (cycle duration for the bottom pick target).

Knowing that performed test runs obtained in the evaluation of the key metric resulted in pick and place cycle durations of 3.67 seconds (top pick target) and 4.97 seconds (bottom pick target), the *Crates'* pick and place operational cycle duration has to be greater than the last value. Furthermore, it has been determined that a set of six-packs needs to be placed on average at every 5.14 seconds, which translates to two sets of six-packs at every 10.28 seconds. Since every pick and place operation carries two crates, the cycle duration associated with this operation can't take longer than 10.28 seconds.

Finally, during the setting of the operational cycle duration, the following factors were taken into account:

- The longer the cycle duration, the slower the acceleration and deceleration can be (for the same moving speed), which decreases the probability of the crates wobbling during their handling.
- The closer the cycle duration to the system's needs (10.28 seconds), the larger the likelihood of failing to meet these needs in case of an operation delay on other parts of the system.
- The picking and placing operations times are estimates and should be adjusted during real-world testing.

Considering these factors, the parameters were set according to Table 5.39.

Table 5.39. Crates' pick and place cycle duration.

Parameters	Duration
Crates' pick and place cycle duration (total)	9.50 s
Angular gripper picking duration	3.00 s
Angular gripper placing duration	1.50 s
Robot movement between pick and place operations duration	5.00 s

3-Pack-Column Sliding Duration

The speed and duration of an equipment driven by a pneumatic cylinder will mainly depend on the cylinder's operating pressure and the force it needs to exert.

Considering there's no significant external force being applied in the cylinder, both the cylinder's maximum speed and stroke (depicted in Table 5.40) allow to determine the actuation duration of the cylinder.

Table 5.40. Sliding barrier duration parameters.

Parameters	Values
Max. cylinder speed	3 m/s
Cylinder stroke	0.320 m

Without considering the deceleration provided by the cylinder cushioning, the equation (5.2) allowed to obtain the minimum theoretical sliding duration of around 0.1 seconds.

The *Sliding Barrier's* advancing speed is thought to be too high, as it could result in an uncontrolled handle of the *3-Pack-Column*. This opinion remains even considering the cushioning of the cylinder.

To reduce the cylinder speed, a flow control valve may be used. Considering the use of such flow control equipment, a sliding duration of 1 second was set for the advancing stroke. The returning stroke speed shouldn't be changed.

Tilting Barrier Opening/Closing Duration

The Tilting Barrier's main operational parameter is the pressure fed to the equipment's pneumatic cylinder. This parameter can be regulated by using a flow control valve resulting in different cylinder actuation speeds and consequent durations.

As previously mentioned in the design scope, the operational pressure of this equipment pneumatic cylinder (and similar equipment) won't be determined. However, an operation duration will be proposed. Doing so is a common application during the MH system design process since it's usually easier to grasp the thought of equipment operating for a specific duration than it is for a specific pressure.

Considering the information above, the operational *Tilting Barrier's* opening/closing duration was set as 0,5 seconds and believed to be within the equipment's capabilities.

Pallet Replacing - Order of Operations and Duration

When replacing an empty pallet of *Crates* with a full one, the operator must execute the following tasks:

1. Remove the empty pallet from the depalletizing structure;
2. Dispose of the empty pallet;
3. Bring a pallet full of crates near the depalletizing structure;
4. Insert the pallet full of *Crates* inside the depalletizing structure;
5. Give the system the information that it's safe to proceed with its operations.

These tasks don't necessarily need to be executed in this order, as long as they are conducted safely.

It is not known where the pallets are stored and disposed of, which as a result, doesn't allow for path planning. However, it is recommended that a hand pallet truck operator should not operate the equipment (when loaded) for distances superior to 33 meters at a time. Furthermore, the operator should use the equipment at an average walking pace (3-4 km/h) [17]. Considering this information, the following assumptions were made:

1. The distance traveled by the operator from the pallet full of crates storage location to the depalletizing station is not superior to 33 meters.
2. The distance traveled by the operator from the depalletizing station to the pallet disposal station is not superior to 33 meters.
3. The average hand pallet truck operation speed is 3 km/h.

In Table 5.41, the traveling duration for each task involved in the pallet replacing operation is set according to equation (5.2).

Table 5.41. Pallet replacing operation decomposition.

Task	Speed	Distance	Duration
Pallet replacing operation (total duration)	NA[20]	NA	$\approx 165\ s$
Remove the empty pallet from the depalletizing structure	NA	NA	$\approx 20\ s$
Dispose of the empty pallet	3 km/h	33 m	$\approx 40\ s$
Bring a pallet full of crates near the depalletizing structure	3 km/h	(33+33) m	$\approx 80\ s$
Insert the pallet full of crates inside the depalletizing structure	NA	NA	$\approx 20\ s$
Give the system the information that it's safe to resume operation	NA	NA	$\approx 5\ s$

The calculations above were made for an order of operations that results in the depalletizing operation being interrupted the least amount of time. This is achieved by having a pallet full of *Crate*s ready to be swapped near the depalletizing station. In further detail, this order of operations can be described as follow:

1. The operator travels 33 meters to the pallet storage location from the pallet disposal location;
2. Loads a pallet into the hand pallet jack;
3. Travels another 33 meters to the depalletizing station;
4. Unloads the pallet outside the depalletizing station;
5. Removes the empty pallet from the depalletizing station and unloads it outside of it;
6. Loads up the pallet full of *Crates* again and unloads it inside the depalletizing station;
7. Loads up the empty pallet again and travels *33 meters* to the pallet disposal location.

