Redesign of the Artechno vertical farm robot

ME54035: ME-MME MSc Thesis

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ARTECHNO Growsystems

Redesign of the Artechno vertical farm robot

by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday February 8, 2024 at 10:00 AM.

Student number:	4666992	
Thesis number:	2024.MME.8893	
Project duration:	May 15, 2023 – January 14, 2024	
Thesis committee:	prof. ir. W. van den Bos,	TU Delft, supervisor
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This thesis is confidential and cannot be made public until February 9, 2024.

Cover:	AVF+ Compact
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Abstract

This thesis focuses on a vertical farming system designed for growing crops. The system's deficiencies were identified during a company visit where the system was operating. An analysis was conducted to see when all deficiencies would be resolved. It revealed that the vertical farm robot had to be redesigned to grab seven benches deep to eliminate the system's shortcomings and significantly enhance its performance. Thus, a literature review was conducted to determine possible solutions. As a result, various alternatives were devised based on the requirements and constraints considering the available design space and a morphological chart. These alternatives were scored with a weighted criteria method, and the best view was elaborated in more detail. Subsequently, a computer-aided design of the best overall-looking design was created. After ordering all materials, a design prototype was built inside a climate cell in the research centre, and all sensors and drives were wired and controlled by a programmable logic controller to fully automate the prototype. A proof of concept was successfully obtained from the test results. Therefore, this redesign of the system's performance was enhanced, and this thesis was successful.

Contents

1
Introduction

1.1. Background

Artechno Growsystems is a company based in Maasdijk, Netherlands. Artechno is an automated vertical farm supplier engaged in developing and realising cultivation systems, from seeding to harvesting machines. Artechno was founded in the late 1980s by Art van Rijn. Its horticultural background and desire to innovate how farmers grow made Artechno successful from the start. Many new technologies have been developed during this quest to revolutionise horticulture: water techniques, water purification, automation, robotics, harvesting, processing, hydroponic growing systems, and vertical farming. Vertical farming is a technology where crops are grown under controlled climates and high density, lending from closed environment agriculture to grow crops in benches in stacked layers, as shown in Figure 1.1. The last leap to large-scale commercial viability is the automation of these systems. Artechno has an automated vertical farming (AVF) system. Artechno operates at more than ten locations worldwide, and more than 50 horticultural experts are employed there [10]. The aim of this thesis is to improve the vertical farming robot inside the AVF climate cell at the automated vertical farm factory, as seen in Figure 1.2.

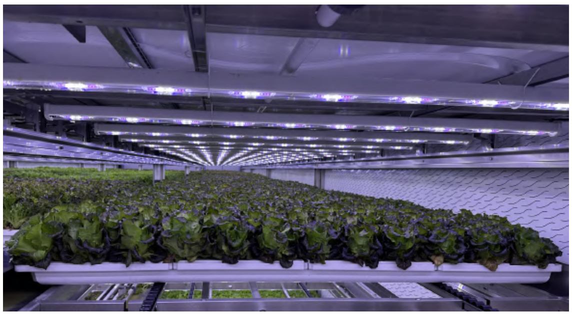

Figure 1.1: Bench with crops.

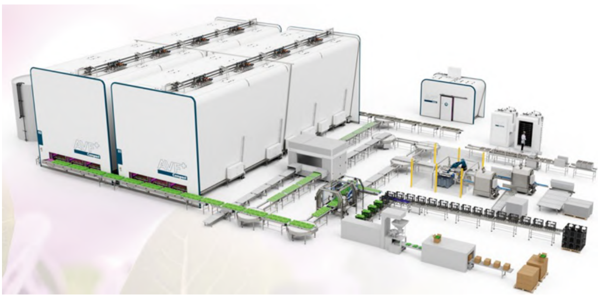

Figure 1.2: Factory configuration.

The factory is a production line for growing crops, as shown in Figure 1.3.

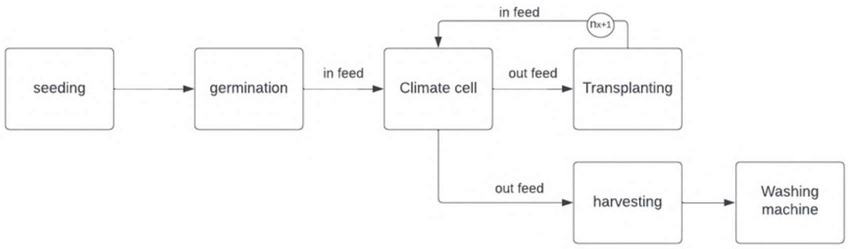

Figure 1.3: Process steps within the factory.

It all starts with seeding, where seeds are placed relatively close to each other on a bench with a substrate. Once the seeds are placed, the benches are placed in a germination cell for one to two days. After germination, the benches are placed in the climate cell, a vertical farming system designed for growing crops on a medium to large scale. The perfect conditions for crop growth are created inside the climate cell by precise control of growing variables like light, climate, irrigation, and nutrients. Once the plants are ready for transplanting, they are removed from the climate cell and placed in the transplanting machine because the seeds are close together and would block each other while continuing to grow without this move. Transplanting increases the quality of the crops and the amount of kg crop per square metre of cultivation area. When the plants are transplanted, they are returned to the climate cell until fully grown and ready to be harvested. Then, the plants are once again taken out of the climate cell to the harvesting machine. After the harvesting machine, the benches continue to the washing machine, where they are cleaned for reuse.

Because all crops are different, they need different crop strategies. A crop strategy consists of three elements:

- how many times a crop needs to be transplanted before it can enter the harvesting machine,
- the multiplication factor N for each phase x, and
- the number of days L (cycle time) the crop needs to be in the climate cell per phase x.

Example: A crop needs to be transplanted twice, meaning the crop undergoes three phases shown in green (phase 1), orange (phase 2), and blue (phase 3) in Figure 1.5, with multiplication factors of N1 = 1, N2 = 5, and N3 = 3 and cycle times of L1 = 18, L2 = 10, and L3 = 10.

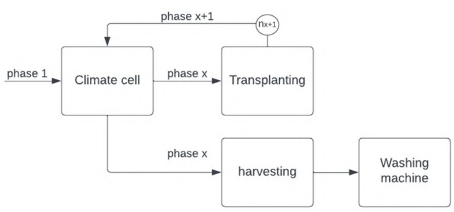

Figure 1.4: Scope of the research

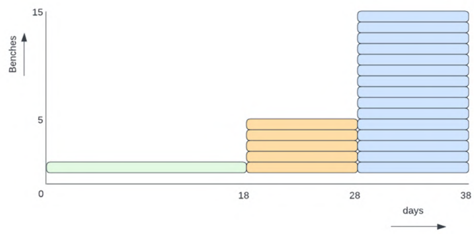

Figure 1.5: Example of the multiplication

Once the crop strategy is determined, the next step is determining how the crop enters the climate cell, requiring the vertical farm robot.

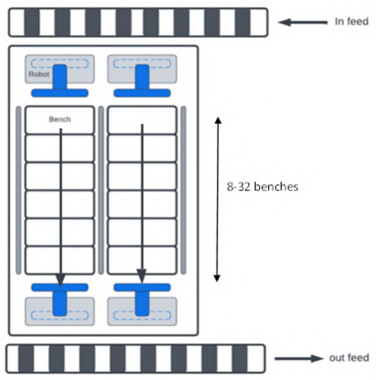

Figure 1.6: Climate cell top view

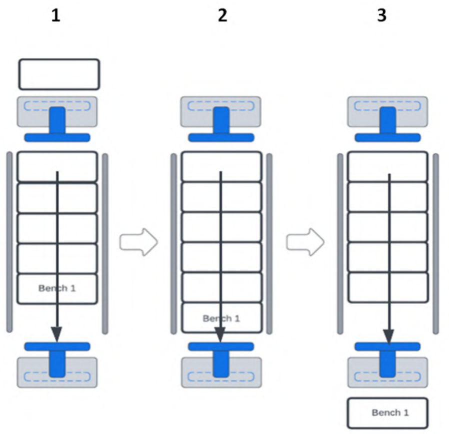

Figure 1.7: Working principle of the robot

Benches enter the climate cell at the in-feed conveyor (step 1 in Figure 1.7). Here, the robot grabs a bench and pushes it into the system (step 2). Once it reaches the end of the climate cell, another robot at the out-feed side grabs the bench and pushes it out of the system onto the out-feed conveyor (step 3). There are two possibilities of where the bench can go: the transplanting machine or the harvesting machine, as shown in Figures 1.8 and 1.9.

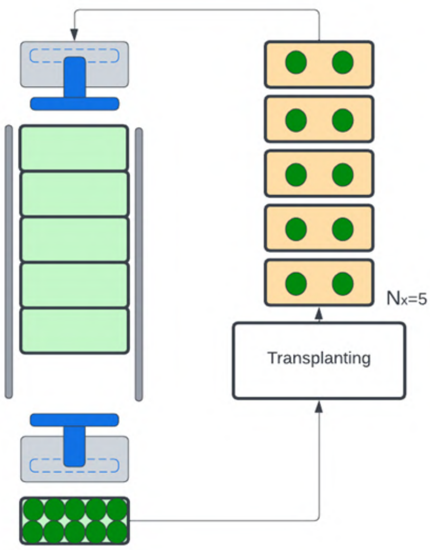

Figure 1.8: Transplanting

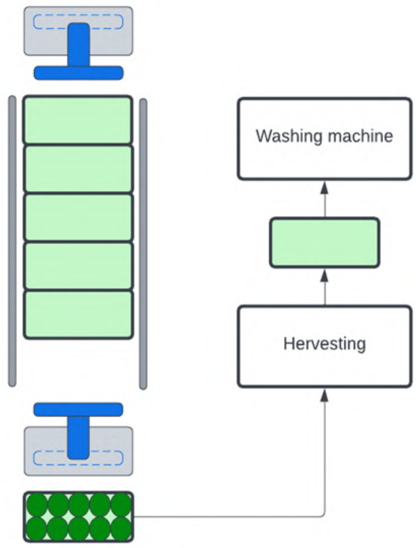

Figure 1.9: Harvesting

With the system's working principle schematically clear, a description of the current technology is next. The climate cell consists of three main components: the cell, the lift mechanism, and the robot.

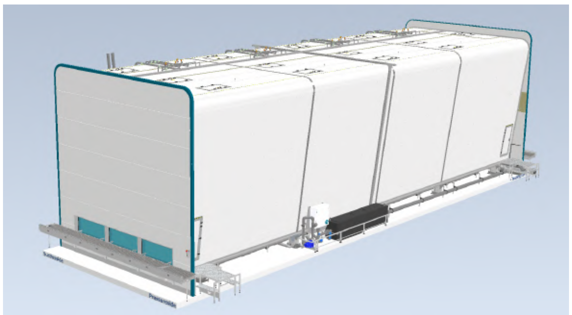

Figure 1.10: Climate cell

Figure 1.11: Cross section of the climate cell

The cell consists of four sections of three rows with ten layers stacked on each other, each consisting of eight benches, totalling 960 benches 160 x 625 mm, with a total of 960 m2 of cultivation area. These dimensions were chosen because the depth of the eight benches is 5,000 mm. These dimensions are also necessary to achieve a homogeneous climate within the cell. Each layer consists of rollers that allow the benches to move from the input side to the output. There are two lift mechanisms, one at the input side and one at the output side. The lift mechanism (Figure 1.12) is a cage containing three robots.The lift mechanism brings these three robots to the wanted layer within the cell. The robot is a grabbing mechanism (Figure 1.13) that grabs a bench from the conveyor at the input side and moves it over to the cage. Once the lift mechanism reaches the destined layer, the robot pushes the bench into the cell. The output side works the other way around, with the robot grabbing the bench from the cell and moving it to the cage. Once the bottom layer is reached, the bench is pushed out of the system onto the conveyor.

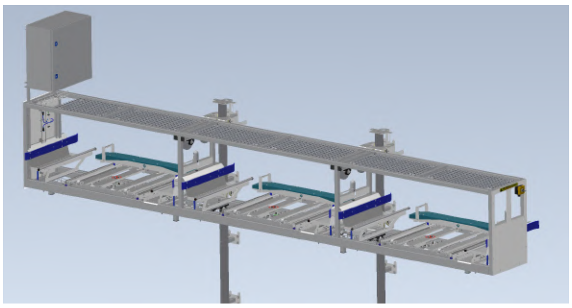

Figure 1.12: Lift mechanism with three robot's

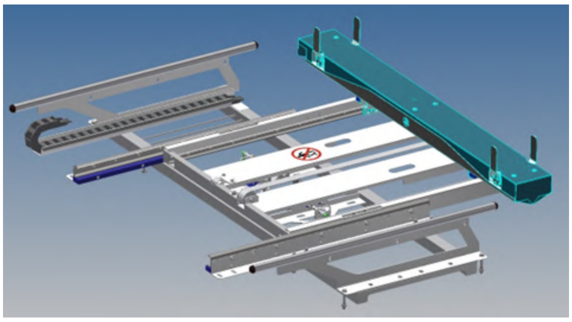

Figure 1.13: The vertical farm robot

1.2. Problem statement and motivation

The system needs to be flexible for growing crops in an automated vertical farm to be efficient. Disturbances no longer come from harsh or unsuitable weather but from fluctuating energy prices and changes in consumer demands. Thus, vertical farming must scale up, scale down, or change the production altogether. The current robot has a variety of limitations that prevent reliable large-scale implementation, with design flaws that limit the technical lifespan of the system. The system is inflexible because the robot can only reach the bench directly at the front of the lane. Additionally, the benches encounter more resistance than initially accounted for in the robot's design. The current strategy for changing or rearranging the benches is by hand or using empty benches to shift the other benches forward. According to Artechno, both solutions lead to sub-optimal performance.

