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Simulation and Mechanical Automation of the Minced Meat Packaging Process

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ABSTRACT

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This bachelor’s thesis presents the design and evaluation of a semi-automated minced meat packaging line developed for Lallin Lammas Oy. The aim of the study was to create a system-level concept that combines tray feeding, robotic handling, filling, packaging, labelling, and safety integration into one coordinated production cell, and to assess whether the proposed design can achieve the required production target of 40 kg/h.

The work was carried out using Visual Components as the main engineering tool. The production line was modelled as a digital simulation in which empty trays are transferred by a robot to the main conveyor, filled with minced meat at a semi-automated filling station, sealed using a simplified ULMA TSB 300 tray sealer model, and labelled using a parametric labelling unit from the Visual Components library. The filling stage includes manual supervision of portion accuracy, while transport, packaging, and downstream handling are automated. The final concept also includes protective fencing, a defined robot operating zone, and emergency stop devices to represent the basic safety requirements of an industrial production cell.

A mathematical capacity analysis was performed using the selected cycle times and a target portion weight of 500 g per tray. The results show that the proposed line must process at least 80 trays per hour to achieve the required production target. Based on the selected process times, the packaging stage is the limiting stage, but the theoretical line capacity was calculated as 360 kg/h, which is substantially higher than the required 40 kg/h.

The study concludes that the proposed packaging line is technically feasible as a concept and suitable for simulation-based engineering evaluation. Although the model is simplified and does not include detailed electrical design, full PLC implementation, or validated safety control, it provides a realistic basis for analysing production flow, machine interaction, and future development of the system.

Keywords: food packaging automation, production line simulation, Visual Components, tray sealing, conveyor systems, industrial automation

CONTENTS

1 INTRODUCTION

1.1 Background and Industrial Context

Food processing is an important part of modern manufacturing, where safe, consistent, and traceable production is required. In meat processing, packaging operations must satisfy hygienic requirements while maintaining product quality, portion consistency, and efficient material flow (Fellows, 2017; Lawrie and Ledward, 2014).

Minced meat packaging typically includes several linked stages, such as tray feeding, product filling, sealing, and labelling. Because these stages operate in sequence, the performance of the entire line depends on their coordination. If one stage is not properly matched with the others, the result may be unstable flow, product accumulation, idle time, or reduced output (Robertson, 2016; Groover, 2019).

For this reason, automation is increasingly used in food packaging. Conveyor systems, sealing machines, sensors, and handling devices can be integrated into a single production line to improve consistency and reduce manual work. However, before such a line is implemented, its operating logic and production capacity should be evaluated systematically (Robertson, 2016; Fellows, 2017).

1.2 Role of Digital Simulation in Industrial Automation

Digital simulation provides a practical method for analysing automated production lines before physical implementation. By creating a virtual model of the system, engineers can study how conveyors, machines, sensors, and handling devices interact under defined conditions. Parameters such as conveyor speed, cycle time, and process order can be tested without modifying real equipment (Banks et al., 2010).

In automation projects, simulation is especially valuable for identifying bottlenecks, evaluating material flow, and estimating whether the proposed system can achieve the required production rate. In this thesis, Visual Components is used as the main engineering tool to analyse the operation of an automated minced meat packaging line (Banks et al., 2010; Groover, 2019; Visual Components, 2026a).

1.3 Problem statement

Smaller food production environments often rely on semi-automated packaging processes in which manual work is still needed at critical stages. Although such systems may be flexible, they can also limit throughput and reduce process consistency. In minced meat packaging, the main challenge is to coordinate filling, sealing, transport, and labelling in a way that maintains stable product flow (Robertson, 2016; Fellows, 2017).
If these stages are not properly synchronized, the line may experience interruptions, tray accumulation, or underutilization of equipment. The engineering problem addressed in this thesis is therefore whether a proposed automated packaging line can maintain stable operation while achieving the target production capacity of 40 kg/h (Groover, 2019; Banks et al., 2010).

1.4 Aim of the Thesis

The aim of this thesis is to develop and analyse a concept for an automated packaging line designed for minced meat products. The study focuses on evaluating the mechanical coordination, operational stability, and production capacity of the proposed system through digital simulation. By modelling the production line in a simulation environment, the research investigates whether the designed system can achieve the required throughput while maintaining efficient interaction between portioning, packaging, transportation, and labelling processes.

1.5 Objectives

To achieve the aim of the study, the following objectives are defined:

- Analyse the operational requirements of an automated minced meat packaging process
- Design a conceptual layout for the proposed packaging line
- Assess whether the system meets the required throughput of 40 kg/h
- Develop a digital simulation model of the system using Visual Components software
- Evaluate the interaction between different processing stages
- Analyse cycle times and overall production capacity
- Identify possible bottlenecks within the production system

1.6 Scopes and Limitations

This thesis is limited to the conceptual design and simulation-based analysis of an automated minced meat packaging line. The work focuses on system-level behaviour, including layout, process sequence, conveyor coordination, and production flow.

The study does not include:

- detailed mechanical design of individual machines
- full electrical design or PLC implementation
- economic analysis or industrial commissioning
- failure modelling, maintenance interruptions, or raw material variability
- detailed weighing control or validated food-process dosing systems

The simulation model is therefore intended as an engineering tool for evaluating production logic and throughput rather than as a complete industrial implementation model.

2 THEORETICAL BACKGROUND

2.1 Food packaging automation

Food packaging automation refers to the use of mechanical equipment and control systems to perform packaging operations with limited manual involvement. In industrial food production, automation is used to increase throughput, improve repeatability, and reduce process variation (Robertson, 2016; Fellows, 2017).

In automated packaging lines, different machines perform specific tasks in sequence. Typical functions include tray handling, product filling, sealing, labelling, and product transfer between stations. Conveyor systems are commonly used to connect these stages and maintain controlled product flow.

Automation is especially important in food production because it supports both productivity and hygiene. Reduced manual handling lowers the risk of contamination, while controlled machine operation helps maintain consistent packaging quality (Fellows, 2017). In addition, automated systems often use sensors, timing functions, and control signals to coordinate operations and improve overall process reliability.

From an engineering perspective, packaging automation is not only a question of machine selection, but also of system integration. The performance of the full line depends on how well the machines, conveyors, and control logic operate together.

2.2 Packaging technologies for meat products

Meat products are commonly packed using tray-based packaging systems in which the product is placed into a preformed tray and then sealed with a plastic film. This method is widely used because it provides product protection, supports retail presentation, and can be integrated into automated production lines (Robertson, 2016).

One important packaging method for fresh meat is tray sealing. In this process, film is applied to the tray flange using heat and pressure to form a closed package. Tray sealing equipment is widely used in industrial meat packaging because it enables repeatable package formation and supports conveyor-based processing.

Another important method is modified atmosphere packaging (MAP). In MAP systems, the air inside the tray is replaced with a controlled gas mixture, typically including carbon dioxide and nitrogen. This slows product deterioration and helps extend shelf life while maintaining the visual quality of fresh meat products (Lawrie and Ledward, 2014).

Packaging systems for meat processing must also satisfy hygienic design requirements. Machine surfaces must be easy to clean, and construction materials must be suitable for food-contact environments. Stainless steel is commonly used because it provides corrosion resistance and supports washdown cleaning procedures. For this reason, packaging technology in meat production must be evaluated not only by productivity, but also by hygienic suitability and integration into controlled processing environments.

2.3 Simulation in manufacturing

Simulation is widely used in manufacturing engineering to evaluate production systems before physical implementation. It is especially useful in systems where multiple machines interact through shared product flow, transport logic, and cycle timing (Banks et al., 2010; Groover, 2019).

A digital simulation model allows engineers to represent conveyors, machines, sensors, and process sequences in a virtual environment. This makes it possible to observe system behaviour under controlled conditions and to test changes without interrupting real production. Parameters such as conveyor speed, machine cycle time, and product sequence can be modified and compared efficiently (Banks et al., 2010).

One of the main engineering benefits of simulation is bottleneck identification. If one station operates more slowly than the others, upstream accumulation and downstream idle time may occur. Simulation makes such behaviour visible before the system is physically built. It can therefore support layout development, capacity estimation, and process optimization.

In automation projects, simulation tools such as Visual Components are useful because they combine three-dimensional visualization with process logic and product flow modelling. This allows both mechanical layout and operational coordination to be evaluated within the same model (Visual Components, 2026a). In the context of this thesis, simulation is used to study the interaction between the main stages of the minced meat packaging line and to estimate whether the proposed concept can achieve the required production rate.

2.4 Mechanical automation principles

Mechanical automation systems are based on coordinated movement of machines, materials, and handling devices. In packaging applications, conveyors are typically used to transport products between stations while maintaining stable spacing and defined movement direction.

Sensors are used to detect product position and to trigger machine actions at the correct moment. For example, a sensor can detect tray arrival at a filling or handling position and initiate a stop, release, or process sequence. In this way, product movement and machine operation are linked through signal-based control.

Another important principle is cycle time. Each station requires a certain amount of time to complete its function. If station cycle times are not properly matched, the result may be unstable flow, machine waiting time, or product accumulation. For this reason, synchronization between process stages is one of the key engineering requirements in automated production lines (Groover, 2019).

In practice, efficient mechanical automation depends on three main factors: controlled transport, reliable detection, and coordinated timing. These principles are directly relevant to the system developed in this thesis, where tray handling, filling, sealing, and labelling must operate as one integrated sequence.

3 SYSTEM DESIGN

3.1 Design of the Feeding and Handling Section

The first stage of the proposed system focuses on the design of the feeding and handling section, which is responsible for introducing empty trays into the production line and positioning them for further processing. This part of the system plays a critical role in establishing a stable and continuous material flow, as all subsequent operations depend on accurate tray positioning and synchronized movement.

In this study, the feeding and handling section integrates several key components, including the tray design, material feeding method, conveyor system, detection sensors, and robotic handling unit. These elements must operate in coordination to ensure reliable transfer of trays from the initial input stage to the filling position.

This section describes the design decisions and technical configuration of each component, as well as the control logic used to synchronize their operation within the simulation environment.

3.1.1 Tray Design and Packaging Specifications

The packaging container used in the simulation represents a standard rPET tray designed for minced meat products. The selected tray dimensions are based on commonly used formats in industrial tray sealing systems and are compatible with equipment provided by ULMA Packaging. The tray dimensions are defined as follows:

- Length: 295 mm
- Width: 233 mm
- Depth: 45 mm
- Material: rPET (recycled polyethylene terephthalate)

These dimensions correspond to standard MAP (Modified Atmosphere Packaging) trays used in meat packaging applications. The geometry provides sufficient volume for portioned minced meat while maintaining compatibility with sealing machines.

The tray design includes structural ribs and rounded edges, which improve mechanical rigidity and ensure stable handling during automated transport. The upper flange is designed to support sealing film application, which is a critical requirement for tray sealing processes.

From a system design perspective, the use of a standardized tray simplifies automation, as all handling operations can be optimized for a single geometry.

This reduces complexity in robot programming and ensures consistent positioning during filling and sealing stages.

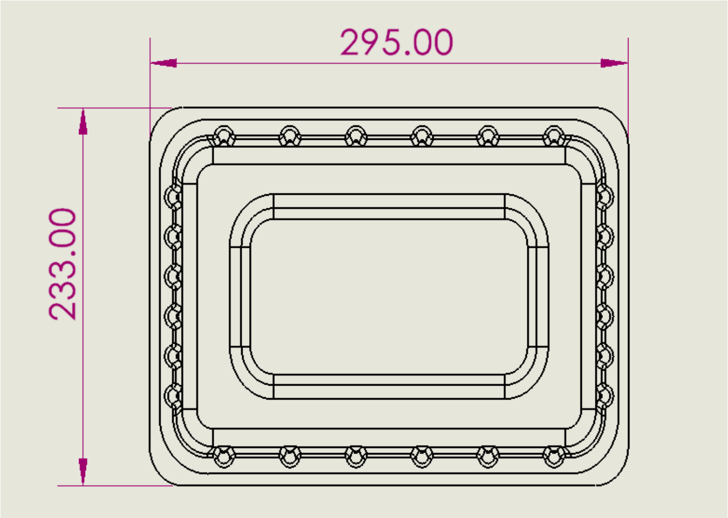


Figure 1. Dimensions of the rPET tray used in the simulation

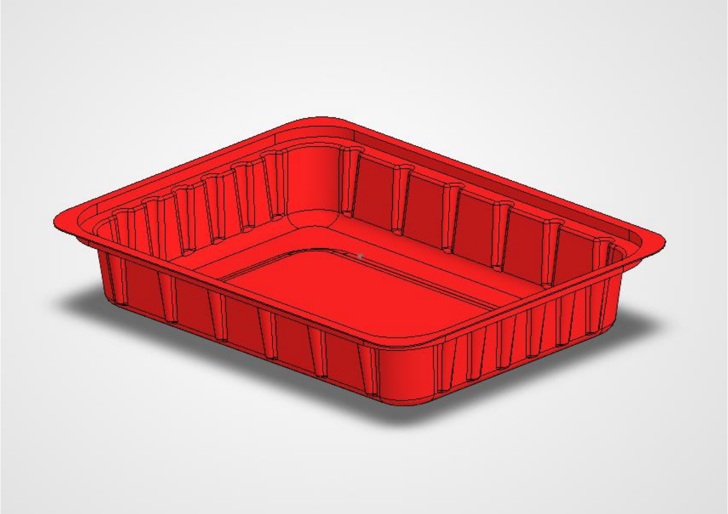


Figure 2. Three-dimensional model of the packaging tray

3.1.2 Material Feeding Concept

The initial stage of the system design focuses on the introduction of empty trays into the production line. In the current simulation model, a feeder component is used to generate trays at a controlled rate. This approach allows simplified representation of the upstream logistics without modelling the entire warehouse system.