Loading and unloading times for each pallet were not considered for the results obtained in Table 5.41 as the duration of each of these occurrences is very short, and their number may vary depending on the order of operations.

Since the system handles a crate around every 10.3 seconds, each pallet will take around 205 seconds (3.5 minutes) to empty. Given that for the considered parameters, the total

[20] NA = Non Applicable

duration of the pallet replacing operation is about 165 seconds (2.75 minutes), the operator will have around 40 seconds to spare between each pallet replacement.

Clamps Closing/Opening Duration

Similar to the **Tilting Barrier Opening/Closing Duration** scenario, where the main operational parameter of equipment is the operating pressure, the clamps closing/opening duration will be set as the operational parameter of the equipment.

Figure 5.40 depicts the maximum tooling weight permissible in relation to the distance from pivot point to the clamp arm center of mass.

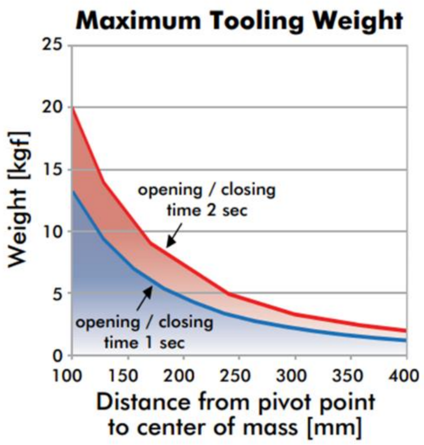


Figure 5.40. Clamp maximum tooling weight[21].

In this graphic, two durations for the opening/closing time of the clamp's arms can be depicted, being the longest 2 seconds. Considering this value as the opening/closing time of the clamp's arms for their operating range of movement, it is thought that this duration is too short and that a flow control valve would be necessary to slow down the *Clamps'* actuation.

Considering the use of a flow control valve, a duration of 5 seconds was set as the equipment's operational closing/opening duration.

Guided Actuator Advance Duration

Similar to the previously mentioned equipment, the *Guided Actuator* closing/opening duration was set as the operational parameter of the equipment. In this case, a duration of 3 seconds for both the advancing and returning stoke was selected and considered to be within

---

[21] Available at: https://www.destaco.com/content/destaco/language-masters/en/clamping/Pneumatic/pneumatic-power-clamps/pneumatic-power-clamps-82m-3e-arms/jcr:content/root/container/vws_tabs_copy_copy_c/tabItems/item_1625664116752/content/destacoresource_copy.pdf?pdfPath=/content/dam/destaco-assets/documents/pdf/catalogs/PC-PPC-TCC-2_82M-3_US-2845.pdf

the equipment capabilities. A flow control valve could be used if needed to achieve this duration.

Delay Between Detecting 3-Pack-Column and Sliding

Although there is one sensor for each pack on the *3-Pack-Column Forming Equipment*, to guarantee the correct detection of the *Packs*, the system should be programmed to only move them after all three sensors detect the presence of a *Pack*, simultaneously, for 0,200 seconds.

Delay Between Detecting Two 3-Pack-Columns and Picking

Similar to the delay between detecting packs column and sliding, to further ensure that both pack columns are in the correct position, a delay of 0,500 seconds will be introduced between both sensors, simultaneously detecting the presence of the *Packs*' columns and both columns being picked.

5.5 Design Evaluation

5.5.1 Determination of the Evaluation Parameters

In this MHS design step, the parameters necessary to evaluate are determined. These parameters are the ones that affect the performance measures and will serve as the input in the evaluation model. Table 5.42 depicts the determined parameters.

Table 5.42. Simulation parameters.

Parameters	Values
Number of *Crates* per pallet	40 units
Pallet replacing duration Removal of an empty pallet from the *U-shaped-structure*; Insertion of a pallet full of Crates inside the *U-shaped-structure*.	40.00 s
Transport duration of the *3-Pack-Columns*	10.72 s
Delay between detecting two *3-Pack-Columns* and picking	0,50 s
Packs' pick and place cycle duration	4.00 s
Crates' pick and place cycle duration	9.50 s
Possible *Crate* buffer size	4 units
Pack input	70 units/min
3-Pack-Column sliding duration	1.00 s
Delay between detecting a *3-Pack-Column* and sliding	0.20 s
Transport duration of the *Crates*	8.15 s
Clamps closing duration	5.00 s
Guided Actuator advance duration	3.00 s
Transport duration of *Crates* between stop_gate_1 and stop_gate_2	2.59 s

Referring to Table 5.42, additional parameters to the ones determined in the

Operational Parameters step can be depicted. Some of these parameters result from combining two or more operational parameters. This is the case with *transfer duration*, as this parameter can be obtained, through the *transport conveyor length* and *speed*, resulting in the need to input only one parameter into the simulation model instead of two. Doing so results in fewer variables to play with, however it allows for creating simulation models faster.