1.3. Research goal

The goal of this research is to identify all problems with their root causes and possible solutions and then choose a solution to provide the highest system performance.

1.4. Research question

The main research question is as follows:

Can the system performance be improved by redesigning the vertical farm robot?

This research addresses this question through four sub-questions linked by chapter:

	Subquestion	**Chapter**
1.	What problems does the system have, how do these problems decrease the system's performance, and what are possible solutions to these problems?	2. Analysis
2.	How have others solved similar problems, and how have these solutions influenced the system's performance?	3. Literature
3.	What are possible solutions, and what does the best solution look like in detail?	4. Conceptual Design 5. Preliminary Design 6. Detailed Design
4.	Does the solution satisfy the requirements, and are the results as desired beforehand?	7. Implementation and Results

1.5. Report outline

This thesis consists of the following chapters:

- **Analysis:** An analysis of the current system's problems due to simulations
- **Literature Review:** A literature review of possible solutions.
- **Conceptual Design:** A design methodology is chosen, requirements and constraints are set, and a collection of different concepts arise from a morphological chart and are weighted against each other using the weighted criteria method
- **Preliminary Design:** The highest-scoring concepts are detailed to provide a more convenient final design choice.
- **Detailed Design:** A CAD model of the chosen concept.
- **Implementation and Results:** A prototype of the CAD model is tested to see if it meets the requirements.
- **Conclusion:** A conclusion and recommendations regarding this research's proposed solutions and findings.

2

Analysis of the climate cell

This chapter answers the first research sub-question:

What problems does the system have, how do these problems decrease the system's performance, and what are possible solutions to these problems?

This chapter discusses the restrictions of the system and the resulting shortcomings, followed by how they influence the system's performance. Moreover, a company where the system operates is visited to see the shortcomings encountered during operation. Finally, a simulation analysis visualises these shortcomings and tests possible solutions.

2.1. Current system

Since the working principle of the climate cell is clear, we can examine its restrictions. The first two restrictions occur if the in-feed is too high or too low, as shown in Figures 2.1 and 2.2.

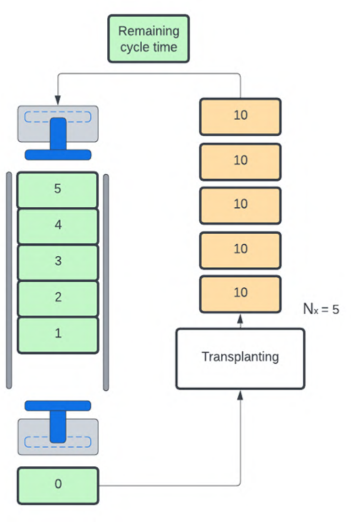

Figure 2.1: Restriction 1: In-feed is too high

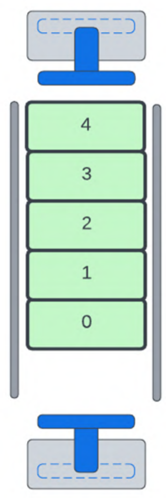

Figure 2.2: Restriction 2: In-feed is too low

To avoid Restrictions 1 and 2, a calculation for each climate cell with a configuration of (L) layers, (R) rows, and (B) benches per row was made to determine the daily in-feed:

Space required per phase:

$$S_i = l_x \prod_{i=x}^{1} N_x$$

Total space required:

$$S_total = \sum_{i}^{0} S_i$$

Daily input:

$$D = \frac{L * R * B}{S_{totaal}}$$

Example: In a climate cell of L x R x B at 10 x 3 x 32, a crop needs to be transplanted two times before entering the harvesting machine with the multiplication factors of N1 = 1, N2 = 5, N3 = 3 and cycle times of L1 = 18, L2 = 10, L3 = 10.

S1 = 18 * 1 = 18, **S2** = 10 * 1* 5 = 50, **S3** = 10 * 1* 5 * 3 = 150

Stotal = 18 + 50 + 150 = 218

D = 960 / 218 = 4,404
With the daily input, the lane configuration within the cell can be made with this calculation:

Lanes required per phase:

$$L_x = \frac{D * \ S_x}{b}$$

L1 = 4,404 * 18 / 32 = 2.48, **L2** = 4,404 * 50 / 32 = 6.88, **L3** = 4,404 * 150 / 32 = 20.64

The rows are not integers, so multiple phases must occupy some rows. However, we now encounter the last restriction of the system: it is a first in, first out (FIFO) system. Figure 2.3 shows it schematically.

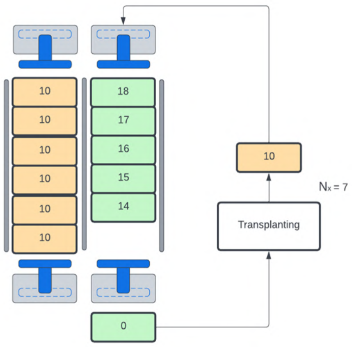

Figure 2.3: Restriction 3: Different cycle times. Crops with a lower cycle time should not be placed behind crops with a higher cycle time.

Because various plants have different strategies, a simulation programme tells the system which bench should be placed at which feed position in the climate cell to maximise the coverage ratio of the cell. The plant's strategy, the daily in-feed calculation, and the cell configuration calculation configure the model's input. Then, the simulation model considers the restrictions and decides the best successive steps, resulting in the output of the cell's content of each consecutive day and a log file with all actions per day.

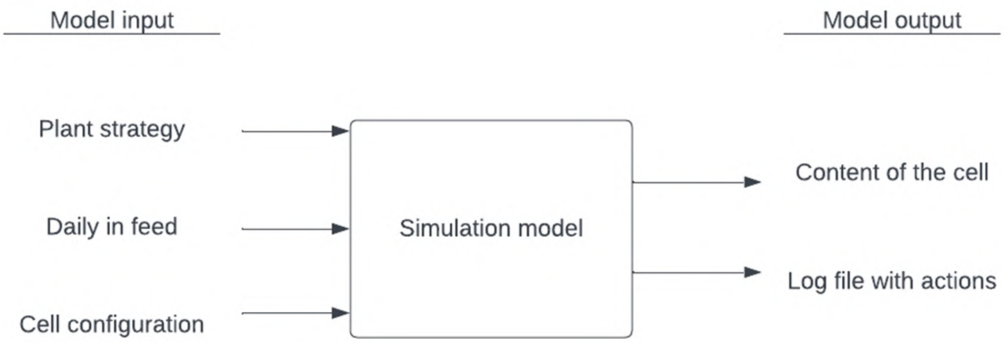

Figure 2.4: Schematic overview of the simulation model

Figure 2.5 shows what the output of the model looks like.

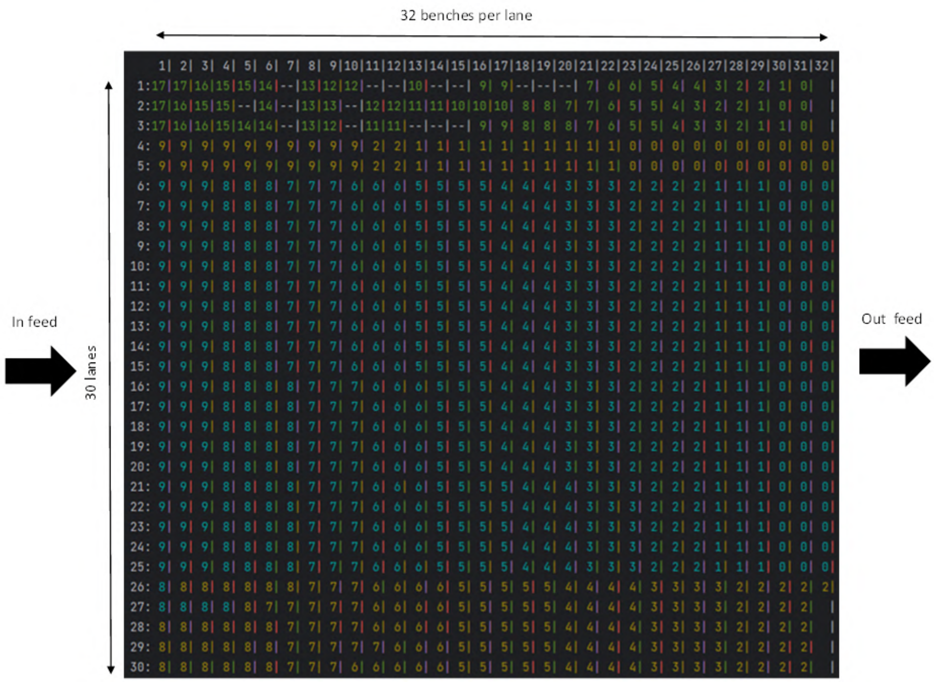

Figure 2.5: Visualisation of the simulation model with the depth of the climate cell (32 benches) on the x-axis and the lanes (10 layers of three rows each) on the y-axis. The benches move from the left (in-feed) to the right (out-feed). The numbers represent the remaining cycle time per bench, while two white lines represent an empty bench. The colours of the numbers represent each phase: green is phase 1, orange is phase 2, and blue is phase 3. The colours beside the numbers represent the crops.

The previous example was used with the multiplication factors of N1 = 1, N2 = 3, and N3 = 5 and cycle times of L1 = 18, L2 = 10, and L3 = 10 to visualise the filling of a climate cell, as seen in Figures 2.6 and 2.7.

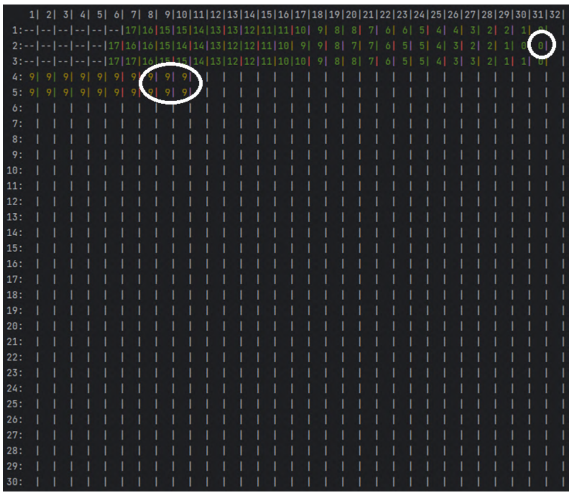

Figure 2.6: Climate cell on day 18

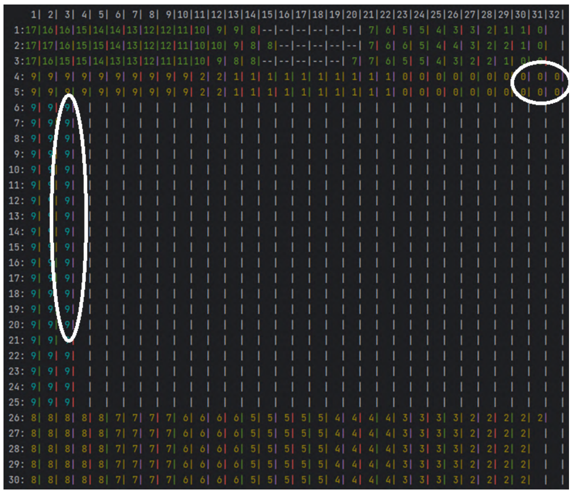

Figure 2.7: Climate cell on day 28

As shown above, on day 18, a phase 1 (green) bench creates five benches of phase 2 (orange). On day 28, these five benches create 15 benches of phase 3 (blue). The coloured strips next to the remaining cycle time represent different crops, which, in this case, all four (green, orange, red, and purple) follow the same strategy. Simulating this forward in time will result in a fixed configuration of the climate cell, shown in Figure 2.8.