From an industrial perspective, the feeder represents a conceptual interface between the packaging line and the storage or production area. In a real implementation, this position would typically be occupied by an automated conveyor system or a buffer unit transporting trays from a storage location or thermoforming machine.

The use of a feeder in the simulation enables controlled testing of system behaviour while maintaining model simplicity. This abstraction is appropriate within the scope of this study, as the primary focus is on the synchronization of downstream processes rather than upstream logistics.

3.1.3 Conveyor System Design

The transport of trays between process stages is performed using a belt conveyor system modelled in Visual Components. A parametric conveyor component was selected and configured according to the required operational conditions.

The main conveyor parameters are defined as follows:

- Length: 1000 mm
- Width: 400 mm
- Height: 700 mm
- Transport speed: 200 mm/s

These values were selected to ensure stable tray movement and sufficient spacing between consecutive items. The conveyor width allows safe transportation of the selected tray geometry, while the speed is chosen to balance throughput and process timing.

The conveyor operates as the primary transport mechanism within the system and plays a key role in maintaining continuous material flow between the feeding, handling, and filling stages.

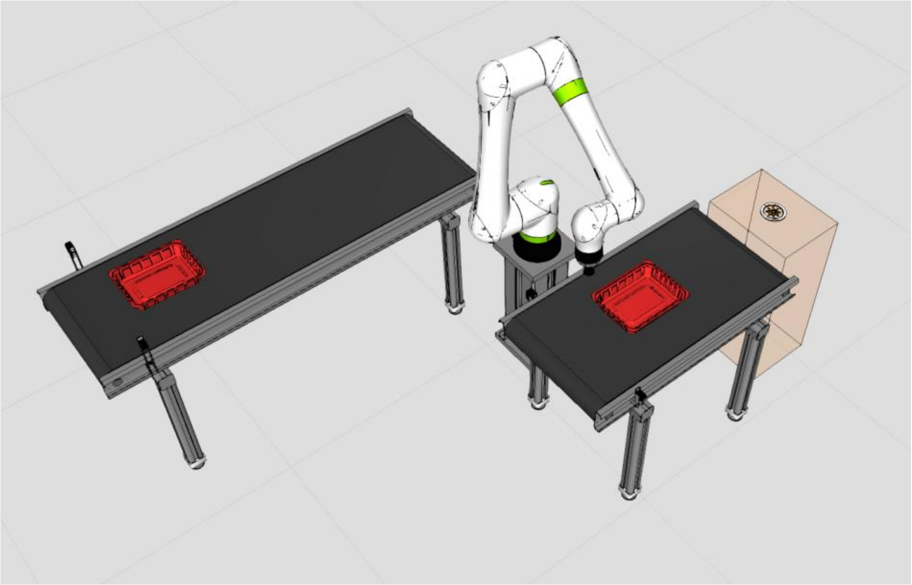


Figure 3. Overview of the feeding and handling section showing feeder, trays, conveyor system, robot and sensors

3.1.4 Tray Detection and Sensor Integration

To ensure reliable synchronization between tray transport and robotic handling, a conveyor-mounted sensor was installed near the tray pick position. The purpose of this sensor is to detect the presence of a tray at the required location and to generate a digital signal for the control system.

The sensor uses the SensorBooleanSignal output as the main tray detection signal. This signal changes state when a tray enters the sensor detection zone. In the developed system, the SensorBooleanSignal is connected directly to the robot controller input:

- SensorBooleanSignal → Robot input IN[21]

As a result, when a tray reaches the sensor position, the robot receives a logical input indicating that the tray is available for handling. The robot main program continuously monitors this signal and only starts the handling routine when IN[21] = True. This approach ensures that the robot does not execute the pick-and-place sequence unless the tray is correctly positioned. In addition to tray detection, the conveyor motion is also coordinated through signal-based control. The conveyor PowerOnSignal is connected to the robot output:

- Robot output OUT[20] → Conveyor PowerOnSignal

This signal arrangement allows the robot program to restart the conveyor after the tray has been handled. In practice, the tray is detected by the sensor, the robot executes the handling sequence, and after completion the program sends an output signal to resume conveyor operation.

The use of Boolean sensor and output signals provides a simple but effective control structure. It reflects common industrial automation practice, where sensors provide binary status information and machine operations are synchronized through digital inputs and outputs.

This signal configuration forms the basis of the handling logic implemented in the simulation model. The sensor provides the trigger for robot execution, while the conveyor restart signal ensures that the material flow can continue after the handling cycle has been completed. The implemented signal architecture is illustrated in Figure 4. The defined signal structure provides the basis for the robot control logic, which is described in the following section.

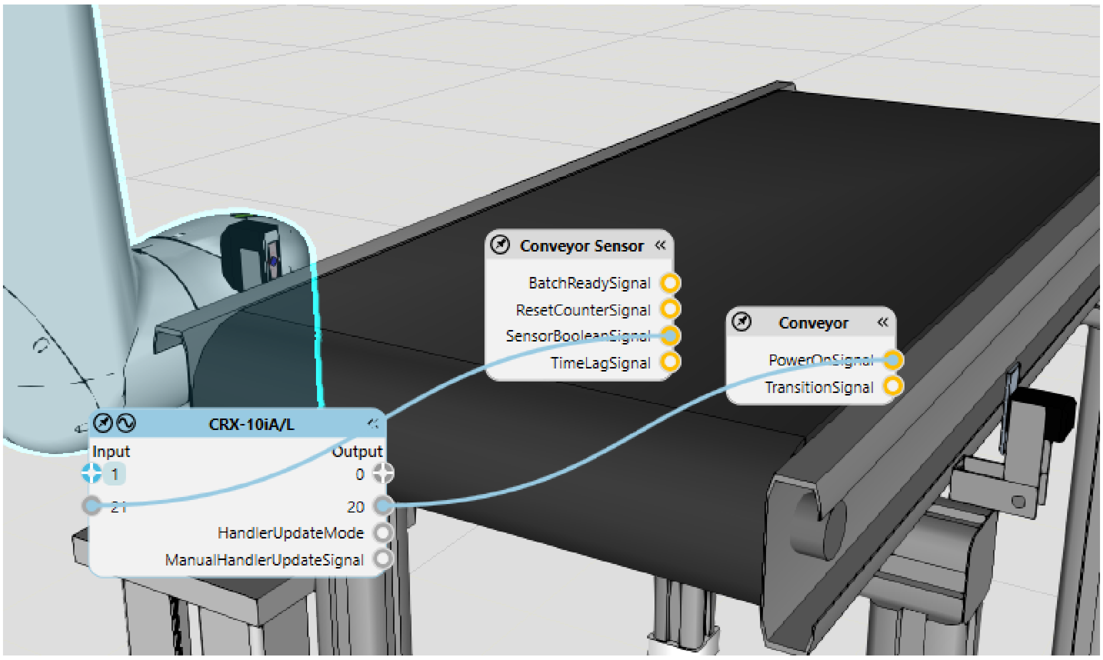


Figure 4. Signal connections between the conveyor sensor, robot controller, and conveyor drive

3.1.5 Industrial Robot Selection

The tray handling operation within the feeding and handling section is performed using a FANUC CRX-10iA/L collaborative robot (FANUC, 2026a; FANUC, 2026b). The selection of this robot was based on technical suitability, operational flexibility, and compatibility with food-related production environments. Key technical characteristics:

- Payload capacity: 10 kg
- Reach: 1418 mm
- Repeatability: ±0.05 mm
- Collaborative operation capability
- Food-grade design suitable for hygienic environments

The robot provides sufficient payload capacity for handling empty trays and offers adequate reach to operate between the feeder conveyor and the main transport conveyor. Repeatability is an important parameter in packaging automation, as precise positioning is required to ensure correct tray placement on the conveyor. The specified repeatability of ±0.05 mm enables consistent handling performance and minimizes the risk of misalignment, which could affect downstream processes such as filling and sealing.

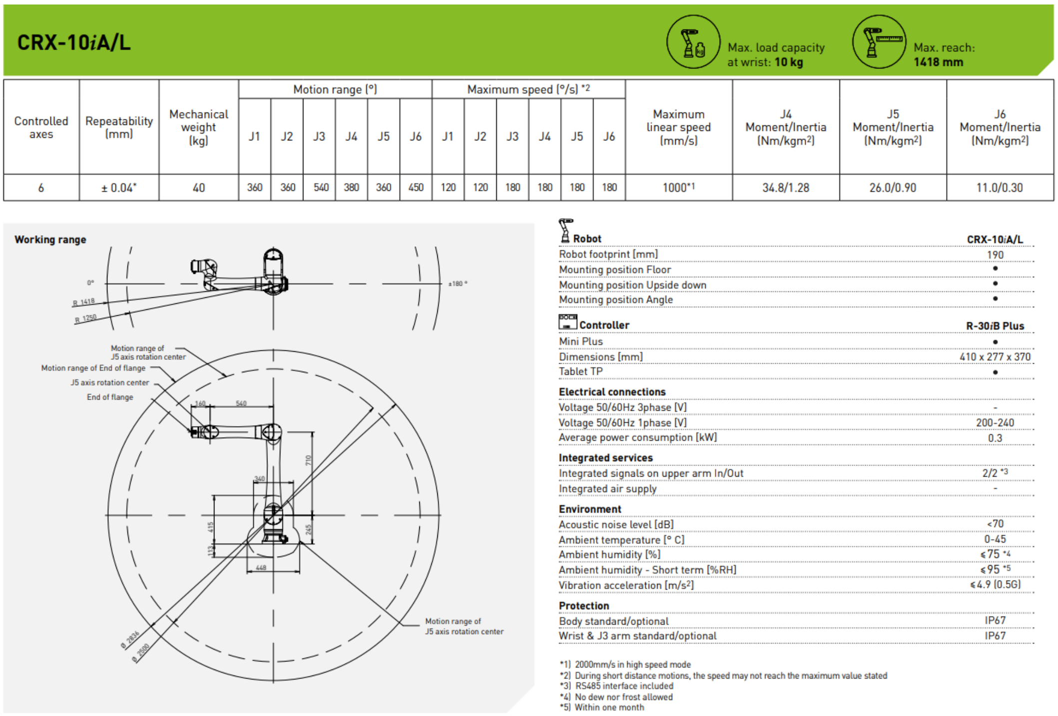
The collaborative design of the CRX-10iA/L provides additional advantages in terms of system integration. Collaborative robots are designed to operate safely in proximity to other equipment and, if required, human operators. Although direct human interaction is not modelled in this simulation, the use of a collaborative robot reflects modern industrial trends toward flexible and adaptable automation systems.

Another important factor influencing the selection is the suitability of the robot for food-related applications. The CRX series is designed with smooth, easy-to-clean surfaces and materials that support hygienic operation. This is particularly relevant in meat processing environments, where equipment must comply with strict sanitation requirements (FANUC, 2026b).

From a control perspective, the robot supports integration with external signals (FANUC, 2026c), allowing it to communicate with sensors and conveyor systems. This capability enables the implementation of a signal-based control architecture, where the robot responds to tray detection signals and coordinates its operation with conveyor movement.

Overall, the selected robot provides an appropriate balance between performance, flexibility, and compatibility with the requirements of the packaging system. Its technical characteristics and design features make it well suited for the handling tasks defined in this study.

Figure 5. FANUC CRX-10iA/L collaborative robot used for tray handling operations (Source: FANUC, 2026a).



CRX-10*i*A/L

Max. load capacity at wrist: **10 kg**

Max. reach: **1418 mm**

Controlled axes	Repeatability (mm)	Mechanical weight (kg)	Motion range (°)						Maximum speed (°/s) *2						Maximum linear speed (mm/s)	J4 Moment/Inertia (Nm/kgm²)	J5 Moment/Inertia (Nm/kgm²)	J6 Moment/Inertia (Nm/kgm²)
			J1	J2	J3	J4	J5	J6	J1	J2	J3	J4	J5	J6				
6	± 0.04*	40	360	360	540	380	360	450	120	120	180	180	180	180	1000*1	34.8/1.28	26.0/0.90	11.0/0.30

Working range

Robot	**CRX-10*i*A/L**
Robot footprint [mm]	190
Mounting position Floor	●
Mounting position Upside down	●
Mounting position Angle	●
Controller	**R-30*i*B Plus**
Mini Plus	●
Dimensions [mm]	410 x 277 x 370
Tablet TP	●
Electrical connections	
Voltage 50/60Hz 3phase [V]	-
Voltage 50/60Hz 1phase [V]	200-240
Average power consumption [kW]	0.3
Integrated services	
Integrated signals on upper arm In/Out	2/2 *3
Integrated air supply	-
Environment	
Acoustic noise level [dB]	<70
Ambient temperature [° C]	0-45
Ambient humidity [%]	≤75 *4
Ambient humidity - Short term [%RH]	≤95 *5
Vibration acceleration [m/s²]	≤4.9 (0.5G)
Protection	
Body standard/optional	IP67
Wrist & J3 arm standard/optional	IP67

*1) 2000mm/s in high speed mode
*2) During short distance motions, the speed may not reach the maximum value stated
*3) RS485 interface included
*4) No dew nor frost allowed
*5) Within one month

Figure 6. Technical specifications of FANUC CRX-10iA/L collaborative robot (Source: FANUC, 2026a)

3.1.6 End Effector Design and Selection

The robot is equipped with a suction cup end-effector used for handling trays. The suction cup operates using a vacuum gripping principle, allowing secure attachment to the tray surface during pick-and-place operations. During release, the control valve introduces compressed air into the system, creating a short blow-off pulse that ensures reliable separation of the tray from the suction surface. The gripper consists of a single vacuum cup with the following parameters:

- Cup diameter: 40 mm
- Cup height: 50 mm

The use of a vacuum-based gripping method is appropriate for this application due to the flat surface of the trays and their low weight. The suction cup provides reliable handling while minimizing mechanical complexity. A single-cup configuration was selected to simplify the model and reduce computational complexity in the simulation. In industrial applications, multi-cup configurations may be used for increased stability; however, for the purposes of this study, the single-cup design is sufficient.