The additional parameters in question, as well as other relevant parameters, were determined as follows:

Transport Time of the 3-Pack-Columns

To determine the transport duration of the *3-Packs-Columns,* the *Secondary Transport Conveyor's* velocity and the distance traveled by the second *3-Pack-Column* need to be considered.

The velocity of the *Secondary Transport Conveyor* has already been determined to be 6 m/min, and the distance the second *3-Pack-Column* needs to travel to reach the *Secondary Transport Conveyor's* end stop (*Columns' End Stop*) can be depicted in Figure 5.41 (1 m).

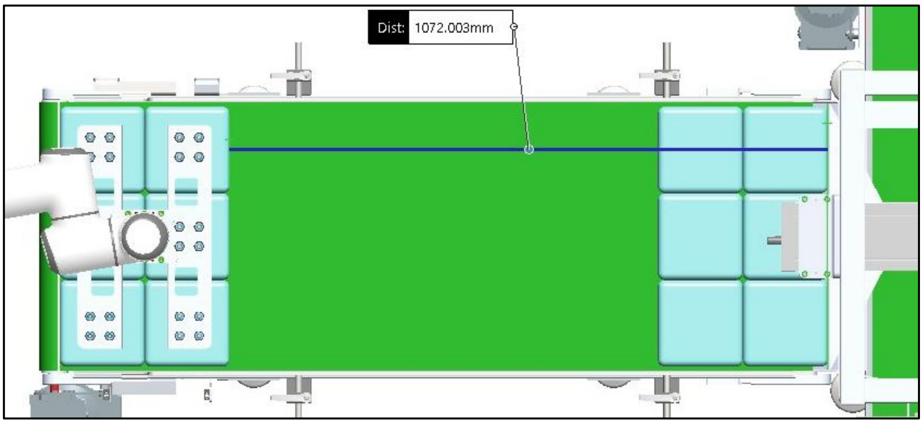


Figure 5.41. 3-Pack-Column transport distance.

With the parameters mentioned above and equation (5.2), 10.72 seconds was obtained transport duration of the *3-Packs-Columns* through the *Secondary Transport Conveyor.*

Transport Time of the Crates

To determine the transport duration of the *Crates* through the chain conveyor, both the chain conveyor's velocity and the distance traveled by the second *3-Pack-Column* need to be considered.

The velocity of the chain conveyor has already been determined to be 18 m/min, and the distance the *Crates* need to travel to reach the first stop gate can be depicted in Figure 5.41 (2.444 m).

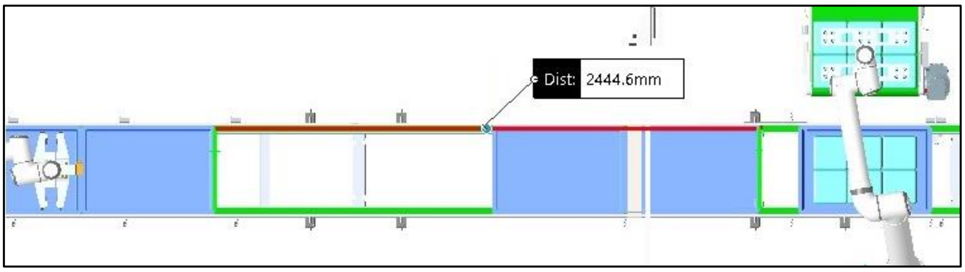


Figure 5.42. Crates transport distance.

With the parameters mentioned above and equation (5.2), a duration of approximately 8.15 seconds was obtained for the transport of the *Crates* through the chain conveyor.

Crate' Transport Time Between Stop Gates

To determine the duration of the transport of a crate between stop gates, both the conveyor velocity and distance traveled by a *Crate* between stop gates are required. These parameters were obtained in the Crates' Transport Equipment subchapter and can be depicted in Table 5.43.

Table 5.43. Transport of crates between stop gates parameters.

Parameters	Values
Conveyor speed	18 m/min
Distance between stations	0.778 m

With the parameters mentioned above and equation (5.2), a duration of approximately 2.59 seconds was obtained for the transport of a crate between stop gates.

Pallet Replacing Duration

Considering the order of operations set in the

Operational Parameters step, the appropriate parameters to consider in the evaluation of the model are the following:

a. Removal of the empty pallet from the depalletizing structure;
b. Insertion of the pallet full of crates inside the depalletizing structure.

These parameters have a combined duration of 40 seconds, and the highest chance of directly impacting the system performance as both can starve the system from crates.