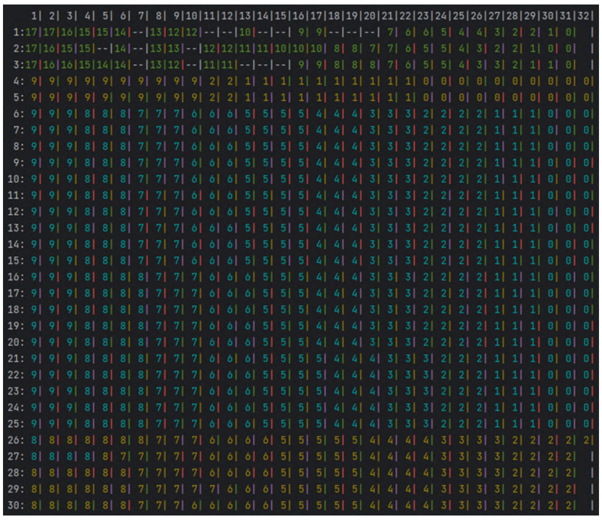

Figure 2.8: Climate cell on day 100

In lanes 26 and 27, phases 2 and 3 are placed on the same lane because they have the same cycle time..

2.2. Shortcomings of the current systems

Once the workings of the current system were clarified, the deficiencies of the current system and their impact on the system's performance were identified. Thus, key performance indicators (KPIs) were determined, as described below:

The key Performance Indicators (KPI's) of the system can be described as:
1) Kilogram crops per square metre of the occupied cultivation area (Yield).
2) Square metre cultivation area per square metre factory ground.
3) Operational costs per square metre factory ground.
4) Coverage ratio = Occupied cultivation area / Total cultivation area
5) Crop quality which is quantified as leaf length, tip burn and taste.

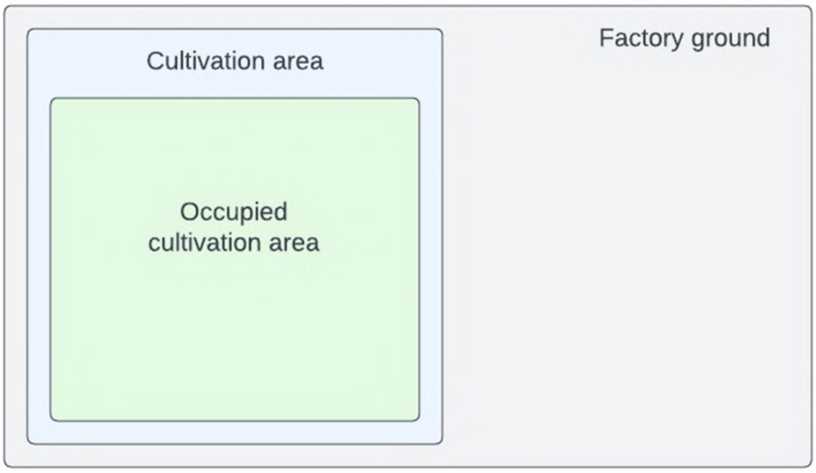

Figure 2.9: Explanation of the KPIs.

The company where the system operates was visited to discover the system's deficiencies. When talking to the owners of the company, the system's problems became apparent:

- 1. Unnecessary infeed of empty benches.
- 2. Processes in the factory were mutually dependent.
- 3. Few same crops in succession to the harvesting machine.
- 4. Seven working days were required.
- 5. Low meantime between failure of the vertical farm robot.

Since most of these problems were related to the logistics of the system, a simulation analysis was selected to understand the origins of the problems. Once the root causes of problems were known, possible solutions could be devised.

1) Unnecessary in-feed of empty benches

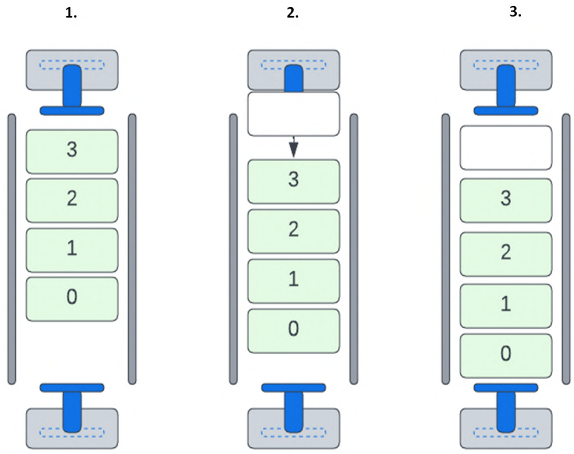

Figure 2.10: The robot could not grab a ready bench. Therefore, an empty bench was inserted to push all the benches forward. Due to a maximum and fixed in-feed amount, inserting a full bench was impossible.

Empty benches yield no crops, causing the number of kg crops per square metre and the coverage ratio to decrease. Moreover, the empty benches had to be cleaned after leaving the climate cell, increasing the costs.

Change in KPI's:
1) Kilogram crops per square metre occupied cultivation area: **Unchanged.**
2) Square metre cultivation area per square metre factory ground: **Unchanged.**
3) Operational costs per square metre factory ground: **Increased**
4) Coverage ratio: **Decreased**
5) Crop quality: **Unchanged.**

Possible solution approaches:
1) Increase the reach of the vertical farm robot.
2) Improve the logistics.
3) Redesign the climate cell.

2) Processes in the factory are mutually dependent

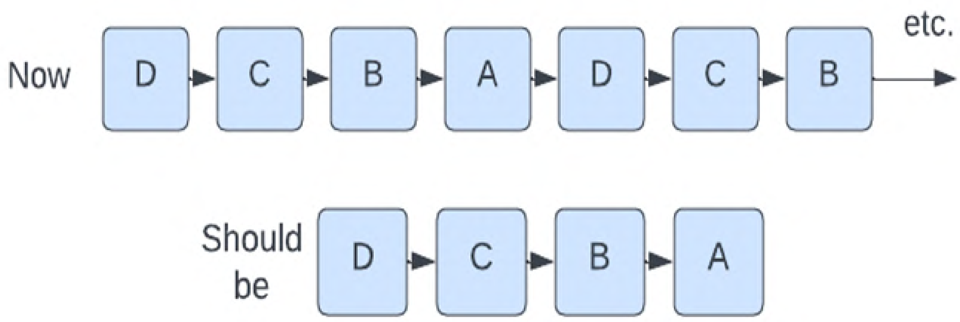

Figure 2.11: Processes in the factory are mutually dependent

If D is the harvesting in phase 3, C is the transplanting in phase 2, B is the transplanting in phase 1, and A is the in-feed of the benches, each process is mutually dependent in the current scenario. Hence, for process D to continue, the other processes must first proceed. Therefore, all processes happen simultaneously. Each process requires a number of workers, which costs money and creates much commotion in the factory. The desired situation should be that each process is executed separately so that process D is totally finished before starting with process C. In this case, one team of personnel can execute all processes, reducing operatinal cost.

Change in KPI's:
1) Kilogram crops per square metre occupied cultivation area: **Unchanged.**
2) Square metre cultivation area per square metre factory ground: **Unchanged.**
3) Operational costs per square metre factory ground: **Increased**
4) Coverage ratio: **Unchanged.**
5) Crop quality: **Unchanged.**

Possible solution approaches:
1) Increase the reach of the vertical farm robot.
2) Redesign the climate cell.

3) Few same crops in succession to the harvesting machine

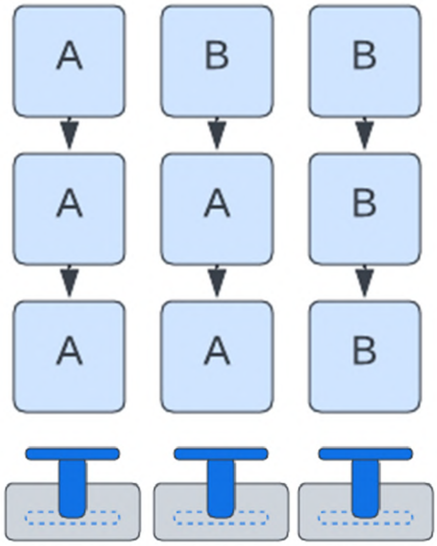

Figure 2.12: The robots can only grab benches row by row

When the climate cell is filled with different crops, crops A and B are in the front row and can be grabbed by the robot, while the benches on the second row are out of reach. Therefore, first, AAB is sent to the harvesting machine, followed by AAB and ABB. Each time a different crop is sent to the harvesting machine, the harvesting machine needs to be cleaned. Because crops are consumer goods, residues of Crop A should not come into contact with Crop B. Therefore, the ideal would be if the robot could grab more benches so that all five benches of Crop A could be grabbed and sent to the harvesting machine, followed by the four benches of Crop B.

Change in KPI's:
1) Kilogram crops per square metre occupied cultivation area: **Unchanged.**
2) Square metre cultivation area per square metre factory ground: **Unchanged.**
3) Operational costs per square metre factory ground: **Increased**
4) Coverage ratio: **Unchanged.**
5) Crop quality: **Unchanged.**

Possible solution approaches:
1) Increase the reach of the vertical farm robot.
2) Create a buffer area.

4) Seven working days are required

The current system requires daily input on all seven days of the week, meaning that the company needs employees on weekends, which are expensive work days. Suppose we choose not to work on the weekend, the situation shown in Figure 2.13 would appear.

Figure 2.13: We enter a crop on Tuesday with a cycle time of 18 days, which has to be taken out two weeks later on a Saturday. However, we do not work on Saturdays, so it only leaves the climate cell two days later on Monday, which influences the quality of the crop.

However, employees are needed on Saturdays and Sundays, which are expensive working days.

Change in KPI's:

1) Kilogram crops per square metre occupied cultivation area: **Unchanged.**
2) Square metre cultivation area per square metre factory ground: **Unchanged.**
3) Operational cost per square metre factory ground: **Increased**
4) Coverage ratio: Unchanged
5) Crop quality: **Unchanged.**

Possible solution approaches:

1) improve the logistics.

5) Low meantime between failure of the vertical farm robot.

The vertical farm robot has many issues, resulting in high system downtime. The main issues are:

1) the robot's misgrabbing
The benches encounter more resistance than initially accounted for, which results in a small deviation of the position of the benches, making it more difficult for the robot to grab the bench, as shown in Figure 2.14.

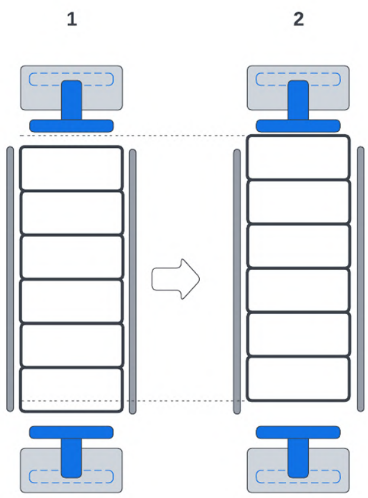

Figure 2.14: The benches should be positioned as in situation 1. However, the bouncing back of each bench when a new bench is pushed in causes the benches to be positioned like in situation 2.

2) High maintenance.
Because the current design has high part count and difficult maintenance to wear parts, the design is highly complex and needs regular maintenance.

Change in KPI's:
1) Kilogram crops per square metre occupied cultivation area: **Unchanged.**
2) Square metre cultivation area per square metre factory ground: **Unchanged.**
3) Operational cost per square metre factory ground: **Increased**
4) Coverage ratio: **Unchanged.**
5) Crop quality: **Unchanged.**

Possible solution approaches:
1) Redesign of the vertical farm robot.

2.3. Case studies

The solution to redesigning the vertical farm robot had to solve all shortcomings, except for problem 4 in Section 2.2. Therefore, four realistic test cases were simulated by changing the parameters, such as the cell configuration and the reachability of the robot. Hence, the influence of grabbing more than the first available bench was clearly shown, which provided strong justification for the choice of redesigning the vertical farm robot while giving insight into how many benches the robot should grab for the highest performance of the system. The test cases were rated based on the criteria related to the mentioned deficiencies: 1) the average coverage ratio, 2) the average number of executed benches of the same crop in succession, 3) the average number of actions in sequence, and 4) the total number of empty benches appended in 100 days.

2.3.1. Leafy greens

Crop type	Distribution*	Cycle time (Lx)	Multiplication factor (Nx)
A	25%	L1 = 18, L2 = 10, L3 = 10	N1 = 1, N2 = 5, N3 = 3
B	25%	L1 = 18, L2 = 10, L3 = 10	N1 = 1, N2 = 5, N3 = 3
C	25%	L1 = 18, L2 = 10, L3 = 10	N1 = 1, N2 = 5, N3 = 3
D	25%	L1 = 18, L2 = 10, L3 = 10	N1 = 1, N2 = 5, N3 = 3

Table 2.1: Test case 1.
***Distribution of crops in the climate cell. With a daily in-feed of four, the daily in-feed of A, B, C, and D is one.*

First, a calculation, explained in Section 2.1, determined the daily input and how the lane layout of the cell would look:

D = 960 / 218 = 4.404

L1 = 4.404 * 18 / 32 = 2.48, **L2** = 4,404 * 50 / 32 = 6.88, **L3** = 4.404 * 150 / 32 = 20.64

The maximum in-feed was 4.4 per day. However, the rows needed for phase 1 were 2.48 (or three rows). The rows needed for phases 2 and 3, with the same cycle time, would be higher than 27, meaning that more than 30 rows would be needed for all three phases, which was impossible. Therefore, the maximum in-feed was 4.3, equalling 1,075 per crop due to the relation. Thus, the new lane configuration was as follows:

L1 = 4.3 * 18 / 32 = 2.42 = 3, **L2** = 4.3 * 50 / 32 = 6.72, **L3** = 4.3 * 150 / 32 = 20.16
L2 + L3 = 6.72 + 20.16 = 26.8 = 27

A simulation was run for 100 days with these fixed model inputs for different robot reachabilities. A Python script was written to convert the log file of all actions to values and plots to visualise the results. These plots appear in Appendix B. The following results were found, as shown in Table 2.2.