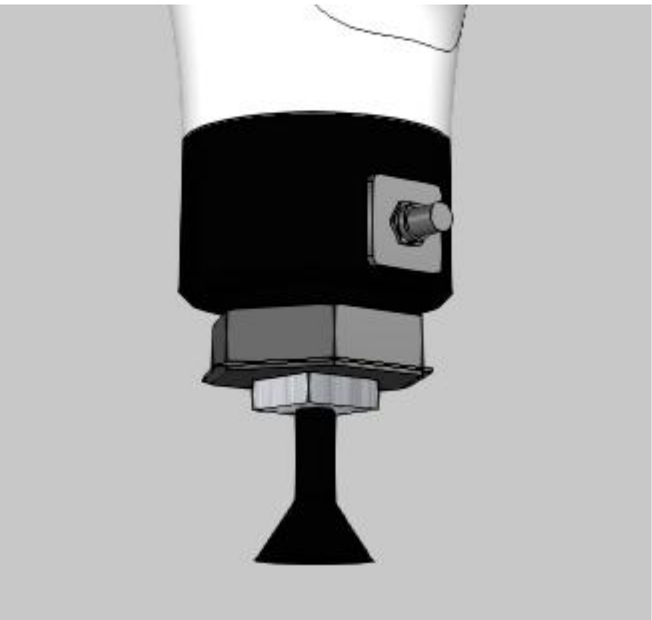


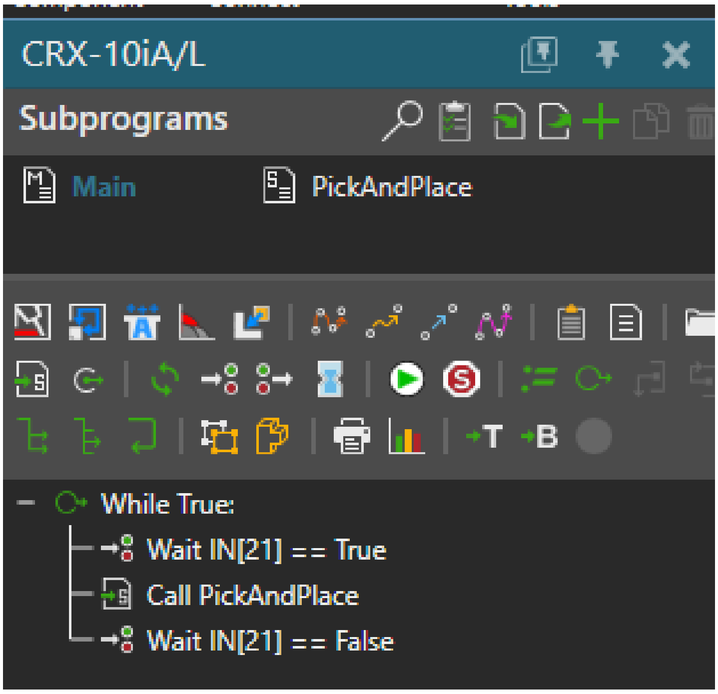
Figure 7. Vacuum suction cup gripper used for picking and placing trays

3.1.7 Robot Control Logic

The operation of the robot is controlled through a structured program consisting of a main execution loop and a dedicated subprogram for the pick-and-place task. This structure improves readability, modularity, and ease of modification within the simulation environment.

The main program operates as a continuous loop that monitors the input signal received from the conveyor sensor. When a tray is detected at the pick position, the program initiates the handling sequence by calling the pick-and-place subprogram. After the operation is completed, the program waits for the sensor signal to reset before starting a new cycle. This prevents repeated execution of the handling routine for the same tray.

This control approach ensures that the robot operates only when required and maintains synchronization with the material flow on the conveyor.



```
While True:
    Wait IN[21] == True
    Call PickAndPlace
    Wait IN[21] == False
```

Figure 8. Main robot program controlling execution based on tray detection signal

3.1.8 Pick-and-Place Sequence Description

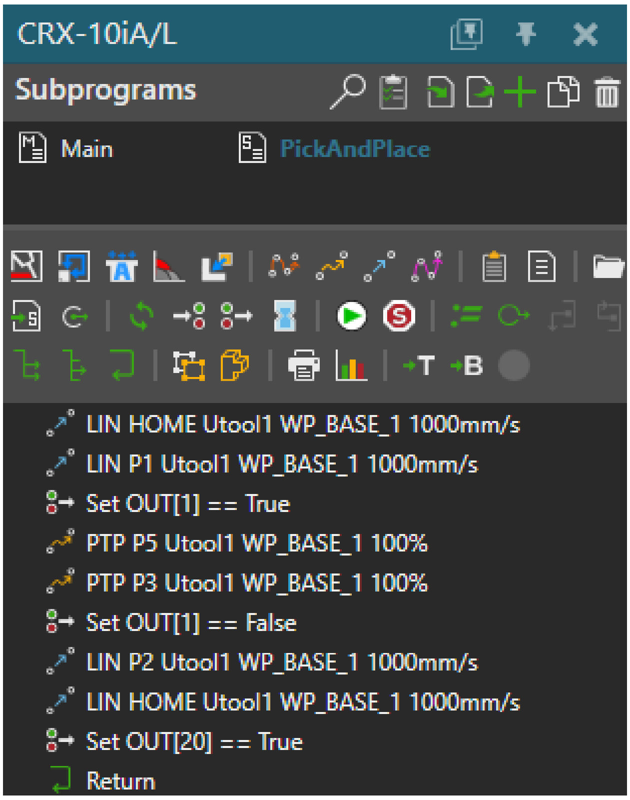
The pick-and-place operation is implemented as a separate subprogram, which defines the sequence of robot movements and gripper actions required to transfer the tray from the feeder conveyor to the main conveyor.

The motion sequence consists of both linear (LIN) and point-to-point (PTP) movements. Linear motions are used when the robot interacts directly with the tray, ensuring controlled vertical movement and minimizing the risk of collision. Point-to-point movements are used for faster positioning when the robot is moving between locations without interacting with objects.

The operation can be described as follows:

1. The robot moves from the home position to a predefined approach position above the tray using a point-to-point (PTP) motion
2. A linear (LIN) motion is executed to move the end effector vertically toward the pick position
3. The vacuum gripper is activated (OUT[1] = TRUE) to establish contact and secure the tray
4. The robot performs a linear lifting motion to a predefined safe height to avoid collisions
5. A point-to-point (PTP) motion is executed to transfer the tray to the placement position above the main conveyor
6. The robot descends using a linear (LIN) motion and deactivates the gripper (OUT[1] = FALSE) to release the tray
7. The robot returns to the home position using a point-to-point (PTP) motion, completing the handling cycle

At the end of the sequence, the robot sends a signal to resume conveyor movement, allowing the next tray to enter the handling area. The detailed signal interaction is described in Section 3.1.4. This modular structure allows the handling sequence to be modified independently from the main control logic and supports further expansion of the system. Sequence ensures repeatable handling and minimizes positional deviation during tray transfer.



```
LIN HOME Utool1 WP_BASE_1 1000mm/s
LIN P1 Utool1 WP_BASE_1 1000mm/s
Set OUT[1] == True
PTP P5 Utool1 WP_BASE_1 100%
PTP P3 Utool1 WP_BASE_1 100%
Set OUT[1] == False
LIN P2 Utool1 WP_BASE_1 1000mm/s
LIN HOME Utool1 WP_BASE_1 1000mm/s
Set OUT[20] == True
Return
```

Figure 9. Pick-and-place subprogram defining robot motion sequence and gripper control

3.1.9 Tool Coordinate System and TCP Definition

Accurate positioning of the robot end effector is essential for reliable handling of trays. For this reason, a Tool Center Point (TCP) was defined at the functional contact point of the gripper. The TCP represents the reference point used by the robot controller to execute motion commands. In this system, the TCP was positioned at the center of the suction cup, which corresponds to the physical location where the robot interacts with the tray.

This configuration ensures that all programmed movements are calculated relative to the actual gripping point. As a result, the robot can approach, pick, and place trays with high positional accuracy. The TCP was defined by adjusting the tool coordinate system parameters within the robot controller. This process involves setting the correct spatial offset between the robot flange and the active gripping point.

By aligning the TCP with the suction cup tip, the following advantages are achieved:

- improved positioning accuracy during pick-and-place operations
- reduced risk of collision with the conveyor surface
- consistent vertical approach when engaging the tray
- simplified programming of motion paths

This approach reflects standard industrial practice in robotic automation, where the TCP is always defined at the point of interaction between the tool and the workpiece.

3.2 Design of the Filling and Portioning Station

The filling and portioning section is responsible for controlled transfer of minced meat into trays before downstream processing. The system consists of a mincer unit, discharge pipe, dedicated conveyor segment, and signal-based control logic implemented within the simulation environment.

The conveyor in this section operates in an intermittent mode. A tray is detected at the filling position using a sensor signal, which initiates the control sequence. Upon detection, the conveyor is stopped to allow the filling process to occur. After a predefined delay representing the filling operation, the conveyor is restarted to transport the filled tray to the next stage.

The control logic is implemented using a loop-based Python script with Boolean signal mapping. A processing state variable is used to prevent repeated triggering while the tray remains in the sensor detection zone. This ensures that each tray is processed only once per cycle and maintains stable system operation.

The filling process in the simulation model is implemented using a time-based control approach rather than a weighing system. This decision was made to maintain focus on system-level behaviour and interaction between production stages. The objective of the simulation is to analyse material flow, process synchronization, and conveyor coordination, rather than to model detailed physical properties of the product.

A weighing system was not included in the model because it would introduce additional complexity without significantly improving the evaluation of overall system performance. In real industrial applications, weighing systems require load cells, feedback control loops, and calibration procedures. These elements are important for precise portion control but are not essential for analysing production flow and timing relationships within a conceptual simulation model.
Time-based control is considered acceptable in this context because it provides a simplified and stable representation of the filling process. By assigning a fixed processing time to each tray, the model ensures consistent operation and allows clear analysis of cycle times and system throughput.

In a real industrial system, the filling process would be controlled using a mass-based approach. Load cells or weighing platforms would measure the product quantity in real time, and the filling operation would be adjusted dynamically to achieve the required portion weight. This would involve closed-loop control, where sensor feedback continuously regulates the filling process. Additionally, variability in raw material properties, machine response time, and environmental conditions would need to be considered. These factors are not represented in the simulation but would play a critical role in a fully implemented production system.

A human operator is included in the model to represent supervision of the filling process and portion accuracy. In industrial practice, this role may involve quality control, system monitoring, and manual intervention if required. In the simulation, the operator serves as a visual and conceptual element rather than an active control component.

3.2.1 Filling Station Layout and Integration

The filling and portioning section is positioned downstream of the tray handling system and represents the stage where trays are filled with minced meat. The section consists of a mincer unit, a discharge pipe, a dedicated filling conveyor, and a human operator supervising the process.

As shown in Figure 10, trays are transported along the conveyor and positioned below the outlet pipe of the mincer. The filling conveyor is separated functionally from the upstream transport conveyors so that it can be controlled independently during the filling process. This arrangement allows the tray to remain stationary during portioning and then continue toward the next stage after filling has been completed.

A human operator is included in the layout to represent manual supervision of the portioning process. In practice, the operator ensures that the tray is correctly positioned and that the target filling amount of approximately 500 g is achieved. This reflects a realistic semi-automated production environment.

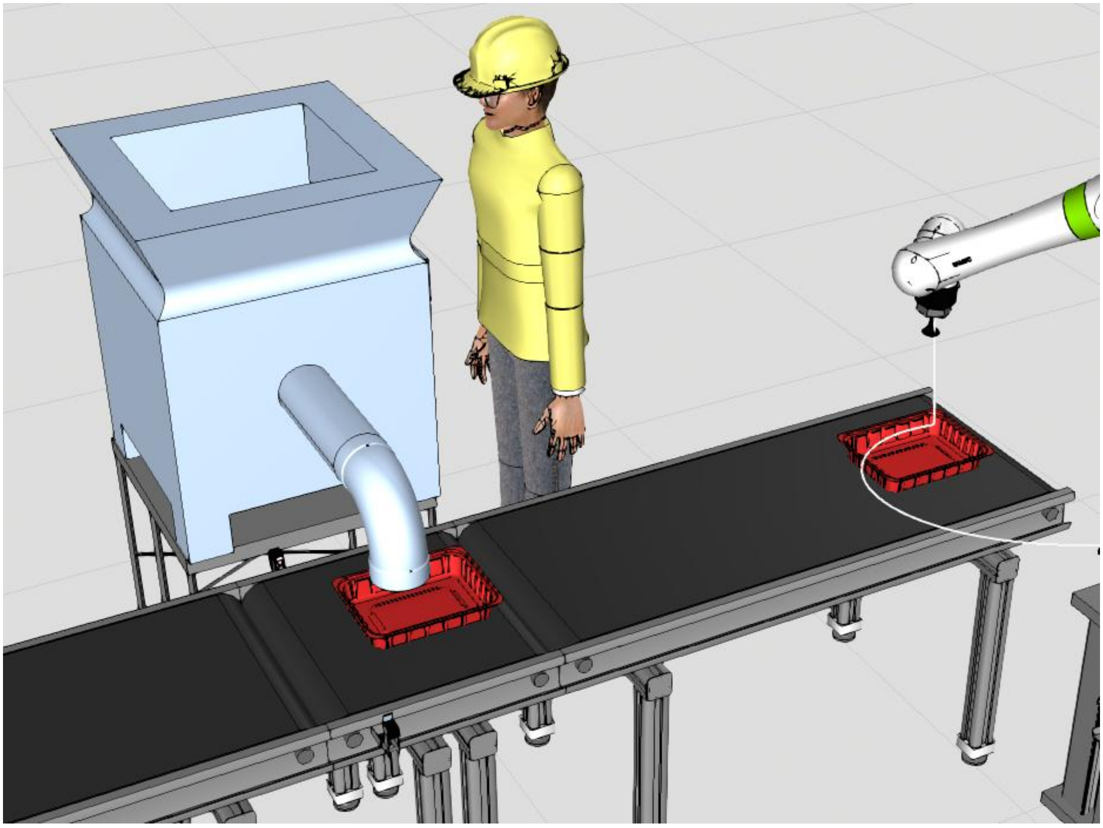


Figure 10. Filling station layout showing the mincer unit, filling conveyor, tray positioning, and operator supervision

3.2.2 Mincer Unit Design

The mincer unit in the simulation represents the machine responsible for dispensing minced meat into the trays. In the developed model, the mincer is implemented as a simplified mechanical structure consisting of a hopper, a main body, support legs, and a discharge pipe.