5.5.2 Model Creation

Although there are a lot of simulation tools available on the market and growing in popularity, Dias, and Pereira [18] compared a set of them based on popularity on the internet, scientific publications, WSC (Winter Simulation Conference), social networks, and other sources, and determined - "As a conclusion of this research study, we were able to identify a simulation tool in the first place (Arena), stands out from the remaining tools." (Dias and Pereira [18]).

Considering the result of the abovementioned study, the simulation and automation software *Arena 14.* was chosen to simulate the operations of the selected MHS equipment.

Arena 14. is a discrete event software developed by Systems Modeling and acquired by Rockwell Automation in 2000 [19]. In *Arena*, the user can build an experiment model by placing modules (boxes of different shapes) that emulate operations or logic. These modules are connected through connector lines to specify the flow of entities. Statistical data, such as cycle time, WIP (work in process) levels, and resource utilization, can be obtained and outputted as reports.

To create a model of the proposed depalletizing and packaging system, the parameters gathered in Table 5.42 were converted into modules that emulate most of the system's operations. These modules were then connected together and to other supporting modules forming the simulation model depicted in Figure 5.43. Additionally, Table 5.44 shows the parameters gathered in Table 5.42 and the modules created to emulate them.

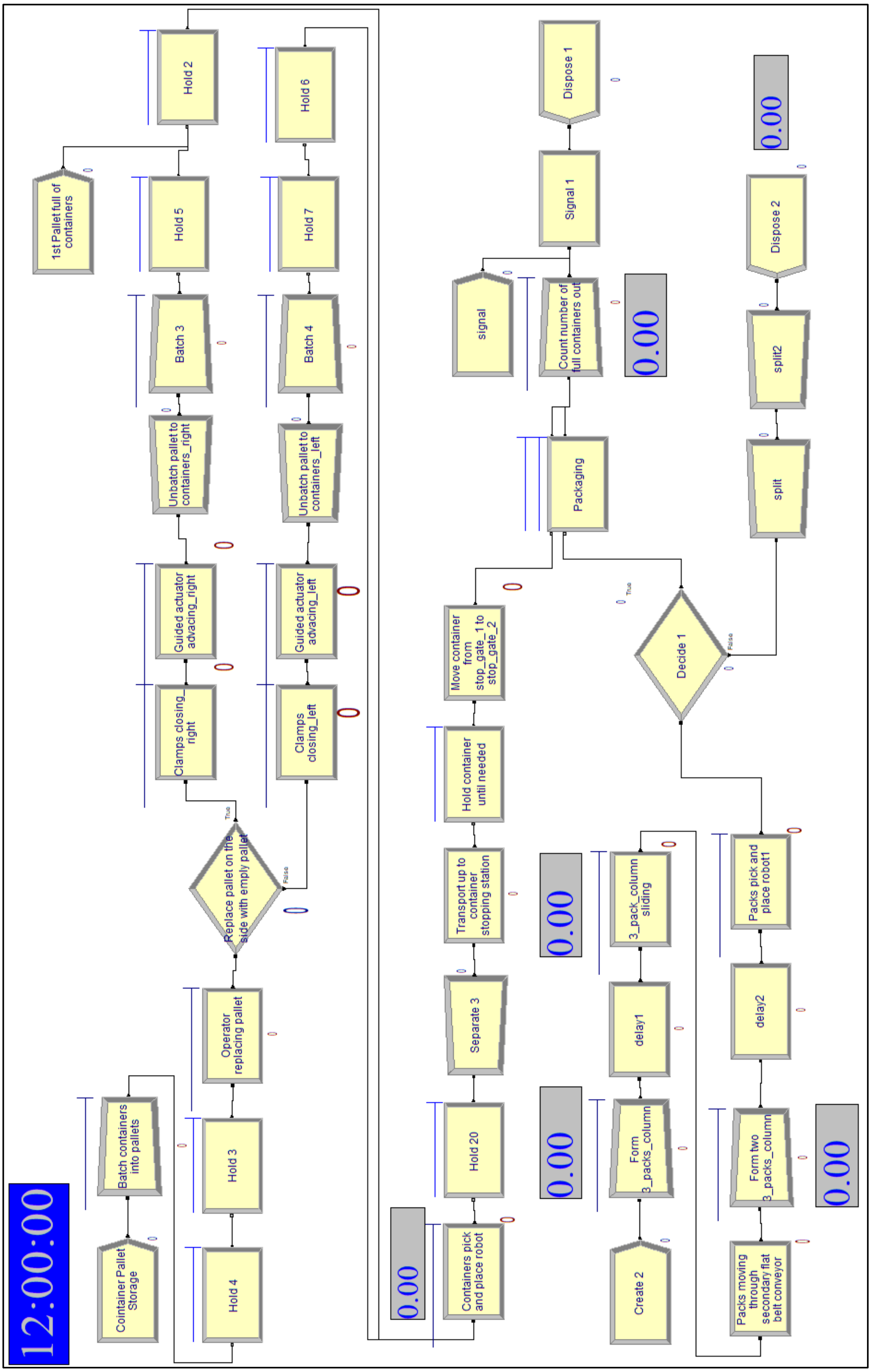


Figure 5.43. Simulation model of the depalletizing and packaging system created in Arena 14.