Reachability of the robot	**Coverage ratio**	**2***	**3****	**4*****
1	97.65%	5.21	82.26	91
2	97.65%	10.03	60.24	65
3	97.65%	14.46	39.94	50
4	97.65%	14.72	31.99	35
5	97.65%	14.86	27.30	20
6	97.65%	15	23.35	5
7	97.65%	15	18.64	0
8	97.65%	15	18.64	0

Table 2.2: Results of test case 1
*=Average number of executed benches of the same crop in succession
**=Average number of different actions in sequence
***=Total number of empty benches appended in 100 days

The coverage ratio should increase, the average number of executed benches of the same crop in succession should also increase, the average number of different actions in sequence should decrease, and the total number of empty benches appended in 100 days should also decrease to increase the system performance. The optimum was reached when the reachability of the robot was **7**, after which the criterion did not improve

2.3.2. Microgreens

Crop type	**Distribution**	**Cycle time (Lx)**	**Multiplication factor (Nx)**
A	50%	L1 = 14, L2 = 14	N1 = 1, N2 = 5
B	25%	L1 = 14, L2 = 14	N1 = 1, N2 = 5
C	25%	L1 = 14, L2 = 16	N1 = 1, N2 = 5

Table 2.3: Test case 2.

The results for test case 2 were as follows:

Reachability of the robot	**Coverage ratio**	**A2***	**B2***	**C2***	**3****	**4*****
1	97.77%	16.70	7.65	5.30	30.05	45
2	97.77%	28.17	11.34	7.36	24.15	6
3	97.77%	28.44	14.46	8.46	19.60	0
4	97.77%	28.45	14.47	11.09	18.68	0
5	97.77%	28.45	14.47	11.45	18.36	0
6	97.77%	28.45	14.47	11.45	18.36	0

Table 2.4: Results of test case 2
*=Average number of executed benches of the same crop in succession
**=Average number of different actions in sequence
***=Total number of empty benches appended in 100 days

The result plots appear in Appendix B.

2.3.3. Herbs

Crop type	Distribution	Cycle time (Lx)	Multiplication factor (Nx)
A	75%	L1 = 12, L2 = 10	N1 = 1, N2 = 2
B	25%	L1 = 10, L2 = 12	N1 = 1, N2 = 2

Table 2.5: Test-case 3

The results for test case 3 were as follows:

Reachability of the robot	Coverage ratio	A2*	B2*	3*	4*
1	98.77%	15	4	51.46	64
2	98.77%	30	7.17	45.18	64
3	98.77%	45	10.57	40.53	46
4	98.77%	48	10.60	36.97	30
5	98.77%	48	10.60	36.97	16
6	98.77%	48	10.60	36.97	0
7	98.77%	48	10.60	36.97	0

Table 2.6: Results of test case 3
*=Average number of executed benches of the same crop in succession
**=Average number of different actions in sequence
***=Total number of empty benches appended in 100 days

The result plots appear in Appendix B.

2.3.4. Soft fruits

Crop type	Distribution	Cycle time (Lx)	Multiplication factor (Nx)
A	50%	L1 = 14	N1 = 1
B	25%	L1 = 14	N1 = 1
C	25%	L1 = 20	N1 = 1

Table 2.7: Test case 4

The results for test case 4 were as follows:

Reachability of the robot	1.	A2.	B2.	C2.	3.	4.
1	99.67%	21.99	9.49	6.10	20.58	0
2	99.67%	35.49	9.49	11.09	8.45	0
3	99.67%	35.49	17.00	11.09	2.27	0
4	99.67%	35.49	17.00	11.09	2.27	0

Table 2.8: Results of test case 4

The result plots appear in Appendix B.

2.4. Conclusion

The first conclusion was that the coverage ratio was not affected by the reachability of the robot but fully depended on the cycle times. Therefore, to increase the coverage ratio, the cycle times should be the same or have a common denominator to ensure different phases can be combined in the same lane to avoid empty spaces.
During the simulation with different cycle times, the second conclusion and the solution to problem 4 emerged. The daily input needed to be increased by

$$\frac{7}{7 - days\ not\ working}$$

to work fewer days, provided the cycle times were a multiple of 7. Otherwise, some benches would need to be removed from the climate cell on the days off from work.

The third conclusion was that all other problems mentioned in Section 2.2 could be solved by increasing the reachability of the robot. However, every test case had a different optimum for how far the robot should reach, meaning that the redesign needed a reachability that worked for the worst-case scenario, or the design had to be scalable to the optimum of the relevant case. It was better to have a scalable design to save costs. In Figure 2.15, each criterion is plotted individually with the results of each test case below to overview the results..

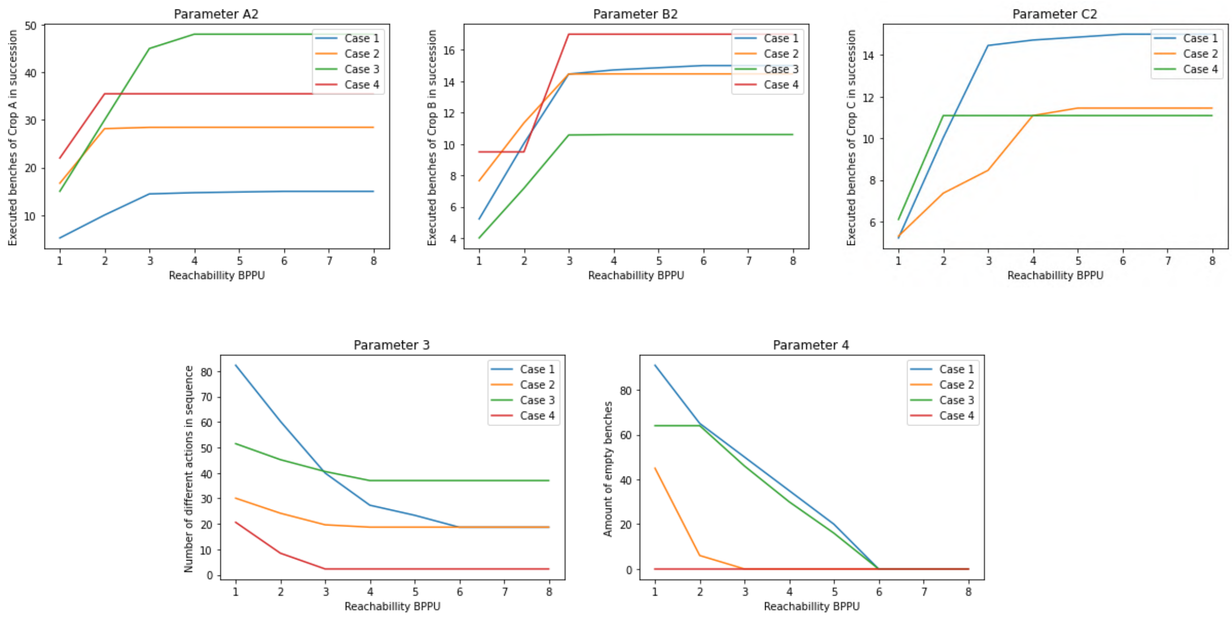

Figure 2.15: The results of each test case for every criterion. The x-axis shows the reachability of the robot, while the y-axis shows the values of the tested criteria. For criteria A2, B2, and C2, the higher the value, the higher the system's performance. For criteria 3 and 4, the value had to be as low as possible.

To conclude,
the coverage ratio and amount of working days depended on the cycle times. The ideal was only cycle times with a multiple of 7. Moreover, to solve the other problems, a redesign of the vertical farm robot on the out-feed side was needed. Therefore, the rest of this thesis focused on redesigning the robot.

3
Literature Review

This chapter answers the second research sub-question:

How have others solved similar problems, and how have these solutions influenced the system's performance?

The previous chapter clarified that the main problem was that the robot could not reach further than the first bench. This chapter examines how competitors have solved this problem and whether their solutions could be applied to our system. Other industries were also examined for possible solutions.

3.1. Competitor analysis

1) Logiqs Vertical farm

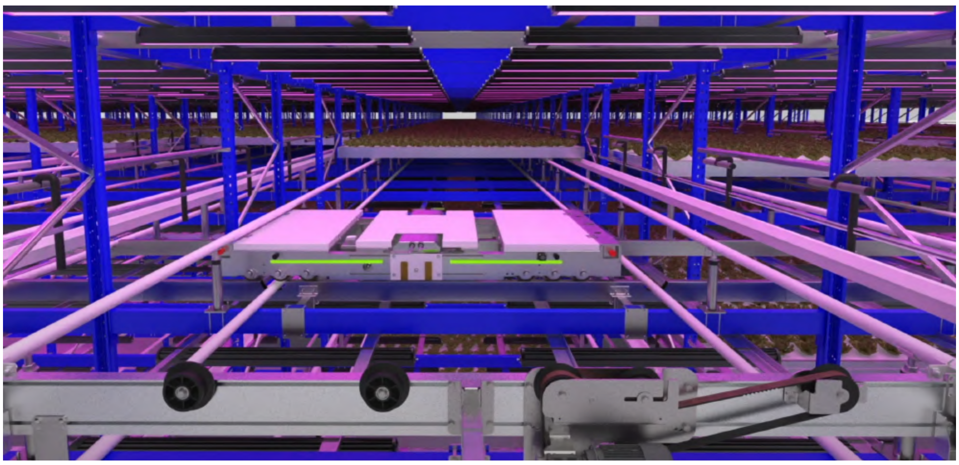

Figure 3.1: Inside view of the Logiqs vertical farm with a 3D shuttle [4].

As shown in Figure 3.1, Logiqs uses a 3D shuttle to grab every bench within the system. However, this shuttle moves under the benches. Because the shuttle has a specific thickness, space must be made for it, ensuring that the number of layers of the Logiqs vertical farm only consists of five layers, as shown in Figure 3.2.

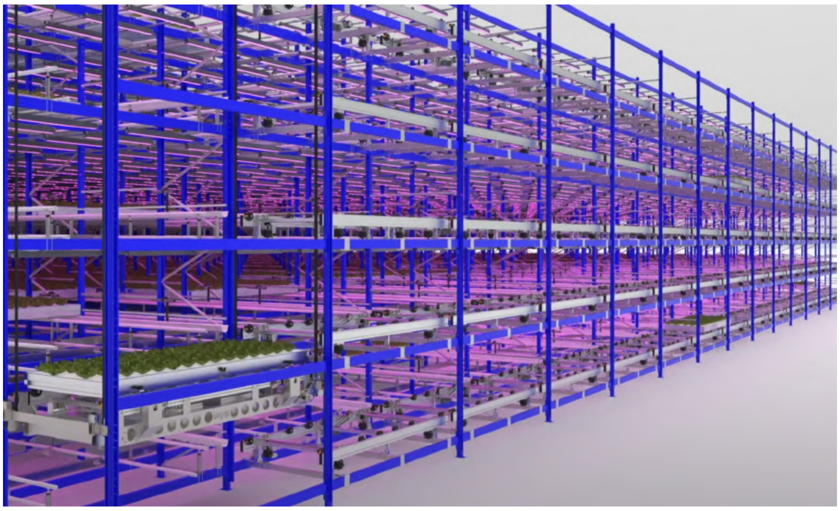

Figure 3.2: Front view of the Logiqs vertical farm.

Implementing the 3D shuttle decreases the number of layers, influencing the KPIs. Namely, the square metre cultivation area per square metre of factory ground decreases. However, the 3D shuttle ensures no more empty spaces within the climate cell, causing the KPIs to increase. A calculation was made to determine which had more impact on the KPIs.

2) SANANBIO Vertical farm

Figure 3.3: Inside view of the SANANBIO's vertical farm with an empty middle row for an automated guided vehicle (AGV) [5].

The inside of the SANANBIO's vertical farm shows that AGVs pick each bench within the system from an empty lane. The AGV brings the bench to the end of the row, where a 2D shuttle grabs the bench, as shown in Figure 3.4.

Figure 3.4: Front view of the SANANBIO's vertical farm with a 2D shuttle

Implementing an empty row in the middle makes it clear that the square metre cultivation area per square metre of factory ground also decreases. Therefore, the same calculation was made here to see which had more impact: the empty row or the empty spaces to be filled.