As illustrated in Figure 11, the hopper represents the loading section of the machine, while the discharge pipe defines the filling point above the conveyor. The pipe is oriented so that the tray can be positioned directly underneath it during the filling cycle.

The front side of the mincer model includes basic operator interface elements, such as start and stop buttons and an emergency stop button. Although these elements are not fully connected to functional control logic in the simulation, they were included to reflect typical industrial machine design and improve the realism of the model.

The mechanical geometry of the mincer was intentionally simplified so that the focus of the simulation remained on process flow, tray positioning, and conveyor control rather than on detailed machine internals.

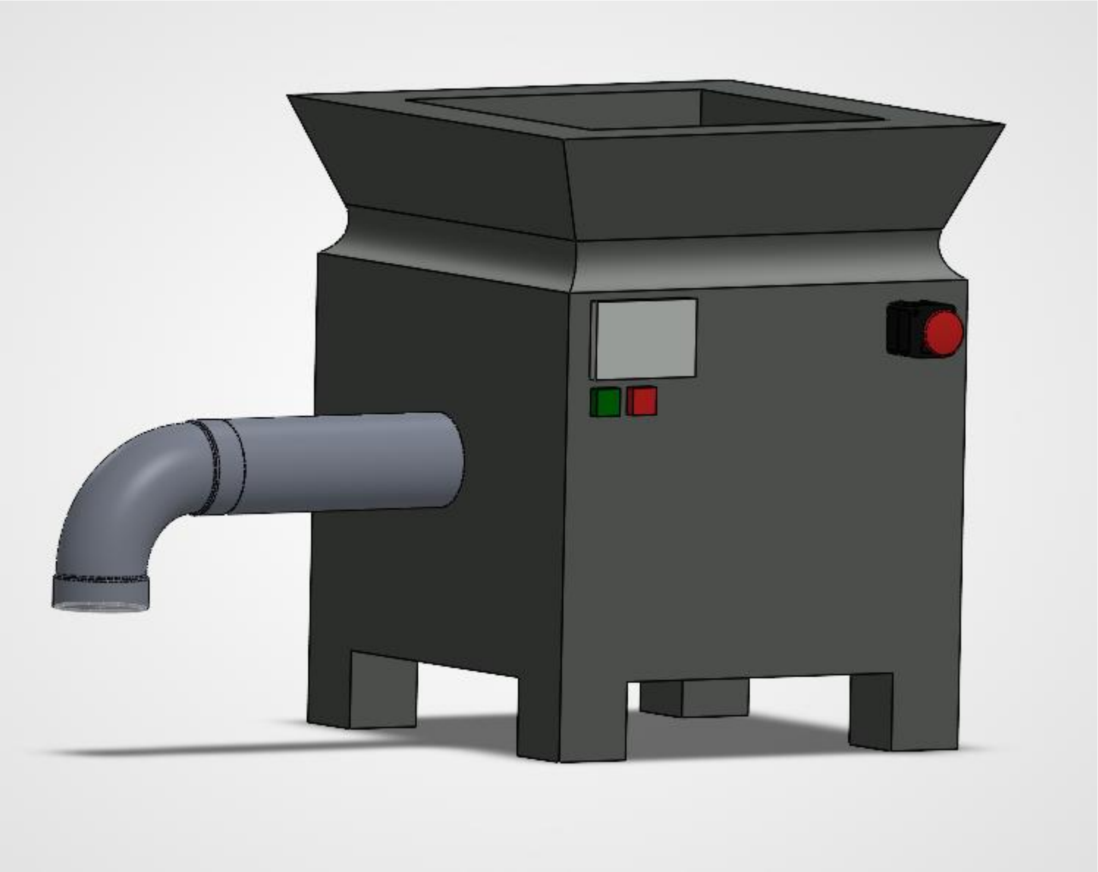


Figure 11. Simplified 3D model of the mincer unit used for tray filling in the simulation

3.2.3 Signal-Based Control Structure

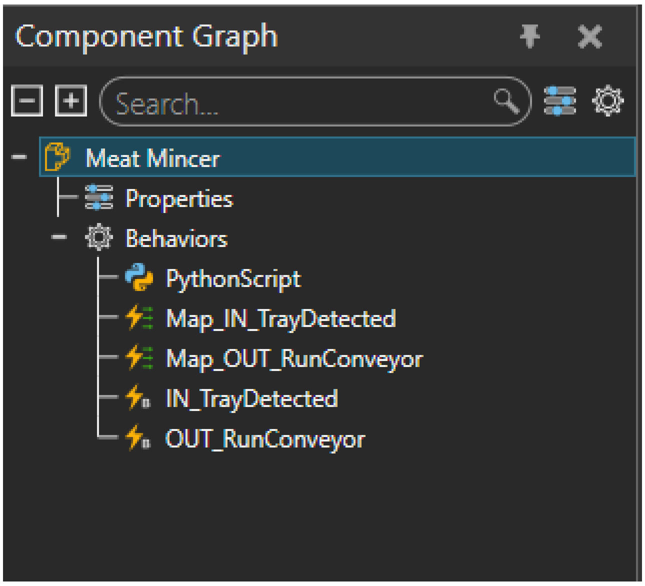


Figure 12. Internal structure of the mincer component showing signal behaviours and Python control script

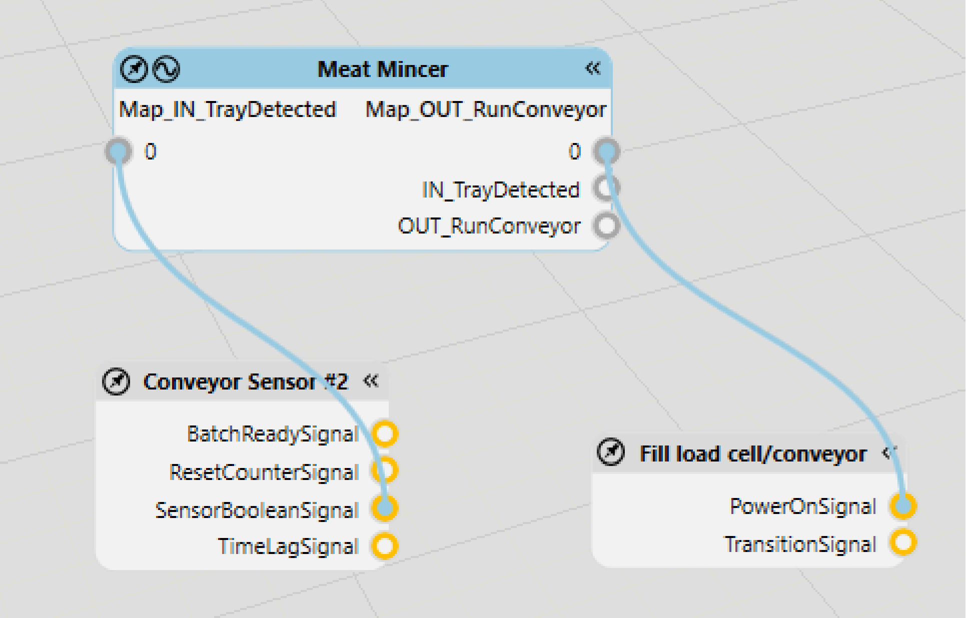


Figure 13. Signal connections between conveyor sensor, mincer control, and filling conveyor

The filling station was designed using a signal-based control structure. The purpose of this structure is to simulate a realistic automation architecture in which sensor signals are used to detect tray arrival and conveyor motion is controlled through an output signal.

As shown in Figure 12, the mincer component contains the following signal-related behaviours:

- IN_TrayDetected
- OUT_RunConveyor
- Map_IN_TrayDetected
- Map_OUT_RunConveyor
- PythonScript

The internal logic is based on Boolean signal mapping. The tray detection signal from the conveyor sensor is connected to the input map of the mincer, and the conveyor run command is transmitted from the output map of the mincer to the conveyor power signal. The external signal architecture is shown in Figure 13.

The implemented signal flow can be described as follows:

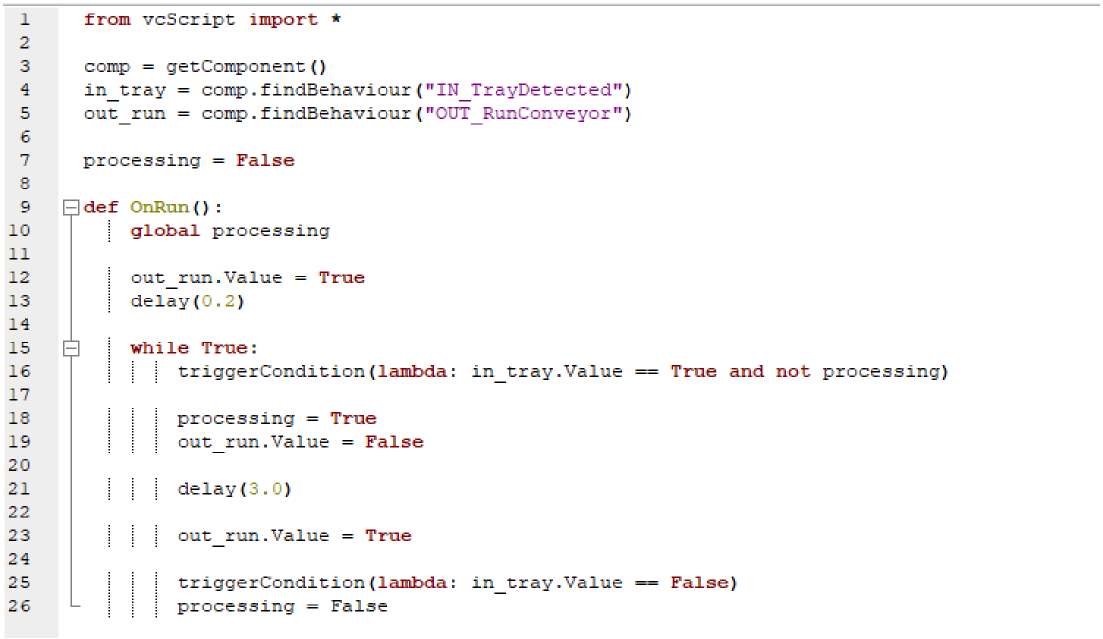
- SensorBooleanSignal → Map_IN_TrayDetected
- internal signal processing in the mincer Python script
- Map_OUT_RunConveyor → PowerOnSignal

This structure represents a closed control loop in which the sensor provides tray position feedback, the control script evaluates the signal state, and the conveyor is stopped and restarted accordingly.

3.2.4 Conveyor and Filling Logic

The conveyor at the filling station is controlled using a signal-based Python script. In this logic, the tray detection signal is monitored continuously. When a tray reaches the filling position, the conveyor is stopped, a delay is used to simulate the filling operation, and the conveyor is then restarted. After this, the system waits for the sensor signal to reset before allowing the next cycle. This approach creates a loop-controlled sequence and prevents the same tray from repeatedly triggering the filling logic.

The control principle is illustrated by the following Python logic:



```python
from vcScript import *

comp = getComponent()
in_tray = comp.findBehaviour("IN_TrayDetected")
out_run = comp.findBehaviour("OUT_RunConveyor")

processing = False

def OnRun():
    global processing

    out_run.Value = True
    delay(0.2)

    while True:
        triggerCondition(lambda: in_tray.Value == True and not processing)

        processing = True
        out_run.Value = False

        delay(3.0)

        out_run.Value = True

        triggerCondition(lambda: in_tray.Value == False)
        processing = False
```

Figure 14. Python script implementing signal-based loop control for tray detection and conveyor operation at the filling station

In this control logic, the conveyor is initially running. When the tray detection signal becomes active, the output signal stops the filling conveyor. A delay of three seconds simulates the filling time required to dispense the product into the tray. After this delay, the conveyor is restarted. The program then waits until the tray has left the sensor area before enabling the next operating cycle.

This loop-based method reflects a more realistic control strategy than a simple periodic stop-start sequence because the process depends on actual tray detection rather than a fixed repeating timer.

3.2.5 Filling Process Sequence

The filling operation follows a signal-triggered sequence:

1. A tray moves toward the filling station conveyor
2. The tray enters the sensor area
3. The sensor sends a Boolean detection signal to the mincer component
4. The mincer control logic stops the conveyor
5. The tray remains stationary below the discharge pipe
6. A three-second delay simulates the filling of minced meat
7. The conveyor is restarted
8. The tray leaves the sensor zone
9. The signal resets and the system becomes ready for the next tray

This sequence ensures that trays are processed individually and in a controlled order. It also prevents repeated actuation for the same tray by requiring the sensor signal to return to the inactive state before the next cycle begins.