Table 5.44. Modules of the evaluation model matched to the evaluation parameters.

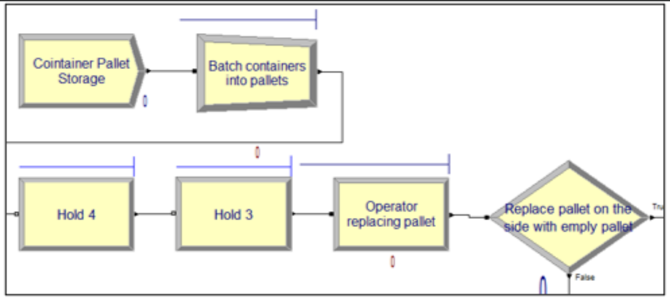
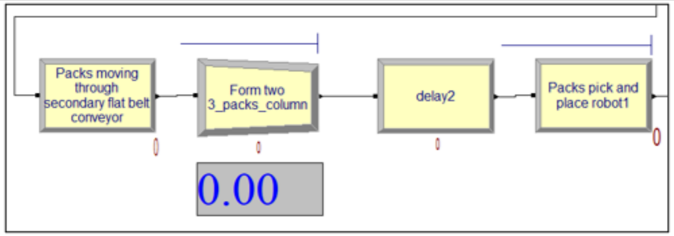
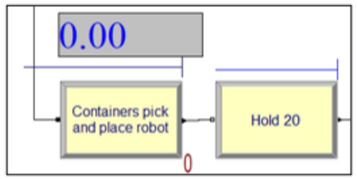
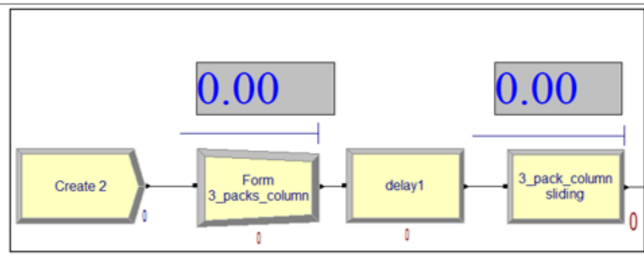
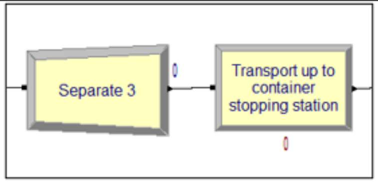
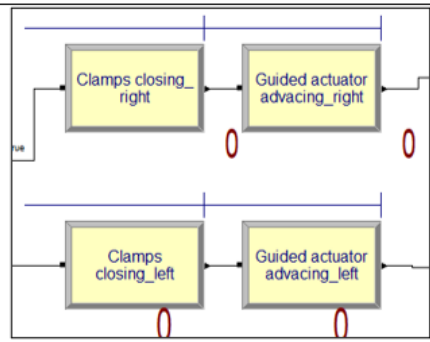
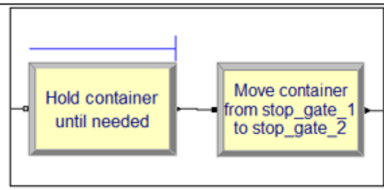
Parameters	Values	Modules designation	Modules illustration
Number of *Crates* per pallet	40 units	Batch containers into pallets	
Pallet replacing duration	40,00 s	Operator replacing pallet	
Transport duration of the *3-Pack-Columns*	10,72 s	Packs moving through secondary flat belt conveyor	
Delay between detecting two *3-Pack-Columns* and picking	0,50 s	Delay2	
Packs' pick and place cycle duration	4,00 s	Packs pick and place robot1	
Crates' pick and place cycle duration	9,50 s	Containers pick and place robot	
Possible *Crate* buffer size	4 units	Hold 20	
Pack input	70 units/min	Create 2	
3-Pack-Column sliding duration	1,00 s	Form 3_packs_column	
Delay between detecting a *3-Pack-Column* and sliding	0,20 s	Delay1	

Table 5.45. Continuation of Table 5.44 (Modules of the evaluation model matched to the evaluation parameters.).