3.2. Other industries

1) Medication storage

Figure 3.5: Medication picking robot inside the medication storage area

Despite medicine being in tiny boxes, this configuration compared quite well with our system, with multiple boxes behind each other, following the FIFO method. The robot uses a telescopic grabbing arm to grab the boxes further back. However, the boxes are still tiny and do not weigh much, which is the opposite of the benches our system handled.

2) Warehouse management

Figure 3.6: AGVs riding on top of a warehouse rack with a grabbing mechanism that can reach the last crate

The climate cell looks like a warehouse rack system; therefore, this industry offers good material for comparison. Logistics are also critical. In many warehouse systems, space utilisation is not an issue; therefore, an empty middle row is often used. However, in some cases where space utilisation is an issue, the AGVs grab the crates from the top. Unfortunately, in the climate cell, the benches needed to be grabbed from the side because, at some point, the plants were fully grown, and the bench could no longer be taken from the top.

3) Perishable products distribution centres

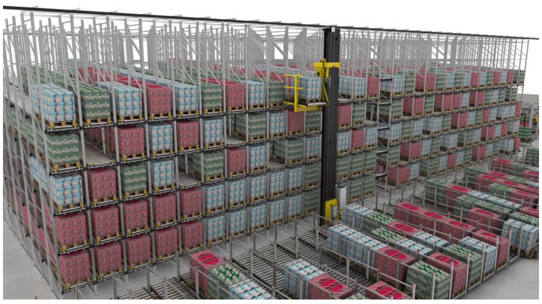

Figure 3.7: overview of a perishable products distribution centre

Figure 3.8: Conveyor belt from the inside of the distribution centre

In the perishable food industry, FIFO is the most important thing. Here, products must be stored until they can be brought to the shops. Therefore, this model is a perfect example of how this problem was solved in an other industry by using a conveyor belt to move the pallets from the in-feed side to the out-feed side.

4 Conceptual Design

The next three chapters answer the third research sub-question:

What are possible solutions, and what does the best solution look like in detail?

This chapter describes how the design methodology was chosen and the requirements and constraints set. A system decomposition with functional analysis resulted in a morphological chart from which different alternatives emerged. These alternatives were weighted against each other using the weighted criteria method.

4.1. Design Methodology

The thesis employed a five-stage prescriptive model for its research methodology, outlined in Figure 4.1 [8]. This model served as a guide for the design process, delineating essential tasks. However, the design process was not a linear progression, so discoveries in later stages could influence and reshape earlier ideas. The process encompassed five key stages: the problem definition from Section 1.1, the conceptual design, the preliminary design, the detailed design, and the design communication. Continuous feedback within and between these phases ensured ongoing refinement. Additionally, external input from Artechno was instrumental in aligning the design with the company's preferences and expectations

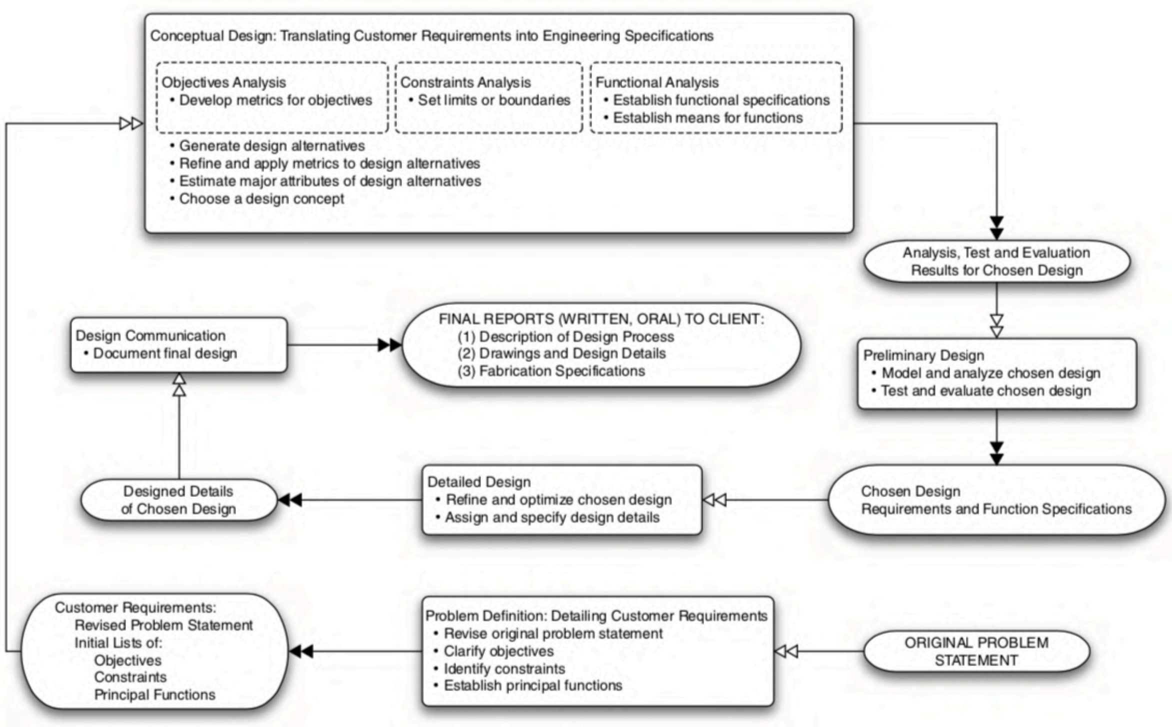

Figure 4.1: The five-stage prescriptive model.

Conceptual design

Divergent thinking is critical in the conceptual design for the idealisation mode designers use to extend their design space as they explore possible solutions. They generate as many new ideas as possible using various methods to explore possibilities [2]. Here, different brainstorm sessions provided alternatives, which were not elaborated but technically and scientifically rated with the help of Artechno's desires. The alternatives were weighed against each other using the weighted criteria matrix, where the weighted criteria arose from the requirements and constraints. Subsequently, the best-scoring concepts moved on to the preliminary design.

Preliminary design

Next, the best-scoring concepts were detailed, often through technical drawings or a test setup, to better visualise the working principle. These concepts were compared. A well-considered choice was made based on a clearer idea of the working principle of each alternative. Subsequently, the best-scoring concept moved on to the final detailed design.

Detailed design

The chosen design was optimised in the detailed design, and a 3D model was made with all details assigned and specified, including dimensions and materials. After this phase, the design parts were made and assembled into a working prototype for testing.

Design communication

In the final phase, a document of the master thesis containing all phases, from the problem description to the specifications and materials of the final design, was delivered.

4.2. Requirements and constraints

All requirements and constraints were determined in consultation with Artechno as follows:

Index	Requirement	Description	Importance	Origin
R-1.0	Reliability	The structure must grab the benches 99,95%* of the time.	MH	Artechno
R-2.0	Cost	The structure must be less expensive than the previous version which cost €2500	NH	Artechno
R-3.0	Complexity	The part count must be less than the previous version which is 930.	NH	Artechno
R-3.1	Complexity	As few electronic features in the cell as possible**.	NH	Artechno
R-3.2	Complexity	Assembly time should be shorter than the previous version which is 1 week.	NH	Artechno
R-4.0	Safety	The structure must be safe according to the ISO 13849-1:2023 standards [1].	MH	Artechno
R-4.1	Safety	The structure must not damage the plants, benches and trays.	MH	Artechno
R-4.2	Safety	Reasonably foreseeable misuses must be taken into account to the ISO 12100:2010 [3].	MH	Artechno
R-5.0	Consideration	The structure must take into account the design of the benches.	MH	Artechno
R-5.1	Consideration	The structure must compensate up to 10cm position inaccuracy of the benches.	MH	Section 2.2
R-6.0	Functions	The structure must be able to reach seven benches deep.	MH	Section 2.4
R-6.1	Functions	The structure must have a capacity of at least 12.5 per hour***.	MH	Artechno
R-7.0	Constraints	The structure must fit into the design space. (Section 4.2.1)	MH	Artechno
R-8.0	Durability	The structure must have a lifetime of at least 219.000 cycles****.	NH	Artechno
R-9.0	Maintenance	Maintenance should be easier for wear parts then the previous version.	MH	Artechno
R-9.1	Maintenance	Protection from touch and water must have the IP value of 55 [7].	MH	Artechno
R-10.0	Public health	The structure must use food-graded materials [9]	MH	Artechno
R-11.0	Effectivity	Fewer possible process steps than the previous version which is 12.	NH	Artechno

*Calculated for the worst case (4), 60 benches for outfeed per day, with an error margin of 1 per month.

**Due to the presence of water and difficult accessibility for maintenance.

***Calculated for the worst case with six working hours per day and a 20% loss of time.

****Calculated for worst case with a life time of ten years.

Table 4.1: Requirements, MH = must have, NH = nice to have.

4.2.1. Design space

The available design space had to be known before making the design. Specifically, the robot base had to be mounted on a lift frame (3,264 mm x 526 mm). Furthermore, the system had three states: state 1) grabbing the bench, state 2) moving the lift, and state 3) moving the bench out of the cell. State 1 is where the robot has to grab the bench and pull it inside the lift. Figure 4.2 shows the dimensions of the first design space.

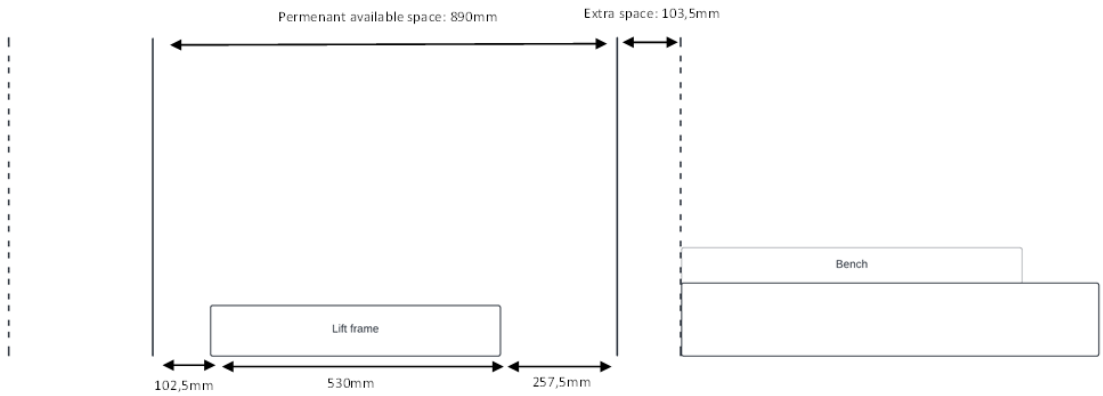

Figure 4.2: Design space of the first state. There is an extra design space of 103.5 mm on the right side of the permanently available space.

For the system to move to the second state, all the structures, including the bench, had to be inside the permanent space to ensure the lift could move. Therefore, the permanently available space was the only available design space. Once the lift reached the bottom layer, the system entered the third state, where the robot moved the bench to the conveyor outside the lift, creating a different design space shown in Figure 4.3:

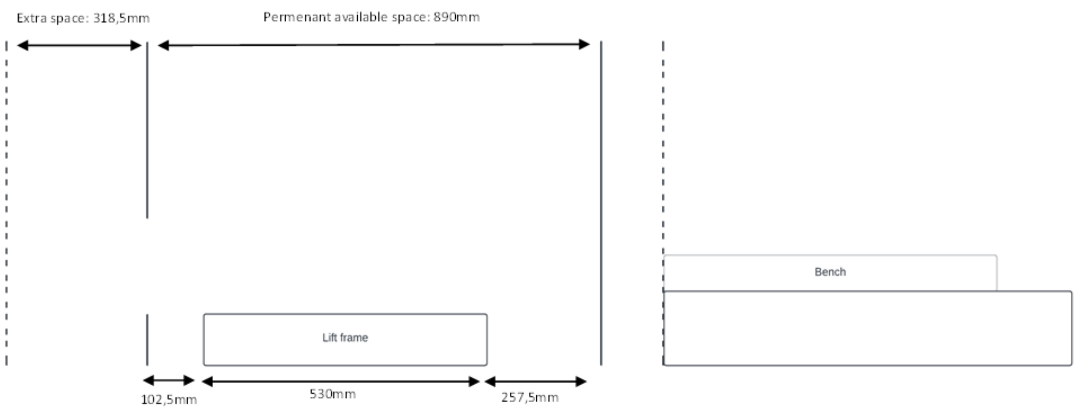

Figure 4.3: Design space of the third state. The hatch on the left side of the lift opens up for the bench to leave the climate cell, creating an extra design space of 318.5 mm.

Knowing the design space inside the cell was also crucial. Figure 4.4 shows that efficient space usage was an important indicator, so everything was very compact, and not much design space was available inside the cell.