3.2.6 Portion Control and Operator Role

In industrial filling systems, portion control is typically achieved using weighing systems, load cells, or dosing units that regulate the amount of product deposited into each package. The target portion in this study is approximately 500 g of minced meat per tray.

In the developed simulation, exact mass calculation is not implemented. Instead, the filling duration is represented by a fixed time delay. This simplification makes it possible to study the timing and control behaviour of the system without modelling a full weighing subsystem. To make the concept more realistic, a human operator is included next to the filling station. The operator represents manual supervision of the filling process and quality control of the final portion size. This is particularly relevant in semi-automated meat packaging environments where automation is supported by human inspection. This reflects semi-automated production environments where human supervision is required for quality assurance and process reliability.

3.2.7 Design Limitations

The filling station model is intended for system-level analysis and therefore includes several simplifications. The main limitations are as follows:

- the filling process is represented by a timed delay rather than real mass flow
- no physical load cell or weighing feedback is modelled
- the loop control uses Boolean tray detection rather than analogue measurement
- the control structure is simplified compared to a full industrial PLC-based implementation

Despite these limitations, the model captures the essential operational logic of the filling station. The signal-based loop control provides a realistic representation of how tray detection, conveyor stopping, and timed filling can be coordinated in an automated packaging line.

3.3 Design of the Packaging and Labelling Section

The packaging and labelling section is located downstream of the filling station and forms the final processing stage of the proposed production line before the packaged trays are transferred to the outfeed area. In this section, the product changes from an open filled tray into a sealed and identified retail package. From an engineering point of view, this stage is critical because it determines package integrity, product protection, and traceability, while also influencing the total cycle time of the line.

In the developed simulation model, the packaging stage is represented by a simplified ULMA TSB 300 tray sealer, while the labelling stage is implemented using a parametric machine model from the Visual Components library (Visual Components, 2026a). Both stages are integrated into the conveyor path and are represented using discrete process logic. This approach is consistent with the objective of the thesis, which is to evaluate production flow, machine interaction, and achievable throughput rather than to reproduce every internal mechanical detail of the real equipment.

3.3.1 Packaging Stage Layout and Integration

The packaging stage was positioned directly after the filling section so that each filled tray could be transferred without manual intermediate handling. This arrangement supports continuous product flow and reflects a realistic industrial layout in which the tray sealing machine is installed immediately after the filling operation. In the final simulation model, the ULMA packaging machine is connected to the downstream conveyor network through a curved conveyor arrangement, which allows the sealed trays to continue toward the labelling stage while maintaining a compact overall footprint. The machine model used in the simulation is a simplified geometric representation based on the ULMA TSB 300 tray sealer. The simplified form preserves the general external dimensions, tray entry direction, and tray discharge logic of the real machine while avoiding unnecessary detail in the internal mechanisms. This was considered appropriate because the main purpose of the model is to evaluate line behaviour and machine interaction, not to perform detailed internal machine design.

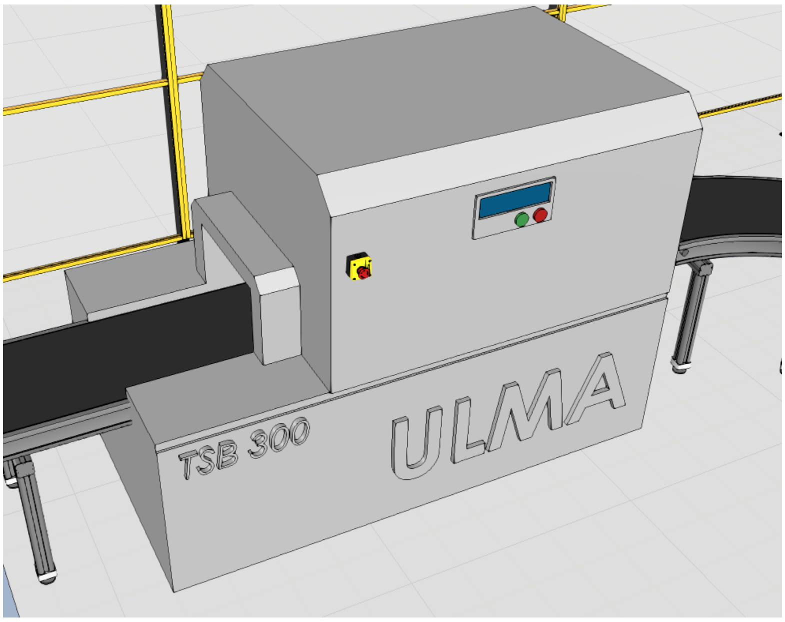


Figure 15. Simplified ULMA TSB 300 model integrated into the Visual Components packaging section

The physical position of the packaging machine within the line was selected so that the incoming tray remains aligned with the conveyor axis at the entry point and can be discharged directly to the downstream path after sealing. This arrangement reduces unnecessary transfer steps and helps preserve stable tray orientation after the filling stage.

3.3.2 ULMA Packaging Machine and Sealing Function

The ULMA TSB 300 was selected as the reference packaging machine for the sealing stage of the proposed production line (ULMA Packaging, 2026). In industrial use, this type of machine is designed for tray sealing applications in food production, where a filled tray is transferred into the sealing area, covered with film, and then discharged as a closed package. In meat processing environments, tray sealers of this category are widely used because they provide a controlled packaging process, compatibility with hygienic design requirements, and integration with conveyor-based production systems.

Figure 16. Reference image of the ULMA TSB 300 tray sealer used as the basis for the simulated packaging unit (Source: ULMA Packaging, 2026).

The main technical specifications considered in the engineering evaluation of the machine are presented in Figure 17 and are based on the manufacturer's published data (ULMA Packaging, 2026). The reference specifications of the ULMA TSB 300 are as follows:

- overall machine dimensions: **2700 × 1180 × 1700 mm**
- sealing area: **300 × 440 mm**
- maximum standard tray height: **80 mm**
- die lifting system: **pneumatic**
- tension control: **motorised**
- tray discharge: **belt-based exit**
- protection class: **IP65**
- compressed air consumption: **40 L/cycle at 6 bar**
- vacuum pump option: **up to 100 m³/h**
- nominal capacity for MAP packaging: **up to 22 packs/min**
- nominal capacity for skin packaging: **up to 12 packs/min**

Standard Technical Specifications

Dimensions L x W x H	2700 x 1180 x 1700mm	**MAP packs / min**	22/min
Sealing Area	300 x 440mm	**Skin on tray packs / min**	12/min
Compressed Air	40L / Cycle 6 Bar	**IP Rating**	IP 65 - allows for direct cleaning
Max. Tray Height	80mm, optional 120/150mm	**Tray Exit**	Exit ramp by belts
Die Lifting System	Pneumatic	**Tension Control**	Motorised
Die Change	Quick and easy change	**Vacuum Pump**	Integration vacuum pump (up to 100 m3/h)
Tray Loading Area	Enlargement of the loading area optional (1 meter increments)	**Availability**	Available for hire

Figure 17. Standard technical specifications of the ULMA TSB 300 used for engineering selection and justification (Source: ULMA Packaging, 2026).

From the perspective of this thesis, the ULMA TSB 300 is a suitable choice for the vacuum-sealing function for several engineering reasons.

First, the sealing area of 300 × 440 mm is compatible with the tray dimensions used in the simulation, which were previously defined as 295 × 233 × 45 mm. This means that the selected tray fits within the available sealing area while also remaining below the standard maximum tray height of 80 mm. As a result, the machine is geometrically compatible with the package format selected for the line.

Second, the machine capacity is considerably higher than the minimum required production target of the thesis. The packaging line was designed around a production target of 40 kg/h, and the intended tray fill is approximately 500 g per tray. This corresponds to roughly 80 trays per hour, or about 1.33 trays per minute. Even if the machine were operated well below its nominal rating, the specified capacity of up to 22 packs per minute would still provide a substantial performance margin. This is an important design consideration, because it means that the sealing stage is unlikely to become the limiting station in the overall line under the studied conditions.

Third, the machine characteristics are appropriate for food-packaging integration. The IP65 rating indicates suitability for direct washdown conditions, which is relevant in meat-processing environments where sanitation requirements are strict. The belt-based tray exit also supports straightforward integration with conveyor transport. In addition, the pneumatic die lifting system and motorised film tension control indicate a machine architecture intended for stable and repeatable sealing performance.

For these reasons, the ULMA TSB 300 was considered the most suitable reference choice for the sealing stage in this thesis. It combines geometric compatibility, hygienic suitability, adequate output margin, and straightforward conveyor integration. In other words, it is not only a realistic industrial choice, but also an appropriate engineering choice for a simulation model whose purpose is to analyse coordinated line operation (ULMA Packaging, 2026).

3.3.3 Packaging Conveyor Interface and Tray Transfer Logic

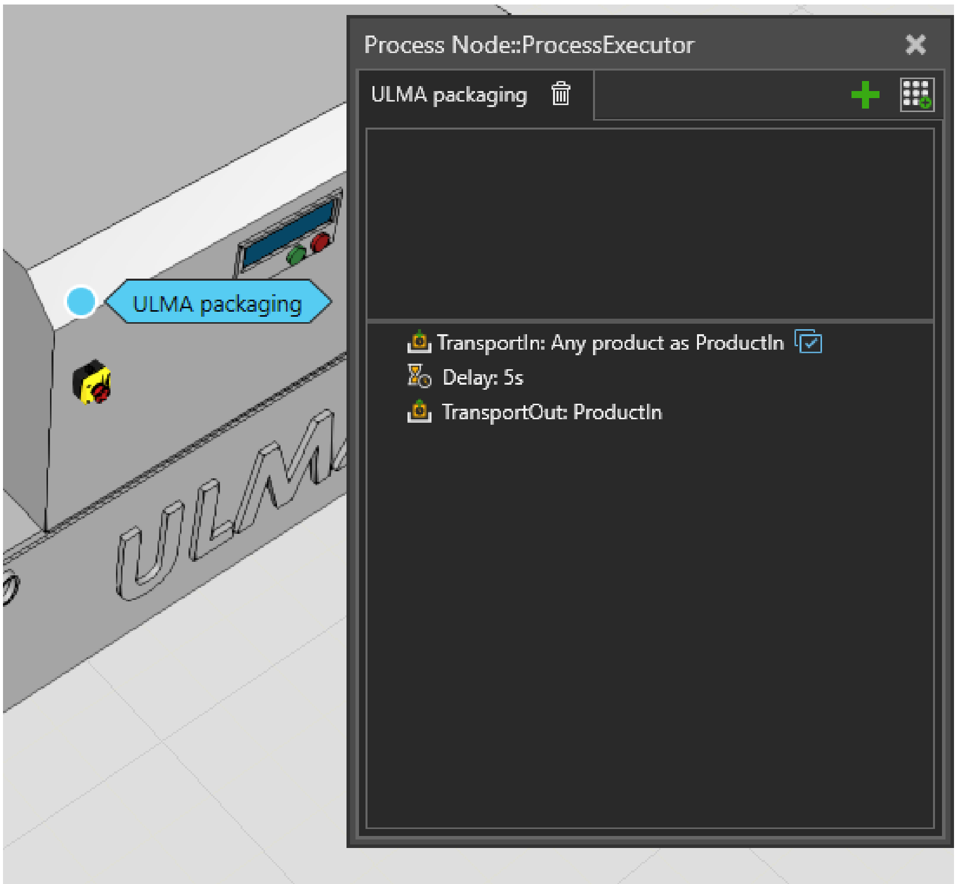
The interface between the filling station and the packaging stage was designed to maintain continuous tray transport while allowing controlled process interruption during sealing. After portioning, the filled tray moves along the conveyor toward the ULMA machine entry. In the final model, the packaging machine is connected to the product flow through a process-based transport link rather than through a fully detailed mechanical infeed system. This simplifies the machine representation but preserves the functional behaviour of tray entry, processing, and discharge.

The conveyor path downstream of the ULMA machine continues through a curved section toward the labelling stage. This routing makes efficient use of the available floor space and allows the packaging and labelling units to be grouped into a compact downstream processing cell. In the final integrated configuration, the downstream conveyor sections were operated at approximately 150 mm/s. This speed was selected because it provides stable transport through the curved path while reducing the risk of excessive spacing variation or unrealistic tray motion in the simulation.

Within this section of the line, tray order is preserved by sequential product transfer through the process nodes. Each tray must complete the sealing stage before it can be released to the labelling stage. This one-directional transfer logic is important because it prevents overtaking, duplication of products, or parallel release of trays from the packaging station. In practical terms, the packaging stage behaves as a controlled single-stage processor inserted into the conveyor system.

3.3.4 Packaging Cycle Representation and Process Timing

In the simulation, the sealing operation is represented using a Process Executor node attached to the ULMA machine model. The implemented logic consists of three basic actions: the incoming product is transported into the packaging process, a fixed delay is applied to represent the sealing operation, and the sealed tray is then transported out to the next stage. In the current model, the sealing delay was set to 5 seconds.



TransportIn: Any product as ProductIn
Delay: 5s
TransportOut: ProductIn

Figure 18. Process Executor configuration used to simulate the ULMA packaging cycle.

This simplified process representation does not model the full physical sequence of tray indexing, chamber closing, vacuum generation, film handling, heating, sealing, and chamber opening. However, for the purposes of system-level analysis, the chosen approach is sufficiently accurate because it captures the most important performance variable of the station, namely its processing time. Since the thesis focuses on line coordination and throughput rather than detailed thermomechanical seal formation, a time-based packaging model is appropriate.