Parameters	Values	Modules designation	Modules illustration
Transport duration of the *Crates*	8,15 s	Transport up to container stopping station	
Clamps closing duration	5,00 s	Clamps closing right/ Clamps closing left	
Guided Actuator advance duration	3,00 s	Guided actuator advancing_right/ Guided actuator advancing_left	
Transport duration of *Crates* between *stop_gate_1* and *stop_gate_2*	2,59 s	Move container from stop_gate_1 to stop_gate_2	

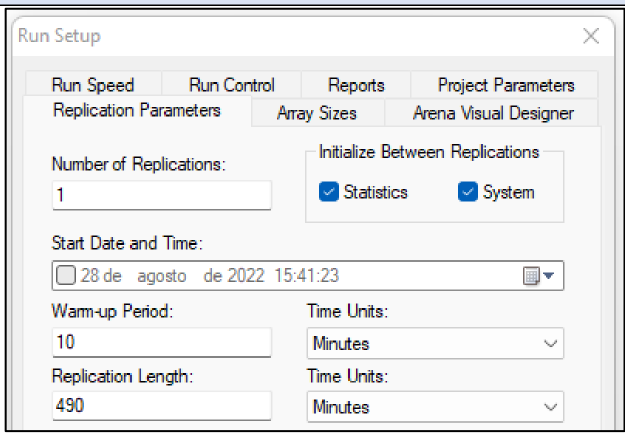
5.5.3 Simulation Results

Before simulating the developed model, some *Run setup* parameters need to be established:

1. ***Number of Replications:*** Corresponds to the number of shifts the software will simulate.
2. ***Warm-up Period:*** Corresponds to the point in time in which the software starts recording statistics. From a statistics point of view, it is used to ignore the time it takes the system to reach a steady state if it starts empty and idling.
3. ***Replication Length:*** Corresponds to the point in time in which the software stops recording statistics. If, for example, a customer wants to record the statistics of the simulation run for an 8-hour shift with a 10-minute *Warm-up Period*, the *Replication Length* would be the sum of these last two values.

Considering the information above, the following *Run Setup* parameters were selected for an 8-hour shift:

Table 5.46. Arena Simulation Run Setup parameters

Run Setup parameters	Duration (minutes)	Run Setup illustration
Number of Replications	1	
Warm-up Period	10	
Replication Length	490	

At last, a simulation run was performed, and the operations statistics were recorded in a report. From this report, the most relevant system performance indicators were gathered as follows:

1. *Number out:* This parameter, depicted in Table 5.47, indicates the system output of crates full of *Packs* obtained per shift.

Table 5.47. System's Number out.

System	Average
Number Out	5,600

2. *Instantaneous Utilization:* This parameter, depicted in Table 5.48 and Figure 5.44, indicates the average utilization rate of the resources (equipment and workers) per shift.

Table 5.48. Instantaneous Utilization of system resources.

Instantaneous Utilization	Average
Clamps_left	0.01215278
Clamps_right	0.01215278
Crates pick and place robot	0.9236
Guided actuator_left	0.00729167
Guided actuator_right	0.00729167
Operator	0.1944
packs pick and place robot	0.7778
Sliding barrier	0.3889

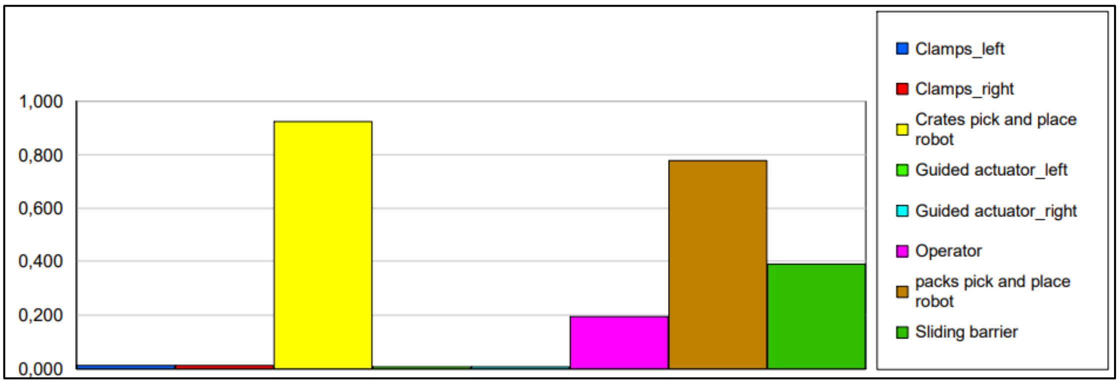


Figure 5.44. Chart of Instantaneous Utilization of system resources. The vertical axis represents the instantaneous utilization.

3. *Total Number Seized:* This parameter, depicted in Table 5.49, indicates the number of operations performed by each resource per shift.

Table 5.49. Total Number Seized by system resources.

Total Number Seized	Value
Clamps_left	70.0000
Clamps_right	70.0000
Crates pick and place robot	2800.00
Guided actuator_left	70.0000
Guided actuator_right	70.0000
Operator	140.00
packs pick and place robot	5600.00
Sliding barrier	11200.00

6 Analysis of Results

The application of the proposed design methodology allowed to achieve a slightly different MHS design compared to the, based upon, MHS design concept initially proposed by Metal-Conser. This difference in design can be mainly associated with the: *Key metrics Identification and Prioritization* and *Key metrics Evaluation* steps, which set apart this methodology from conventional MHS design methodologies.