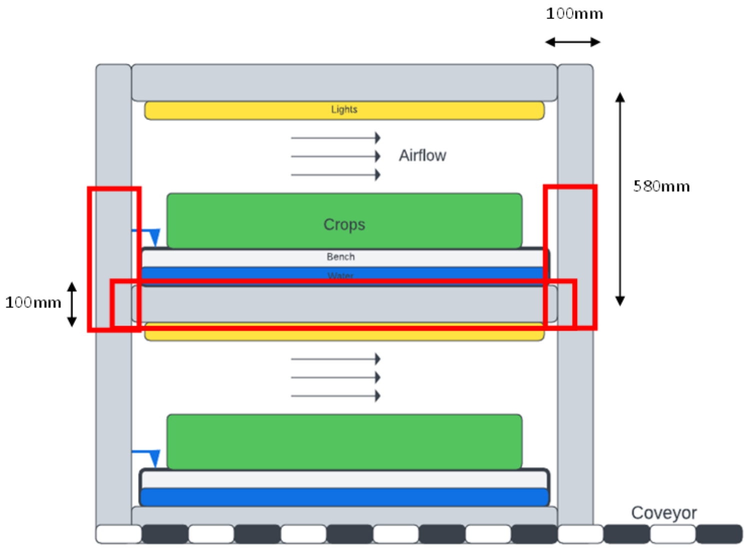

Figure 4.4: The red boxes indicate the design space inside the cell. The rest of the space is used for the bench with water, airflow, lighting, and crop growth.

4.3. System decomposition and functional analysis

Next, determining the vertical farm robot's functionality required developing a morphological chart with various alternatives. Therefore, a system decomposition of the vertical farm robot was made.

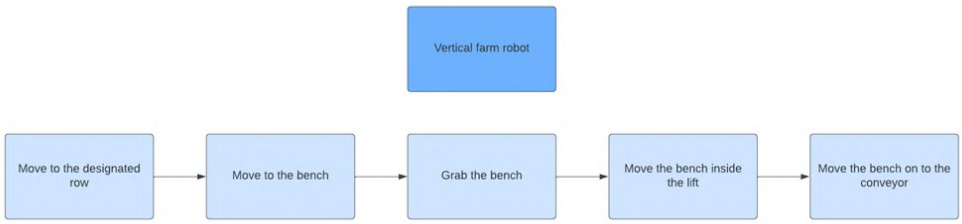

Figure 4.5: System decomposition of the vertical farm robot.

When the lift mechanism reaches the designated layer, the robot moves to the corresponding row with the bench to be grabbed. Once at the bench, the robot should grab it and move it back to the lift. Finally, the bench has to be moved onto the conveyor.

4.3.1. Morphological chart

The system decomposition was visualised in a morphological chart. The movements were separated into a y movement, representing the movement in the lift to reach the right row, and an x movement, with the position within the cell representing the movement to the bench in the cell. The grabbing mechanism for the bench was self-explanatory. The push-off mechanism was the last step of the robot, where the bench is pushed from the lift out of the system on to the conveyor. The movements had to be propelled, so the drive of the movements was also included. Appendix C shows the morphological chart and how each alternative was constructed.

4.4. Alternatives

AGV

The first alternative was a shuttle, which could move in the x and y direction. The x direction used a linear bearing, while the y direction used a groove bearing. Electric motors drove both movements. The shuttle moved under the bench and used its raised edges to grab the bench and push it off to the conveyor outside the climate cell.

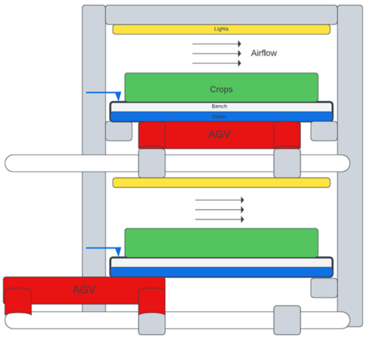

Figure 4.6: Front view of the climate cell

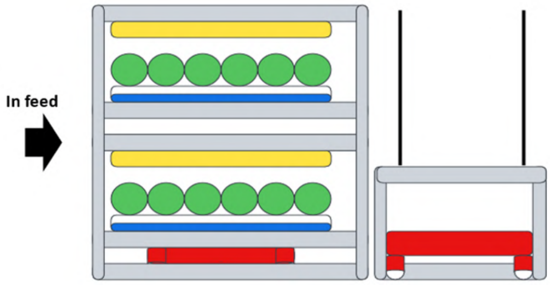

Figure 4.7: Side view of the climate cell

Conveyor belt

The second alternative used three robots for the x direction and a hook-up mechanism to power the conveyor under the benches for the y direction. An electric motor drove this movement. The conveyor also represented the grabbing mechanism. A belt conveyor was used in the lift as a push-off mechanism.

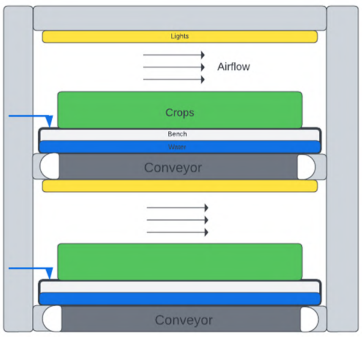

Figure 4.8: Front view of the climate cell

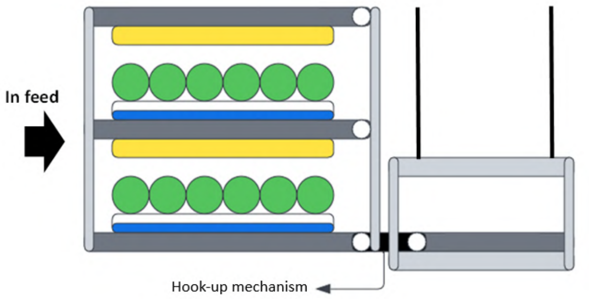

Figure 4.9: Side view of the climate cell

Pull track

The third alternative also used three robots for the x direction. However, it used a screw thread for the y direction within the lift driven by an electric motor. The grabbing mechanism used a hinge mechanism inside the cell and a hook gripper on the robot. The hinge mechanism went under the benches so that they could move over the hinges from the in-feed side but could not move back. The hook gripper moved to the construction inside the cell to grab it. Once grabbed, the hinges behind each bench caused them to move in the y direction. Raised edges were used for the push-off mechanism.

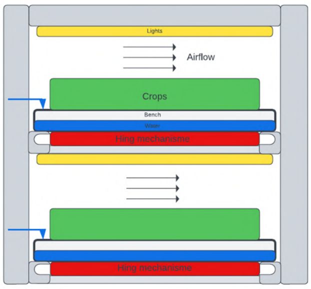

Figure 4.10: Front view of the climate cell

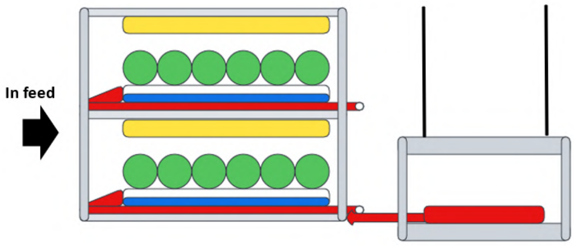

Figure 4.11: Side view of the climate cell

XTS movers

The fourth alternative again used three robots for the x direction but with a linear motor with a grabbing mechanism with raised edges for the y direction, positioned on the side of the bench. Pushing the bench onto the conveyor outside the climate cell used a belt conveyor inside the lift.

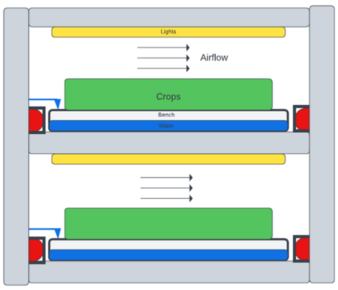

Figure 4.12: Front view of the climate cell

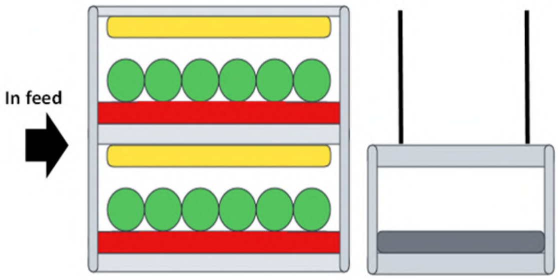

Figure 4.13: Side view of the climate cell

Telescopic arm

The fifth alternative also used three robots for the x direction. The y direction used a telescopic conductor arm mounted on a moving platform, with a toothed belt driven by an electrical motor. The telescopic arm consisted of hinge grippers to grab the bench and move it onto the conveyor outside the cell.

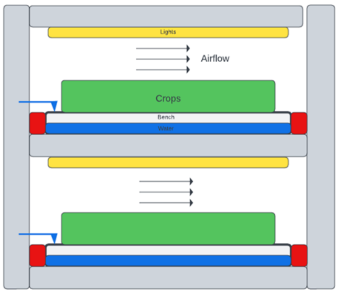

Figure 4.14: Front view of the climate cell

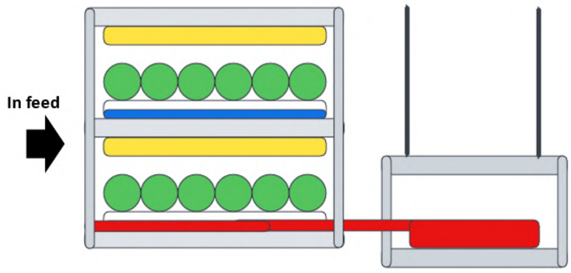

Figure 4.15: Side view of the climate cell

Use of gravity

The sixth alternative had a different approach and changed the design of the climate cell instead of the vertical farm robot. Once the benches need to be grabbed, this alternative put the lanes of the climate cell at a minimal angle, causing the benches to move forward due to gravity. Raised edges were placed at the end of the row to ensure the benches did not fall out of the climate cell. These edges were lowered once the lanes returned to the original state, and the bench was ready to be grabbed. Gravity was used inside the lift to guide the bench outside the lift on to the belt conveyor.

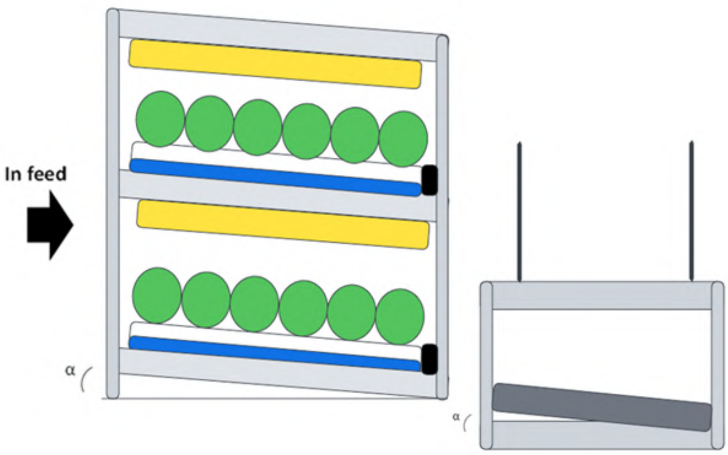

Figure 4.16: Side view of the climate cell where the lanes are at an angle of α degrees

Scissor mechanism

The seventh alternative also had a different approach, changing the climate cell's design by eliminating the lift's use. There was no structure in the middle under the benches, so an AGV could drive through the climate cell. Once the AGV was at the desired bench, it elevated a grabbing platform to grab the bench. A significant disadvantage was that if the first layer was full, no benches could be taken from the layers above

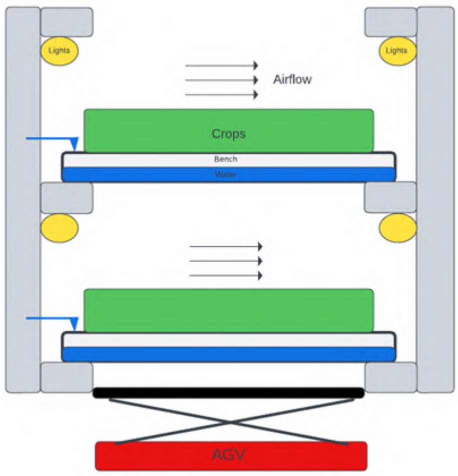

Figure 4.17: Front view of the climate cell where an AGV reaches the benches from driving under the climate cell

4.5. Selection

After clearly understanding the alternatives, they were weighted against each other based on the objectives established, as shown in the objective tree (Figure 4.18)and the weighted criteria method.

4.5.1. Objective tree

When starting with the design process of a system, it is fundamental to understand the stakeholders' needs, objectives, and values. This phase requires comparable high efforts due to the adverse effects misunderstanding between the developers and the stakeholders can have. Needs are often clearly communicated and are reformulated into requirements. However, the underlying objectives and values are often not. Objectives provide reasoning for certain requirements and help develop them. In contrast, values accompany the whole development process and influence decision-making. According to [8], objectives can be arranged within objective trees. Objectives trees enable the graphical representation of objectives in hierarchical order and ease the process of understanding them.