The selected 5-second cycle is also conservative when compared with the nominal capacity of the real machine. A nominal rate of 22 packs per minute corresponds to approximately 2.7 seconds per pack under favourable operating conditions. By using a 5-second cycle in the simulation, the model includes a practical time margin for indexing, transfer, and line coordination. Even at this slower simulated rate, the packaging stage would still be capable of processing 12 trays per minute, which is equivalent to 720 trays per hour. This remains well above the required thesis target of approximately 80 trays per hour for 500 g portions.

From an engineering standpoint, this means that the packaging stage is not expected to be the throughput bottleneck in the final system model. Its main role in the simulation is therefore to act as a controlled processing stage that interrupts and releases the product flow in a predictable and repeatable manner.

3.3.5 Labelling Stage Layout and Integration

After sealing, the trays are transferred to the labelling stage. In the developed model, the labelling unit is positioned on the downstream conveyor after the ULMA packaging stage, so that only sealed trays enter the labelling area. This follows common industrial practice, since labelling is typically performed after the package geometry and film position have been stabilized by the sealing process.

The labelling machine itself was not custom-modelled. Instead, a parametric labelling model from the Visual Components library was used. This decision was made to maintain focus on the engineering analysis of production flow rather than on the detailed mechanical construction of a print-and-apply system. The selected model provides a realistic visual representation of a labelling station and allows the stage to be incorporated into the overall production sequence without requiring additional custom machine design.

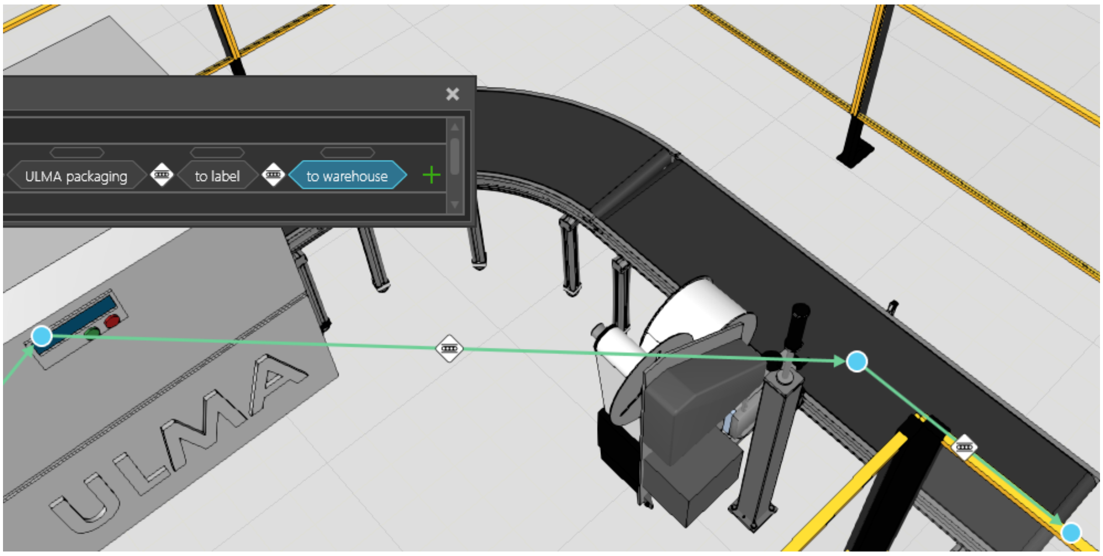


Figure 19. Product flow sequence from the ULMA packaging stage to the labelling stage and further to the outfeed.

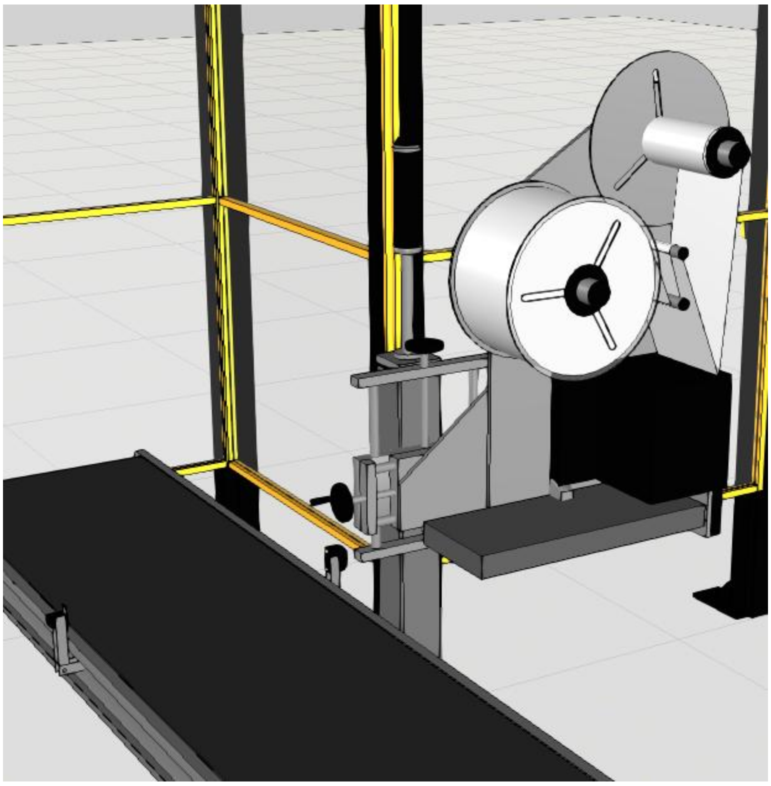


Figure 20. Parametric labelling unit from the Visual Components library used in the final model (Source: Visual Components, 2026a).

The labelling station is integrated into the same conveyor path as the packaging machine discharge. This preserves tray orientation and avoids the need for a separate transfer mechanism. As a result, the downstream process remains mechanically simple: the sealed tray exits the packaging machine, travels to the labelling unit, receives the labelling delay, and then continues toward the outfeed or warehouse area.

3.3.6 Labelling Process Representation and Timing

The labelling process was represented in the simulation as a simplified timed operation. In practical terms, the tray enters the labelling stage, remains there for a fixed process delay of 1 second, and is then released to the next product path segment. This modelling method was selected because the thesis does not require detailed analysis of label peeling mechanics, print data generation, adhesive behaviour, or label position verification.

The use of a 1-second delay provides a realistic representation of a short downstream auxiliary process. Compared with the packaging stage, labelling is significantly faster and therefore does not govern the line capacity. A nominal 1-second labelling cycle corresponds to a theoretical handling capacity of 60 trays per minute, which is well above both the simulated packaging cycle and the required line throughput. This confirms that, under the assumptions of the current model, labelling is not expected to form a bottleneck.

The simplified labelling model is sufficient for the purposes of this study because it preserves the correct process order and contributes to the total downstream cycle time without introducing unnecessary model complexity. In a full industrial implementation, the labelling station would typically include additional devices such as a product sensor, label presence verification, encoder-based speed synchronization, and possibly print data communication. These features were not included here because the emphasis of the thesis remains on overall system interaction.

3.3.7 Sequence Coordination Between Packaging and Labelling Stages

The sequence coordination between packaging and labelling was implemented through ordered product-flow connections in Visual Components. After the tray completes the packaging cycle, it is released to the next stage labelled as the transfer toward the labelling station. After completion of the labelling delay, the product is transferred again to the final downstream path leading toward storage or warehouse handling.

This structure creates a clear process chain:

1. filled tray enters packaging stage
2. sealed tray exits packaging stage
3. sealed tray enters labelling stage
4. labelled tray exits to outfeed

Because the packaging delay is longer than the labelling delay, the sealing stage governs the local capacity of Section 3.3. This is desirable from a control perspective, since it means the labelling stage has sufficient time margin and does not require complex buffering in the present model. The sequence therefore remains stable, and the trays continue through the downstream section in the same order in which they entered it.

The product flow architecture shown in Figure 19 also supports future expansion. Additional nodes, such as an inspection point, rejection mechanism, or palletizing step, could be added after the labelling stage without changing the basic logic of the existing system. This confirms that the selected coordination method is not only functional for the current thesis but also structurally suitable for more advanced automation concepts.

3.3.8 Design Limitations

The packaging and labelling section was developed for conceptual system analysis and therefore contains several simplifications. The ULMA machine is represented as an external geometric model combined with a timed process node, rather than as a full internal simulation of tray indexing, film feed, vacuum generation, heat sealing, and chamber motion. Similarly, the labelling stage is represented using a standard parametric Visual Components model with a fixed delay and does not include print logic, label inspection, or positional correction.

In addition, the current model does not include detailed electrical control architecture, PLC programming, or sensor-level interlocking between the packaging and labelling stations. Product jams, film faults, label roll depletion, and sealing defects are also outside the scope of the simulation. These omissions are acceptable because the thesis is explicitly limited to system-level analysis of machine interaction, line coordination, and achievable throughput rather than full industrial commissioning or detailed machine design.

Despite these limitations, the section captures the essential engineering behaviour of the downstream process. It shows how trays are transferred from filling to sealing, from sealing to labelling, and from labelling to outfeed in a controlled sequence. It also provides a clear basis for later simulation analysis of cycle time, bottlenecks, and total production capacity.

3.4 Safety Design and Integration

Safety was considered as an integral part of the production cell design. Although the developed model is a simulation-based concept rather than a fully validated industrial installation, the layout was designed to reflect the basic safety principles typically applied in automated packaging systems. The final configuration includes protective fencing, a restricted robot operating zone, controlled access to the machine area, and emergency stop devices positioned at key locations in the cell.

The purpose of these safety elements is to reduce the risk of unintended human access to hazardous machine areas during operation and to provide a clear conceptual separation between automatic machine movement and manual supervision tasks. In the proposed production line, this is particularly important because the system combines conveyor transport, robotic tray handling, packaging machinery, and operator presence near the filling station.

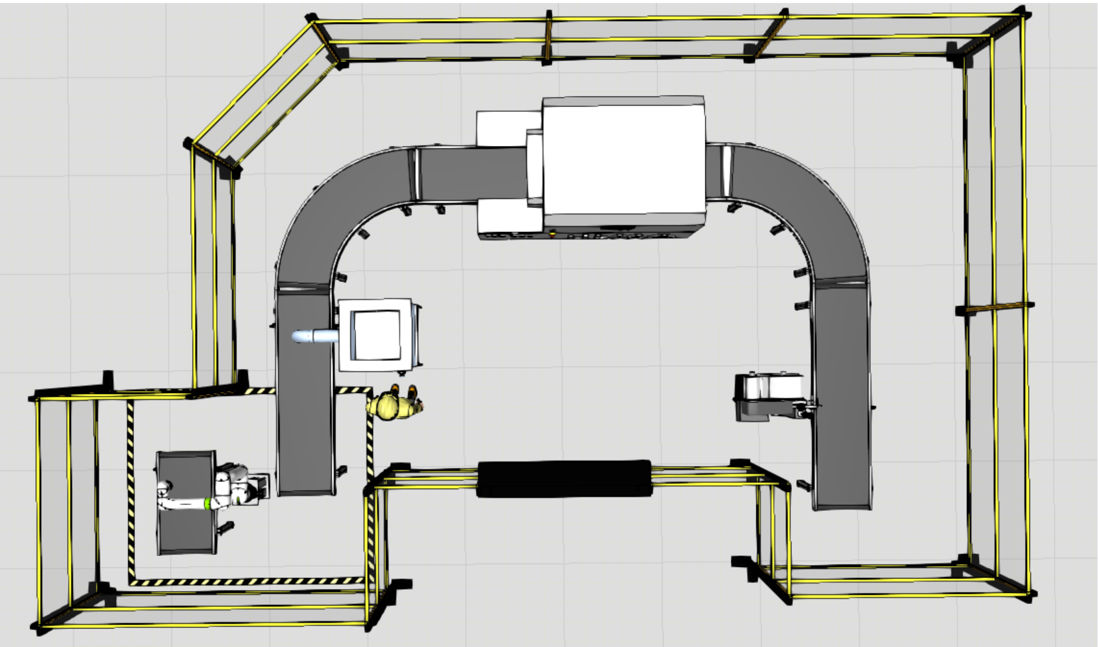


Figure 21. Final integrated layout of the production cell showing the safety fence, guarded machine area, robot cell, filling station, packaging section, and downstream conveyor path.

3.4.1 Protective Fencing and Access Control

The final production cell is surrounded by protective fencing that defines the machine operating area and restricts access during automatic operation. The fencing forms a physical perimeter around the main hazardous zones of the line, including the packaging machine area and the robot handling section. This design approach is consistent with standard industrial practice, where guarding is used to separate personnel from moving machinery, rotating components, and automatic handling equipment.

In the developed model, the fencing serves several engineering purposes. First, it establishes a clear boundary between the production cell and the surrounding workspace. Second, it improves layout readability by showing where machine operation is intended to occur without direct human interference. Third, it supports the overall system concept by demonstrating that safety was included already at the design stage rather than added as an afterthought.

A dedicated access opening with a gate is included in the fence structure. The gate represents the controlled entry point for maintenance, setup, cleaning, or manual intervention. In a real industrial installation, this access point would normally be equipped with an interlock device connected to the machine safety circuit so that opening the gate would stop hazardous motion. In the simulation model, the gate is represented as a physical safety element, while the detailed interlock logic is outside the scope of the thesis.

The fenced layout is especially important in this project because the cell includes both fixed machinery and automated motion systems. Without guarding, the operator could move freely into the same area as the robot or packaging equipment, which would not be acceptable in an industrial environment. By defining the guarded area with fencing, the model reflects a more realistic and professionally engineered packaging cell.

3.4.2 Robot Operating Area and Safety Separation

A dedicated robot safety zone was defined around the tray-handling robot. This zone is marked on the floor and visually separates the robot working envelope from the surrounding cell area. The marked area represents the region in which automatic robot motion may occur and where unrestricted human presence should be avoided during normal operation.