The first deviation from Metal-Conser's design concept occurred during the *Key metrics Evaluation* step, where it was determined that *2 Crates* could be picked, at the same time, by the *Crates' Pick and Place Robot*. With this result, the system design changed from one *Crate* per *Pick and Place Operation* to two *Crates* per *Pick and Place Operation*, as it was considered a better use of recourses.

The second deviation from the initial design concept also occurred during the *Key Metrics Evaluation* step, where the simulation software - RoboDK allowed to generate code to test run both the system's pick and place operations in a real-world robot model. The results of these test runs permitted to set lower operational pick and place cycle durations for both applications compared to the values considered by Metal-Conser (see Table 6.1).

Table 6.1. Pick and place operations durations compared through percentage error.

	Expected Duration		
Operation	**MHS design developed in this dissertation**	**MHS design concept developed by Metal-Conser**	Error[22]
Packs' Pick and Place Cycle Duration	4,000s	10,000s	60%
Crates' Pick and Place Cycle Duration	9,500s	10,000s	5%

Differences in pick and place cycle duration are expected when comparing data obtained through empirical knowledge with data set based on real-world testing. However, the *Packs' Pick and Place* cycle duration obtained through real-world testing (≈2,820 s) was significantly lower than the duration estimated by Metal-Conser and, most importantly, lower than the time

---

22 $$Percentage\ Error(\%) = \frac{|measured\ value - true\ value|}{true\ value} \cdot 100$$

Where:

$measured\ value = value\ from\ the\ MHS\ design\ developed\ in\ this\ dissertation$

$true\ value = \ value\ from\ the\ MHS\ design\ concept\ developed\ by\ Metal\ Conser$

it takes to form a batch of 6 *Packs* (≈5,143 s). This result allowed to reduce the number of collaborative robots assigned to the *Packs' Pick and Place* to one robot, departing from the previous two robot-system proposed in Metal-Conser's initial design concept.

The above-mentioned design changes not only resulted in a reduction of collaborative robots but also in a reduction in the number of pieces of equipment that supported these robots' operations (see Table 6.2).

Table 6.2. Number of systems per proposed design.

	Number of systems	
Equipment designation	**MHS design developed in this dissertation**	**MHS design concept developed by Metal-Conser**
Pack's Pick and Place Collaborative Robot	1	2
Crate's Pick and Place Collaborative Robot	1	2
Pack's Staging Equipment (Secondary Transport Conveyor)	1	2
Crate's Staging Equipment (Crate's Transport Equipment)	1	2

Designing the depalletizing system with a mechanical approach resulted in unusual equipment applications such as:

1. The use of a collaborative robot for a depalletizing operation.
2. Picking two plastic crates with a clamping motion as proposed in the MH system design.
3. Correcting the position of the crates and *Crates'* stacks with the proposed equipment.
4. Placing sequence of the *Crates.*

Although the systems mentioned above work on paper, due to their uncommon application, they are more likely to present unforeseen problems during real-world testing.

The performance indicators recorded during the model simulation of the achieved MHS design revealed, among others, a system output of *5600 crates full of packs* per shift, which perfectly matches the customer output requirements calculated in the *Performance Measures* step.

7 Conclusions and Future Work

7.1 Conclusions

The primary purpose of this dissertation was to propose a MHS design methodology suitable for developing MHS design concepts, followed by an attempt to validate the methodology through its application to a packaging and depalletizing system concept developed by Metal-Conser.

The first conclusion achieved in this dissertation is that the data provided to Metal-Conser for the design of the MHS concept lacked important information. As a result, several parameters had to be estimated to establish the control data during the application of the proposed design methodology. To avoid scenarios such as the one described, it is advised that to develop a MHS concept, the customer should provide at least the following information:

1. Objectives that it (customer) intends to achieve with the implementation of MHS. These should be already prioritized.
2. Requirements and constraints.

Although there were limitations with data collection, a sound system design is thought to have been achieved, given the available resources.

Even though an FMEA wasn't performed on the achieved MHS solution, given the unusual collaborative robot application, the depalletizing system is considered the most significant liability of the proposed MH system design.

During the development of the MHS solution, the use of *RoboDK* as a simulation tool in conjunction with being able to run the simulations on a real-world robot model allowed to achieve better than expected duration values for the system's pick and place operations. In addition, using *Arena 14* allowed to evaluate the achieved MHS solution and obtain performance measures that can be used to balance the system. Since these software tools are readily available, it is recommended that small companies, such as Metal-Conser, implement them to achieve better MHS designs.

Overall, the evaluation results obtained in *Key Metrics Evaluation* step allowed to take more advantage of the pick and place equipment compared to the concept design proposed by Metal-Conser, making this dissertation’s proposed design solution the most affordable of the two.

When creating an initial MH system design concept proposal for a customer, the project design team at Metal-Conser often has a limited amount of time and resources to dedicate to such a task. Implementing both the Key metrics Identification and Prioritization and Key metrics Evaluation steps in the MH system concept design process increases the likelihood of detecting unforeseen problems or opportunities for improvement sooner. In addition, if performed, these steps allow Metal Conser and any company that operates similarly to achieve and propose design concepts truer to the eventual complete systems.