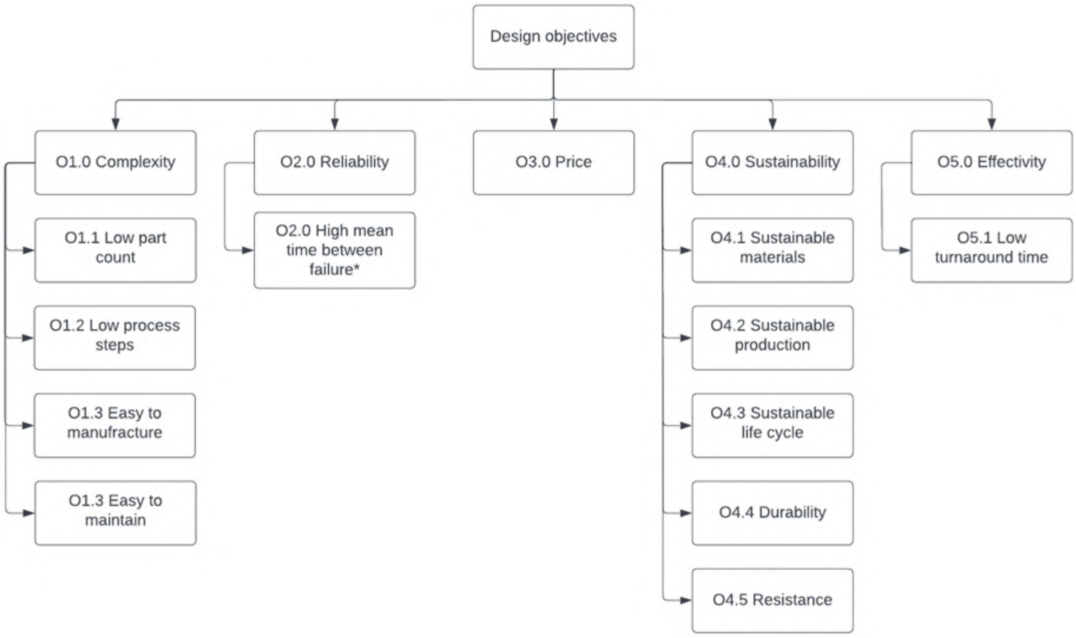

Figure 4.18: Design objectives and their evaluation. Each sub-objective had the same weight, meaning that low part counts and low process steps had the same weight.

4.5.2. Rating

First was determining which objectives were the most important and would have the strongest rating score by comparing them. This process led to the scores in Table 4.2.

	Complexity	Reliability	Price	Sustainability	Effectivity	Total
Complexity	**x**	0	0	1	0	1
Reliability	1	**x**	1	1	1	4
Price	1	0	**x**	1	0	2
Sustainability	0	0	0	**x**	0	0
Effectivity	1	0	1	1	**x**	3

Table 4.2: Determining the weight of each objective by weighting them against each other.

4.5.3. Chosen design

		AGV		Conveyor Belt		Pull Track	
	Weight	Score	Weighted score	Score	Weighted score	Score	Weighted score
Complexity	2	1	2	4	8	4	8
Reliability	5	2	10	4	20	4	20
Price	3	1	3	3	9	4	12
Sustainability	1	2	2	3	3	4	4
Effectivity	4	2	8	4	16	3	12
Total			**25**		**52**		**60**

XTS Movers		Telescopic Arm		Use of Gravity		Scissor Mechanism	
Score	Weighted score	Score	Weighted score	Score	Weighted score	score	weighted score
5	5	3	6	3	12	1	2
3	15	2	10	3	15	2	10
1	3	4	12	3	15	1	3
1	1	4	4	3	4	2	2
5	20	3	12	2	12	1	4
	44		**44**		**58**		**21**

Table 4.3: Weighted criteria method.

The conveyor belt, pull track, and the use of gravity concepts scored the most points, but the scores were close together. Therefore, all three alternatives were included in the preliminary design, as outlined in the next chapter.

5 Preliminary design

The three most promising alternatives from the chosen design were elaborated on to make the final decision. The design challenges for each alternative were examined to determine potential problems, followed by the process steps, part count, and price.

5.1. Conveyor belt

5.1.1. Design challenges

This concept encountered two main design challenges. The first challenge was how the design would fit into the design space. Figure 5.1 illustrates this alternative to ensure that the bench could move from the last position to the lift and from the lift onto the conveyor outside the lift. Figure 5.2 shows the plan to deal with this design challenge.

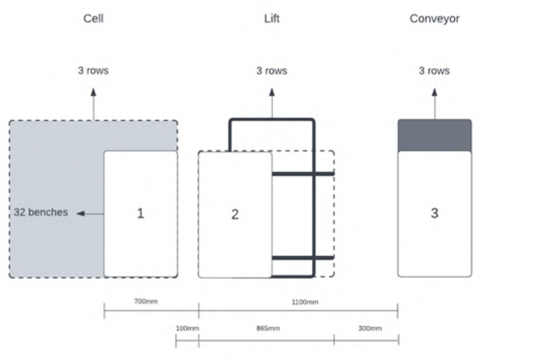

Figure 5.1: Area 1 is the starting position of the bench. Area 2 is the second position of the bench just enough for the lift to move. Area 3 is the final position of the bench on the conveyor outside the cell. Therefore a moving belt conveyor that can move 100mm to the right to align with the layer in the cell and 300mm to the left to align with the conveyor outside the cell is needed.

Figure 5.2: An extendable conveyor belt to cover the gaps between the cell and the lift as well as between the lift and the conveyor.

The second design challenge was how the structure inside the lift would hook to the structure inside the cell to drive the conveyor inside the cell, as seen in Figure 5.3.

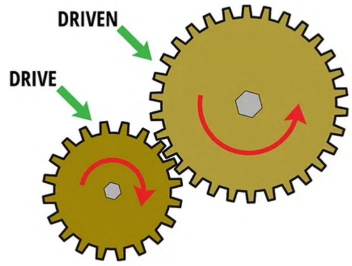

Figure 5.3: A driven gear inside the lift hooks on the gear inside the cell to drive the conveyor.

5.1.2. Process steps

The process steps are in a block diagram and shown schematically:

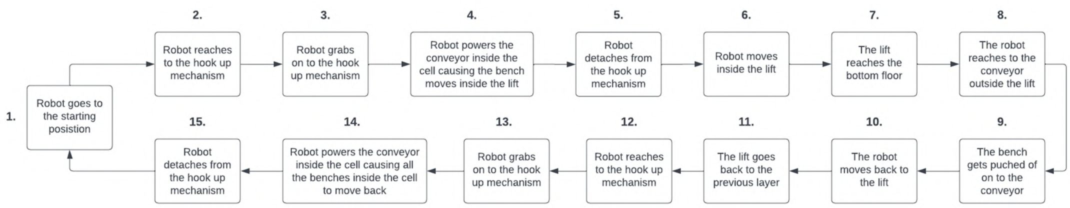

Figure 5.4: Block diagram of the process steps of alternative 2.

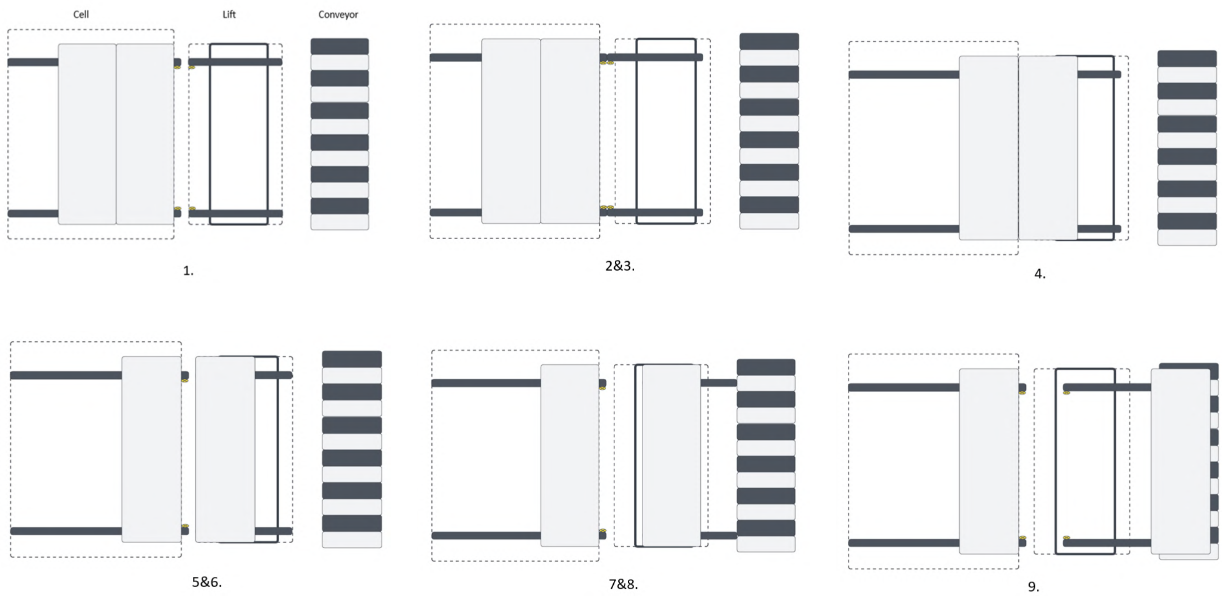

Figure 5.5: Steps 1 through 9 are shown. After step 9, the robot has to return to the previous layer to move all the benches back into 1's place. If this is not done, then a bench at the end will fall out of the system for every bench inserted into the cell, resulting in 15 total process steps.

5.1.3. Part count and price

Artikelen per cell	Artikel nr.	Aantal	Kostprijs	Totaal	Marge	Verkoopprijs
Structure in the cell (					0	
Pulley's + shaft + bearing		60	€ 70,00	€ 4.200,00	€ 1.680,00	€ 5.880,00
Bearing seat / holder		240	€ 25,00	€ 6.000,00	€ 2.400,00	€ 8.400,00
Timing belt (price/10m)		60	€ 50,00	€ 3.000,00	€ 1.200,00	€ 4.200,00
Gear with shaft		30	€ 50,00	€ 1.500,00	€ 600,00	€ 2.100,00
conveyor belt inside the lift						
spindel 400mm + bearing block + start and end bearing		3	€ 325,00	€ 975,00	€ 390,00	€ 1.365,00
Structure + shafts		3	€ 200,00	€ 600,00	€ 240,00	€ 840,00
Ball bearing guide		2	€ 175,00	€ 350,00	€ 140,00	€ 490,00
Stepper drive		1	€ 500,00	€ 500,00	€ 200,00	€ 700,00
Pulley's + shaft + bearing		4	€ 70,00	€ 280,00	€ 112,00	€ 392,00
Bearing seat / holder		8	€ 25,00	€ 200,00	€ 80,00	€ 280,00
Timing belt (price/10m)		1	€ 20,00	€ 20,00	€ 8,00	€ 28,00
Hook up mechanism						
Gear with shaft		6	€ 50,00	€ 300,00	€ 120,00	€ 420,00
Electric motor						
Gearbox						
motor						
encoder						
servo drive						
Drive shaft						
Control panel						
Safety I/O						
Totaal materiaal		418		€ 17.925,00	€ 7.170,00	€ 25.095,00

Figure 5.6: Part count and cost estimation of Alternative 2: Part count = **418**, Cost = **€17,925.00**

5.2. Pull track

5.2.1. Design challenges

The pull track concept encountered three main design challenges. Because this design consisted of a structure inside the lift and the cell, the first design challenge was where to place the pull track inside the cell to avoid additional displacement or decreasing strength of the transverse beams. Figure 5.7 shows a front view of the cell, the attached cross beams, the bench resting on the roller profiles, and the options for the pull track.

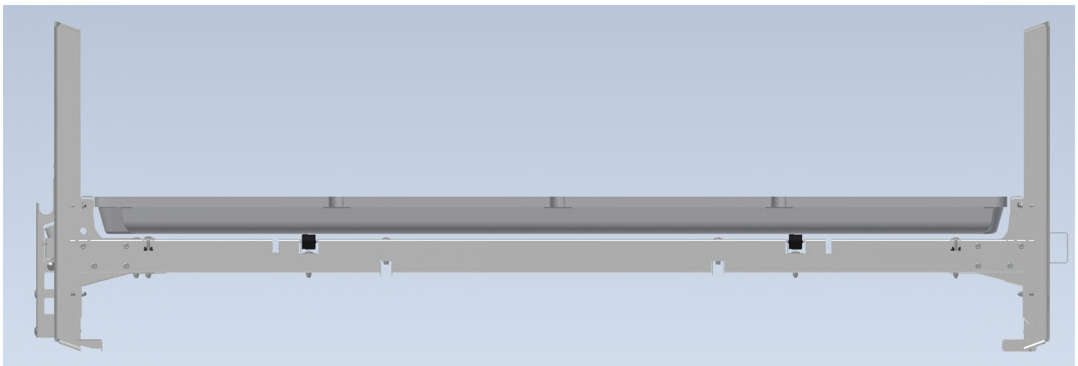

Figure 5.7: Front view of the cell.