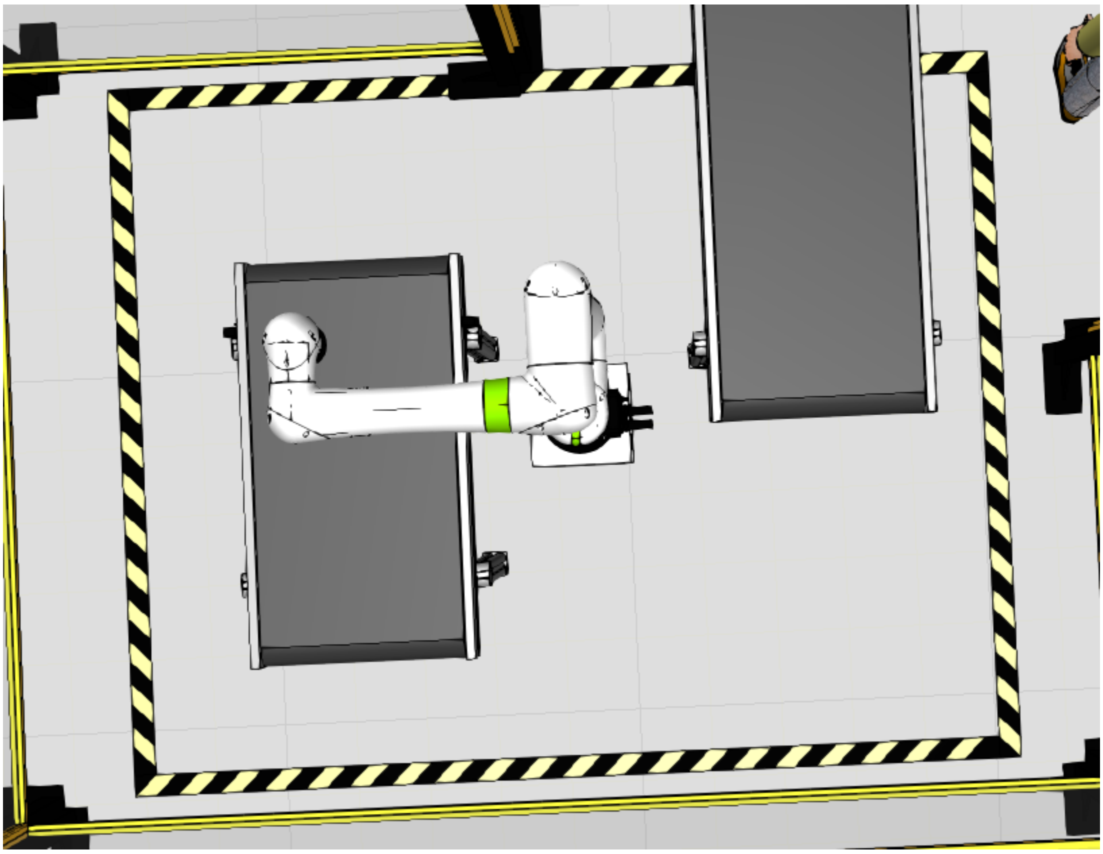


Figure 22. Top-view of the robot handling area showing the marked safety zone around the robot and the separation between the infeed and outfeed positions

From a safety engineering perspective, the robot zone is important because the robot performs repeated pick-and-place movements between conveyor locations. These movements create a dynamic hazard area that differs from the more static hazard presented by fixed conveyor frames or machine guards. Even though the selected robot type is collaborative in principle, the system in this thesis was treated as a guarded industrial cell rather than an open human-robot collaboration workstation. This approach was chosen because the robot operates as part of a larger automated packaging line and is surrounded by additional machine elements and conveyor equipment.

The top-view layout shows that the robot is installed within a defined rectangular work area. This arrangement gives two advantages. First, it creates predictable motion geometry for the robot program, since the pick and place locations are fixed relative to the robot base. Second, it allows the hazardous motion zone to be clearly identified in the general cell layout. In engineering terms, a clearly defined robot area improves both operational clarity and safety planning.

The robot safety concept in this model is therefore based on spatial separation rather than on advanced sensing functions. No laser scanner, safety mat, or speed-and-separation monitoring system was implemented in the simulation. Instead, the hazardous area is controlled through physical guarding and floor marking. This is a reasonable concept for the scope of the present work, because the thesis focuses on system-level layout and process integration rather than advanced functional safety design.

The operator included at the filling station is also separated functionally from the robot task. The operator represents manual supervision of portion accuracy and quality control of tray weight, whereas the robot performs only the tray transfer task in its own dedicated area. This functional separation supports safe coexistence between manual and automated activities within the overall line concept.

3.4.3 Emergency Stop Arrangement

Emergency stop devices were included in the main hazardous parts of the production cell to represent the manual shutdown function required in automated machinery. In the developed model, emergency stop buttons were placed at the access gate, at the ULMA packaging machine, and at the mincer or filling station. These locations were selected because they correspond to the areas where an operator is most likely to require immediate machine stop capability.

The emergency stop arrangement provides a basic conceptual safety layer for the cell. If an abnormal situation occurs, such as unexpected tray movement, operator intervention, or machine malfunction, the nearest emergency stop should allow rapid interruption of operation. This is particularly relevant in a packaging line where several stations are mechanically linked through conveyor flow. Stopping only one local motion source may not always be sufficient in a real system; therefore, emergency stop functions are generally considered part of a wider machine safety architecture.

In the simulation, the emergency stop devices are represented primarily as design elements rather than fully programmed safety functions. Their inclusion nevertheless strengthens the engineering credibility of the model because it shows that manual emergency shutdown was considered at all critical operating points. From a thesis point of view, this is important because it demonstrates awareness of safe machine operation in addition to production efficiency and layout design.

The emergency stop mounted on the packaging machine reflects the need for local control at the main processing unit. The device at the filling station reflects the operator’s close proximity to the semi-automated portioning area. The emergency stop near the gate represents the need for accessible stop control at the entry point to the guarded zone. Together, these devices form a distributed emergency stop concept rather than relying on a single stop location.

Although the model does not include a full safety relay or safety PLC structure, the chosen arrangement is sufficient for conceptual system design. It communicates the correct engineering principle: emergency stop access should be available where hazards are present and where operator intervention may be required.

3.4.4 Safety Design Limitations

The safety concept presented in this thesis remains at the layout and system-design level. The model does not include a formal risk assessment, safety category calculation, performance level verification, or validated interlock design. In addition, no detailed safety control system was implemented for the robot, gate, conveyors, or packaging machine. These aspects would be required in a real industrial installation but were outside the scope of this thesis.

Despite these limitations, the developed safety layout provides an appropriate conceptual representation of how the production cell would be organized in practice. The combination of protective fencing, dedicated robot area, controlled access, and distributed emergency stop devices supports the overall objective of the thesis by showing that the proposed automation concept was developed with both operational functionality and basic industrial safety principles in mind.

3.5 Final Integrated Layout

The final integrated layout combines the feeding and handling section, filling and portioning station, packaging and labelling section, and safety elements into one coordinated production cell. The purpose of this final arrangement is to ensure that the individual stations operate as a single continuous system rather than as separate machine units. From an engineering perspective, the layout must provide logical material flow, controlled interaction between automatic and manual operations, and sufficient space for safe and stable operation.

In the developed model, the production cell was arranged so that trays move through the system in a fixed downstream sequence. Empty trays are introduced at the feeding section and transferred to the main conveyor by the robot. The trays then move to the filling station, where minced meat is dispensed and portion accuracy is supervised manually by the operator. After filling, the trays continue to the packaging stage, where sealing is represented by a timed process operation. The sealed trays are then transferred to the labelling stage and finally discharged to the downstream outfeed path.

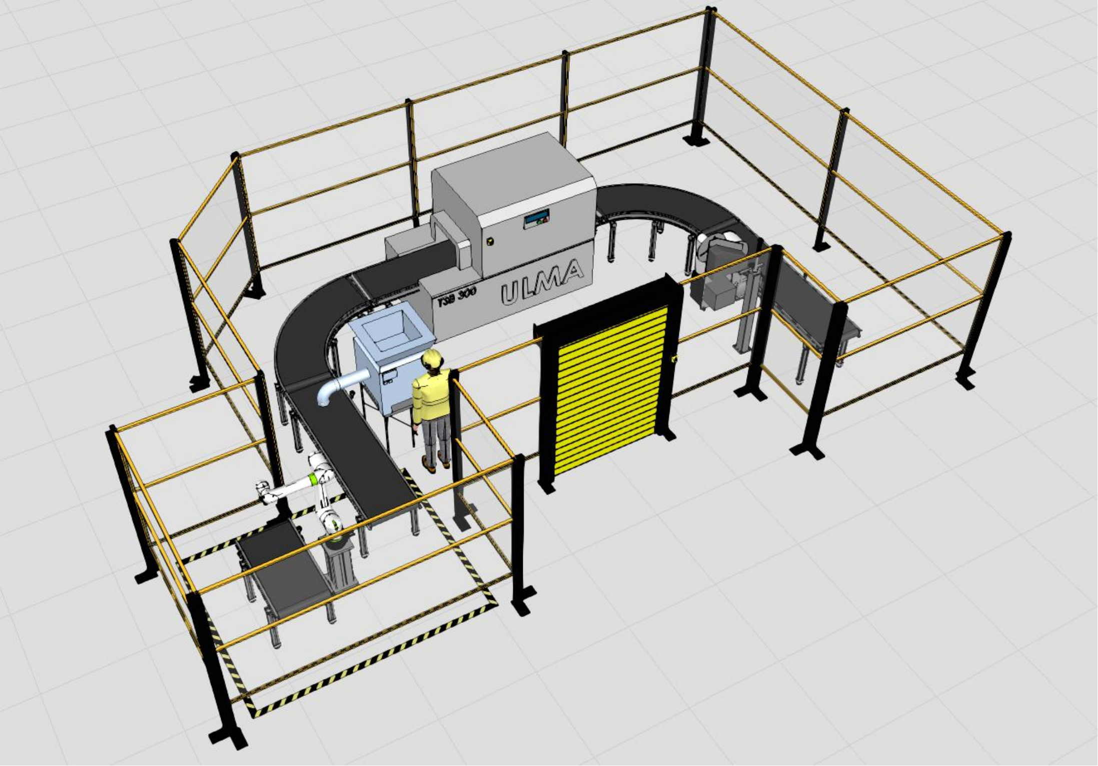


Figure 23. Final integrated layout of the automated minced meat packaging line in Visual Components.

The final layout was developed with emphasis on compactness, continuity of product flow, and practical integration of the main process stages. The use of curved conveyor sections allows the downstream packaging and labelling stations to be connected without introducing unnecessary transfer mechanisms. This reduces layout complexity and supports a compact production cell structure suitable for small and medium-scale food processing environments.

3.5.1 Overall System Arrangement

The final arrangement represents a semi-automated production concept. Conveyor transport, robotic tray handling, packaging, and labelling are automated, while the filling stage still includes manual supervision of portion accuracy. This reflects a realistic industrial solution in which repetitive handling and transport tasks are automated, but quality-critical product verification remains under operator control.

The layout also provides clear spatial separation between the main functional areas of the cell. The robot handling section is located at the infeed side, the filling station is positioned downstream of tray placement, and the packaging and labelling stages are grouped into the final processing section. Safety fencing and controlled access define the machine operating area and separate automatic movement zones from the surrounding workspace. This arrangement improves both technical clarity and operational safety.

3.5.2 Material Flow Through the Final Layout

Material flow in the final layout follows a single-direction process sequence:

- empty tray feeding
- robotic tray transfer
- filling and portion supervision
- packaging and sealing
- labelling
- downstream outfeed

This one-directional arrangement provides a clear process structure and avoids unnecessary routing complexity. Each station performs a defined function and releases the tray to the next stage in sequence. As a result, the layout supports stable conveyor-based transport and predictable product progression through the line.

From a system perspective, the final layout also supports throughput analysis. The filling and packaging stages represent the main time-governing operations, while the labelling stage remains comparatively short and is therefore not expected to limit line capacity. This makes the final configuration suitable for evaluating process coordination, cycle times, and bottleneck behaviour in the simulation model.

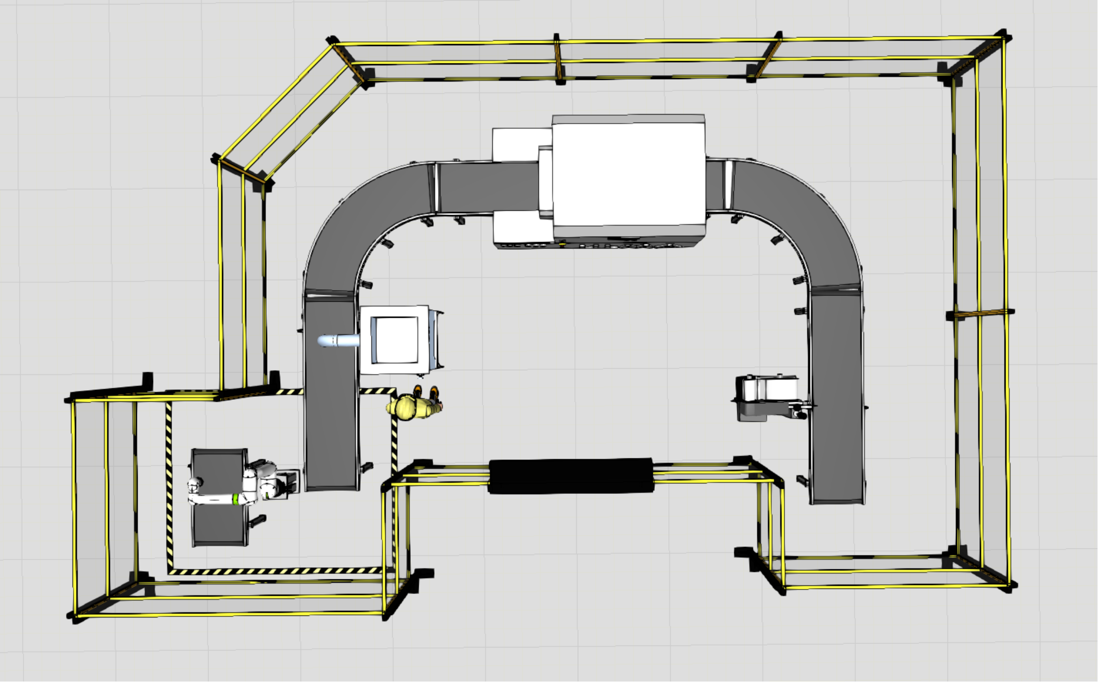


Figure 24. Top view of the final production cell layout showing the complete process flow from tray handling and filling to packaging, labelling, and outfeed.