At last, the methodology for the design of MHSs, proposed in this paper contemplates all the steps required to design and develop a complete MHS. However, it is thought to have potential for improvement when addressing the design of custom equipment.

7.2 Future Work

In the present chapter, some proposals for future work are enumerated. These proposals represent opportunities to improve the study that was carried out and presented in the previous chapters:

- Further develop a MH system design methodology more suited for systems that require several custom-made pieces of equipment.
- Explore the simulation of operations of transport conveyor systems with RoboDK (or similar software).
- Further expand Arena 14. (or similar software) model creation knowledge to model and simulate MH systems in further detail.
- Explore the application of AGVs (Automated Guided Vehicles) for the pallet replacing operation of the proposed packaging and depalletizing system.

8 BIBLIOGRAPHY

[1] Grand View Research, “Material Handling Equipment Market Size, Share & Trends Analysis Report by Product (Storage & Handling Equipment, Automated Storage & Retrieval System, Industrial Trucks), By End Use, By Region, And Segment Forecasts, 2021 - 2028,” 2021. Accessed: Feb. 13, 2022. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/materials-handling-equipment-market#

[2] Coyle, J. J., Langley, C. J., Gibson, B., Novack, R. A., Bardi, E. J., *Managing Supply Chain – a Logistics Approach*, 8th ed. South-Western, 2008.

[3] Tompkins, J. A., White, J. A., Bozer, Y. A., and Tanchoco, J. M. A., “Facilities_Planning_John_A_White_Yavuz_A,” 2003.

[4] Hassan, M. M. D., “A framework for selection of material handling equipment in manufacturing and logistics facilities,” *Journal of Manufacturing Technology Management*, vol. 21, no. 2, pp. 246–268, 2010, doi: 10.1108/17410381011014396.

[5] Apple, J. M., *Material Handling Systems Design*. 1972.

[6] “Metalomecânica Metal-Conser,Lda,” 2022. http://www.metal-conser.com/category/homepage (accessed Feb. 13, 2022).

[7] Lambert, D. M. and Stock, J. R., *Strategic Logistics Management*, 4th Edition. New York: McGraw Hill, 2001.

[8] Welgama, G. P. R., “An integrated methodology for automating the determination of layout and materials handling system,” *Int J Prod Res*, 1996, doi: 10.1080/00207549608905023.

[9] Nadler, G., “An Investigation of Design Methodology,” *Manage Sci*, vol. 13, no. 10, p. B-642-B-655, Jun. 1967, doi: 10.1287/mnsc.13.10.B642.

[10] Lightstead, A., “What is a Pick and Place Robot and How Does it Work?” https://www.pwrpack.com/what-is-a-pick-and-place-robot/ (accessed Aug. 05, 2022).

[11] “Description of the robot movement”, Accessed: Aug. 05, 2022. [Online]. Available: https://www.li.rs/en/robotics/robot-controllers-and-industrial-robot-language/l-irl-and-ide/description-of-the-robot-movement

[12] Ahmed, F., Robinson, S., and Tako, A. A., “Using the structred analysis and design technique (SADT) in simulation conceptual modeling,” in *Proceedings - Winter Simulation Conference*, Jan. 2015, vol. 2015-January, pp. 1038–1049. doi: 10.1109/WSC.2014.7019963.

[13] "ISO/TS 15066 Explained," May 25, 2016. https://www.automate.org/tech-papers/iso-ts-15066-explained (accessed Aug. 27, 2022).

[14] "About RoboDK - Team." https://robodk.com/about (accessed Jul. 30, 2022).

[15] "Friction coefficients between different wheel/tire materials and concrete", Accessed: Aug. 13, 2022. [Online]. Available: https://mae.ufl.edu/designlab/Class%20Projects/Background%20Information/Friction%20coefficients.htm

[16] "SAFETY GUIDE ISO 13857-SAFETY DISTANCE FOR MACHINE GUARDS."

[17] "Pushing & Pulling - Handcarts." https://www.ccohs.ca/oshanswers/ergonomics/push2.html (accessed Jul. 31, 2022).

[18] Dias, L. M. S., Vieira, A. A. C., Pereira, G. A. B., and Oliveira, J. A., "DISCRETE SIMULATION SOFTWARE RANKING-a Top list of the Worldwide most Popular and Used Tools." [Online]. Available: http://www.dps.uminho.pt<Phone:+351253604764/+351934774014Fax:+351253604741

[19] "Arena Simulation Software." https://www.rockwellautomation.com/en-us/products/software/arena-simulation.html (accessed Jul. 25, 2022).

2022

Filipe Vieira

PROPOSAL OF A MATERIAL HANDLING SYSTEM DESIGN METHODOLOGY
– AN INDUSTRIAL APPLICATION ON A PACKAGING AND DEPALLETIZING SYSTEM

NOVA SCHOOL OF SCIENCE & TECHNOLOGY