3.5.3 Layout Evaluation

The final integrated layout can be considered technically suitable for the purpose of this thesis. It includes all main functional stages required for the proposed minced meat packaging process and connects them into a coherent production system. The arrangement supports continuous tray flow, clear process order, and practical integration of automated and manually supervised operations.

A further strength of the final layout is that safety was incorporated as part of the overall cell design. Protective fencing, robot area separation, and emergency stop locations were included in the final configuration rather than treated as independent additions. This improves the engineering credibility of the model and makes the production cell more representative of a real industrial concept.

Although the layout remains simplified and does not include full electrical design, detailed machine internals, or validated safety control architecture, it is sufficiently complete for simulation-based system analysis. Within the scope of this thesis, the final integrated layout provides an appropriate basis for evaluating production flow, station interaction, and operational performance in Visual Components.

4 MATHEMATICAL CALCULATIONS OF PRODUCTION CAPACITY

The purpose of the mathematical analysis is to determine whether the proposed production line can achieve the required output of 40 kg/h. In this thesis, the production capacity is evaluated using the target portion weight per tray and the cycle times of the main process stages. The calculation is based on simplified system assumptions and is intended to support the engineering evaluation of the proposed line design. The production target of the thesis is defined as 40 kilograms of minced meat per hour, and the target filling amount is approximately 500 g per tray.

4.1 Basis of the Calculation

The required number of trays per hour can be calculated from the total hourly production target and the product mass in one tray:

$$N = \frac{Q}{m}$$

where:

- N= required number of trays per hour
- Q= production target (kg/h)
- m= product mass per tray (kg)

Using the design values of the proposed system:

$$Q = 40\ kg/h$$

$$m = 0.5\ kg/tray$$

the required tray output becomes:

$$N = \frac{40}{0.5} = 80\, trays/h$$

Thus, the line must be capable of processing at least 80 trays per hour to achieve the required production target.

To express this value as trays per minute:

$$N_{min} = \frac{80}{60} = 1.33\, trays/min$$

This means that the system must produce at least 1.33 trays per minute.

4.2 Capacity of the Main Process Stages

The capacity of each process stage can be estimated from its cycle time. The general relationship between cycle time and hourly output is:

$$C = \frac{3600}{t}$$

where:

- C= theoretical capacity $(trays/h)$
- t= cycle time per tray (s)

In the developed model, the main process times are:

- filling stage: 3 s
- packaging stage: 5 s
- labelling stage: 1 s

<u>Filling stage</u>

$$C_f = \frac{3600}{3} = 1200\, trays/h$$

<u>Packaging stage</u>

$$C_p = \frac{3600}{5} = 720\, trays/h$$

Labelling stage

$$C_l = \frac{3600}{1} = 3600\, trays/h$$

These results show that the packaging stage has the lowest theoretical capacity and therefore represents the controlling stage of the downstream process.

4.3 Bottleneck-Based Throughput Evaluation

In a sequential production system, the theoretical throughput is limited by the station with the lowest capacity. Therefore, the maximum theoretical line throughput can be estimated as:

$$C_{line} = \min\,(C_f, C_p, C_l)$$

$$C_{line} = \min(1200{,}720{,}3600) = 720\, trays/h$$

The corresponding mass throughput is:

$$Q_{line} = C_{line} \cdot m$$

$$Q_{line} = 720 \cdot 0.5 = 360\, kg/h$$

Thus, the theoretical maximum production capacity of the line is:

$$Q_{line} = 360\, kg/h$$

This value is significantly higher than the required target of 40 kg/h.

4.4 Comparison with the Required Production Target

The calculated theoretical line capacity can be compared directly with the required production target:

$$Q_{line} = 360\, kg/h$$

$$Q_{target} = 40\, kg/h$$

Since:

$$360\,kg/h > 40\,kg/h$$

the proposed system is theoretically capable of achieving the required production rate.

The capacity margin can also be expressed as:

$$M = \frac{Q_{line}}{Q_{target}}$$

$$M = \frac{360}{40} = 9$$

This means that the theoretical capacity of the model is approximately 9 times greater than the minimum required output.

4.5 Interpretation of the Results

The mathematical analysis indicates that the proposed production line is capable of meeting the required production target with a substantial capacity margin. Based on the selected cycle times, the packaging stage is the limiting stage of the process, but even this station provides considerably higher throughput than required by the thesis objective.

It must be noted, however, that these values represent theoretical capacity under simplified operating conditions. The calculation does not include machine stoppages, product variability, operator delays, maintenance interruptions, or disturbances in tray flow. Therefore, the real industrial output would be lower than the theoretical maximum. Nevertheless, the results show that the proposed design is sufficiently capable of achieving the target production rate of 40 kg/h within the scope of this study.

5 CONCLUSION AND REFLECTION

The aim of this thesis was to develop and evaluate a concept for an automated minced meat packaging line using digital simulation. The work focused on the mechanical coordination, operational stability, and production capacity of the proposed system. Based on the completed design, integrated layout, safety concept, and mathematical capacity analysis, it can be concluded that the main objective of the thesis was achieved. The final concept forms a coherent semi-automated production cell in which tray feeding, robotic handling, filling, packaging, labelling, and outfeed are combined into one system-level solution.

The developed line follows a fixed downstream process sequence. Empty trays are introduced into the system and transferred by the robot to the main conveyor. The trays then move to the filling station, where the conveyor is stopped by signal-based control and the filling operation is represented by a fixed time delay. Portion accuracy is supervised manually by the operator, which reflects a realistic arrangement for smaller-scale food processing, where repetitive handling tasks are automated but quality-critical product verification remains under human control. After filling, the trays continue to the packaging and labelling section, where the ULMA TSB 300 tray sealer and a simplified labelling stage are integrated into the downstream conveyor path. This arrangement provides logical material flow, avoids unnecessary routing complexity, and supports a compact production cell structure.

One of the main technical outcomes of the thesis is that the proposed layout supports stable and understandable process integration. The final arrangement provides clear separation between the robot handling area, the filling station, and the downstream packaging section. The packaging machine was selected appropriately for the concept because its sealing area is compatible with the selected tray dimensions, its technical characteristics are suitable for hygienic food-packaging environments, and its nominal capacity is well above the required production level of the thesis. Within the simulation, the packaging stage was simplified as a timed process rather than a full internal machine model, but this level of abstraction was sufficient for evaluating production flow and stage interaction at system level. The same principle was applied to the labelling stage, which was represented using a parametric Visual Components model with a short process delay.

The mathematical analysis confirmed that the designed system is theoretically capable of meeting the required production target of 40 kg/h. With a target portion of 500 g per tray, the line must process at least 80 trays per hour, or approximately 1.33 trays per minute. Based on the selected process times of 3 seconds for filling, 5 seconds for packaging, and 1 second for labelling, the packaging stage becomes the limiting stage with a theoretical capacity of 720 trays per hour. This corresponds to a theoretical mass throughput of 360 kg/h, which is approximately nine times higher than the required target. These results indicate that, under the simplified assumptions of the model, the proposed system has a sufficient capacity margin to achieve the thesis objective.

Another important outcome of the work is that safety was included as part of the engineering design. The final concept includes protective fencing, a controlled access gate, a clearly defined robot operating zone, and emergency stop devices at critical locations. Although the model does not include a validated safety control architecture, formal risk assessment, or functional safety verification, it reflects the basic safety principles expected in an automated packaging cell. This improves the engineering credibility of the design and makes the final concept more representative of a realistic industrial solution.

At the same time, the limitations of the thesis must be recognized. The work is based on conceptual design and system-level simulation rather than on full industrial implementation. The filling stage was modelled using time-based logic instead of weighing feedback, the packaging machine was simplified as a process node, and the labelling unit was represented by a standard library model. The study also excludes detailed electrical design, PLC implementation, machine failures, maintenance interruptions, and raw-material variability. For this reason, the calculated production capacity should be understood as theoretical rather than as a direct prediction of real factory output. Even so, within the defined scope of the thesis, the model is sufficiently detailed to support engineering evaluation of line structure, stage interaction, and production capability.

From a professional perspective, this thesis provided useful experience in combining mechanical design, automation logic, process flow analysis, and digital modelling into one engineering study. One of the most important lessons was that successful automation design depends not only on the choice of individual machines, but also on the coordination between them. The work also demonstrated the value of simulation as an engineering tool for evaluating layout alternatives, material flow, and bottleneck behaviour before physical implementation. If the work were continued, the next development steps would include more detailed modelling of the filling stage with weighing feedback, a more advanced control structure, and extension of the downstream process to include inspection, rejection, or palletising functions. It would also be useful to study additional operating conditions, such as stoppages, flow disturbances, and tray spacing variation, in order to produce a more realistic estimate of industrial performance.

In conclusion, the thesis shows that the proposed automated minced meat packaging line is technically feasible as a concept and suitable for simulation-based engineering evaluation. Within the defined scope, the developed system meets the thesis objective by combining process flow, machine interaction, safety considerations, and production-capacity analysis into one coherent design. The results indicate that the proposed line can maintain stable operation and exceed the required production target of 40 kg/h, while also providing a practical basis for future engineering development.

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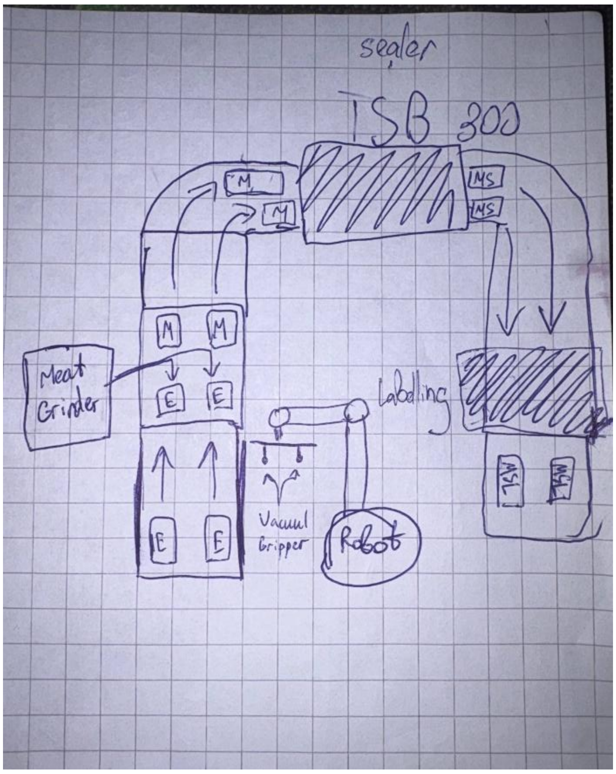
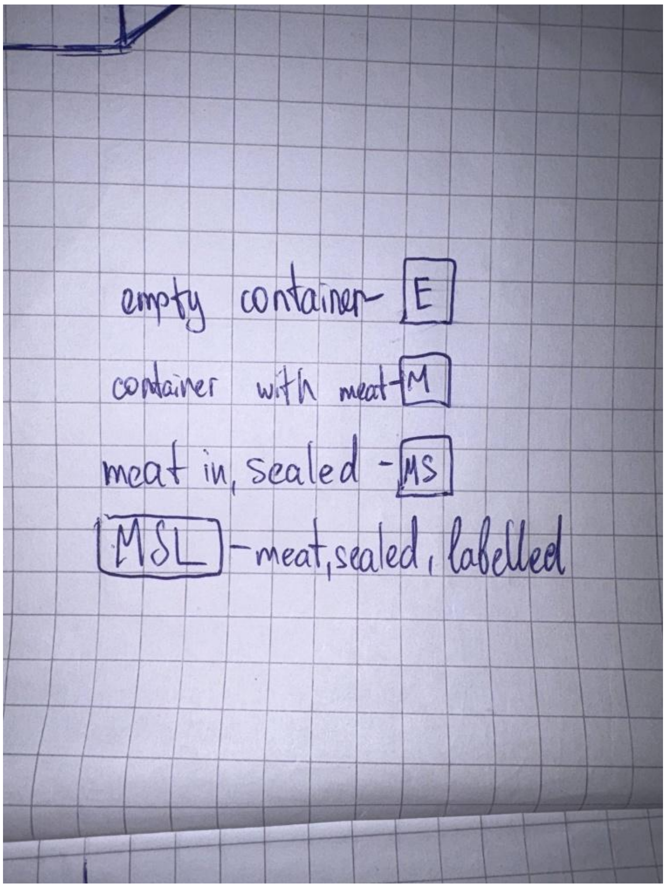
APPENDIX 1. EARLY STAGE OF DESIGN AND FIRST SKETCHES




empty container - E
container with meat - M
meat in, sealed - MS
MSL - meat, sealed, labelled

1/3 OF DESIGN DONE. FIRST SKETCH