Figure 5.8 shows the difference in placement of the pull track and the corresponding Von Mises stress and displacements according to a finite element analysis (FEM) analysis. Because one section consisted of eight benches and eight transverse beams, and the roller profile supported these benches weighing up to 60 kilograms each, two forces of 300 N each were used.

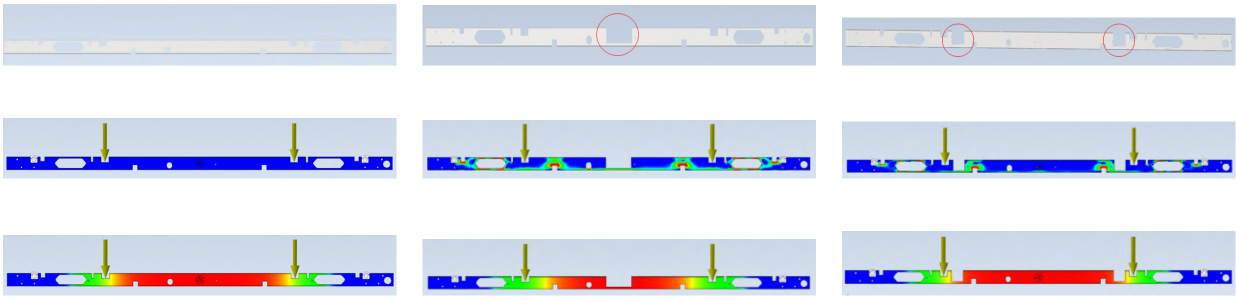

Figure 5.8: The left side is the current situation with a maximum Von Mises stress of 108 Mpa and displacement of 0.60 mm. The middle was a situation where the pull track would be placed in the middle. However, the maximum stress was 228.2 MPa, and the displacement was 1.28 mm. On the right side, two pull tracks were placed next to the roller profiles, with a maximum stress of 167.7 MPa and a displacement of 0.89 mm.

After making the depth of the holes smaller for the situation where two pull tracks were used, the maximum stress quickly moved towards the same as the current situation, making it possible to use this situation, provided the depth of the holes was not too large. The second design challenge concerned the structure inside the lift. Figure 5.9 illustrates how this alternative would fit inside the design space, while Figure 5.10 shows the plan for dealing with this design challenge.

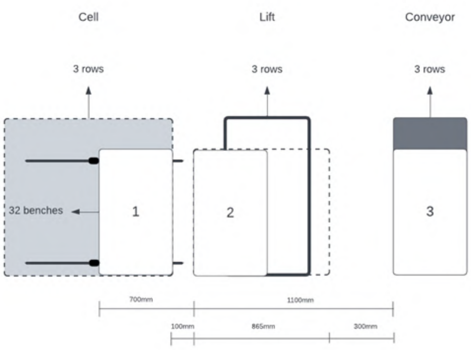

Figure 5.9: From the first to the second position, the bench had to move at least 700 mm for it to be in the elevator sufficiently for the elevator to go to the lower level. From the second to the last position outside the cell, the bench had to move 1,100 mm, which was impossible with one linear movement in the useable space of 865 mm within the elevator. Therefore, a telescopic mechanism was needed.

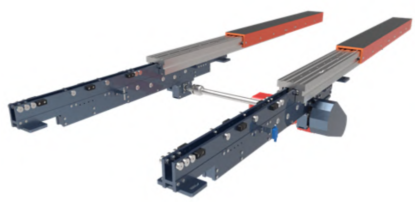

Figure 5.10: A telescopic fork with two arms grabbed the structure in the cell and moved it 700 mm inside the lift. It could also push the bench outside the lift to cover the last 1,100 mm.

The last design challenge was how the robot's mechanical structure would look when grabbing the structure inside the cell and pushing the bench on the conveyor. Figures 5.11 and 5.12 show how a single structure could fulfil both functions:

Figure 5.11: Hook-up mechanism

Figure 5.12: Push-off mechanism

5.2.2. Process steps

The process steps are shown in a block diagram and schematically:

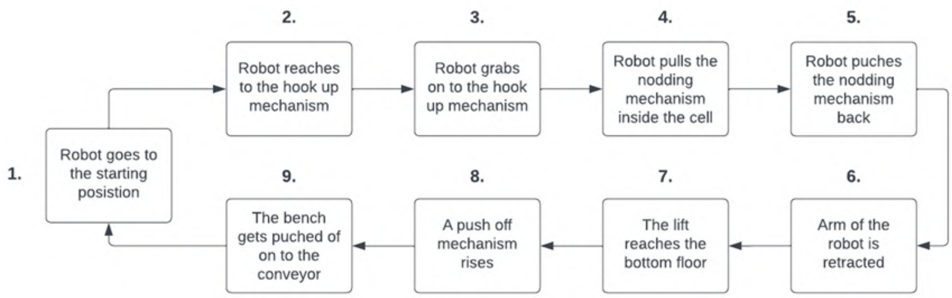

Figure 5.13: Block diagram of the process steps of alternative 2

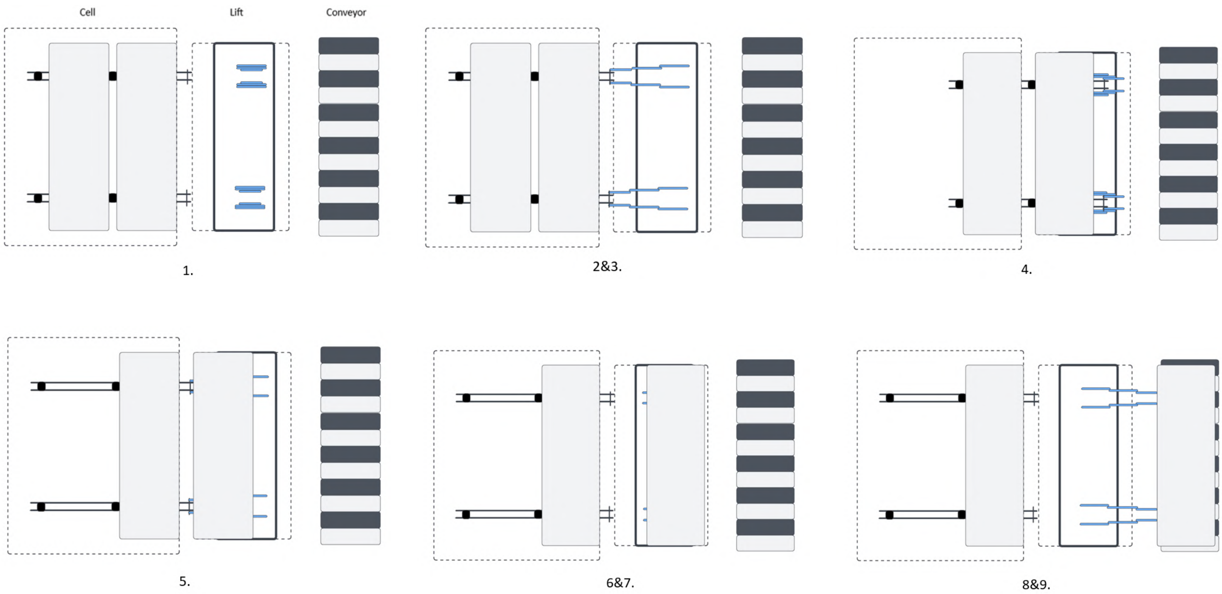

Figure 5.14: Steps 1 through 9

5.2.3. Part count and price

Artikelen per cell	Artikel nr.	Aantal	Kostprijs	Totaal	Marge	Verkoopprijs
Structure in the cell					0	
Nodes + U-profiel		60	€ 150,00	€ 9.000,00	€ 3.600,00	€ 12.600,00
Slide block (price/m)		150	€ 10,00	€ 1.500,00	€ 600,00	€ 2.100,00
Hook up+ push off mechanism						
hook + connection material		4	€ 100,00	€ 400,00	€ 160,00	€ 560,00
air solenoid		2	€ 30,00	€ 60,00	€ 24,00	€ 84,00
Pneumatic cilinder		2	€ 75,00	€ 150,00	€ 60,00	€ 210,00
Driving system						
Pulley's + shaft + bearing		6	€ 70,00	€ 420,00	€ 168,00	€ 588,00
Timing belt (price/m)		20	€ 5,00	€ 100,00	€ 40,00	€ 140,00
hiwin rail		4	€ 120,00	€ 480,00	€ 192,00	€ 672,00
connection materials		1	€ 100,00	€ 100,00	€ 40,00	€ 140,00
Base		2	€ 100,00	€ 200,00	€ 80,00	€ 280,00
extension profile		4	€ 100,00	€ 400,00	€ 160,00	€ 560,00
hiwin bearing wagon						
Electric motor						
Gearbox						
motor						
encoder						
servo drive						
Drive shaft						
Control panel						
Safety I/O						
Totaal materiaal		255		€ 12.810,00	€ 5.124,00	€ 17.934,00

Figure 5.15: Part count and cost estimation of Alternative 3: Part count = **255**, Cost = **€12,810.00**

5.3. Use of gravity

5.3.1. Design challenges

This concept had one big design challenge: how big the angle needed to be for the benches to overcome the friction and start to move per gravity's force. If this angle were too big, the plants on one side of the bench would be drowned by the water while drying out on the other side. Therefore, the following test setup was created to determine the exact angle: two roller profiles 5 metres long were mounted on a sandwich panel leaning on two wooden beams on both ends. The height was added on one side until the bench started to move, as shown in Figure 5.16.

Figure 5.16: Angle test setup

Testing determined that 17 cm of height resulted in the bench moving to the end, with or without extra weight. The angle was determined by the calculation tan-1(0,17/5), showing that the angle needed to be at least **2 degrees.** Thus, the climate cell became 0.17 metres higher when efficient space usage was one of the KPIs, while the height difference in the bench width (625 mm) was 20 mm. Thus, one side of the bench would be full of water while the other would be empty, as shown in Figure 5.17.

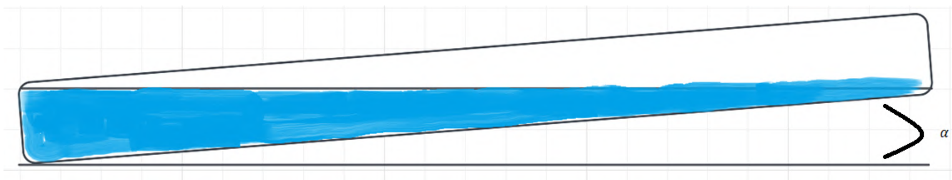

Figure 5.17: With an angle of 2°, the lower side of the bench would be full of water while the other side would be empty

This result would drown the plants on one side while drying them out on the other. Moreover, the water could overflow and be lost. Therefore, a permanent slope was impossible. However, a structure to raise the first section of the climate cell for a certain amount of time was considered. Nevertheless, it was much more complex than the other alternatives, so it was eliminated.

5.4. Final decision

After further elaboration, the pull track concept had manageable design challenges, the fewest process steps and part count, and the lowest price. As a result, this alternative was chosen with certainty, and a 3D model and prototype for this alternative were made, as described in the next chapter.

6
Detailed design

This chapter presents a CAD model of the pull track design in a 3D model to visualise the working principle of the design.

6.1. CAD Model

The model was separated into two main components: the construction inside the cell (the pull track) and the construction inside the lift (the robot with the grabbing mechanism). These components were designed separately (proof of principle) and integrated (proof of concept) at the end. Therefore, this chapter is divided into two sub-chapters.

6.1.1. The Pull Track

The idea for the pull track was to create a sliding bar with multiple notches behind the benches. Once the sliding bar moved, it would move along each notch and bench, ensuring that each bench would move up one place and the bench most upfront would move inside the lift (see Figure 5.14). As explained in the previous chapter, the first bench had to move at least 700 mm to be far enough inside the lift, while the other benches had to move the width of a bench or 625 mm. It also had to account for the position deviation of the benches of ±5 mm, which determined the distance between the notches shown in Figure 6.1

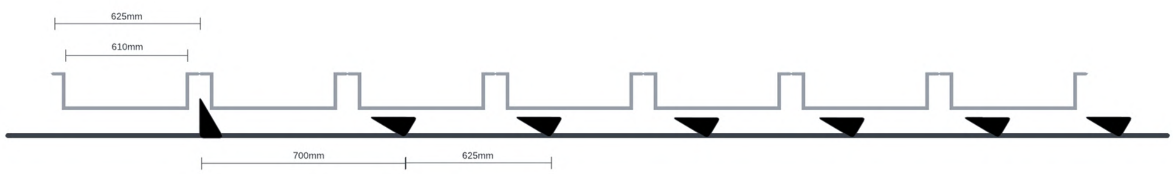

Figure 6.1: Distance between the notches inside the pull track.

The stress analysis determined the design space of the pull track. The analysis showed that the frame of the pull track should be up to 60 mm wide and 25 mm high. Because of the low height, a sliding profile was used instead of a roller profile. The difference is shown in Figure 6.2

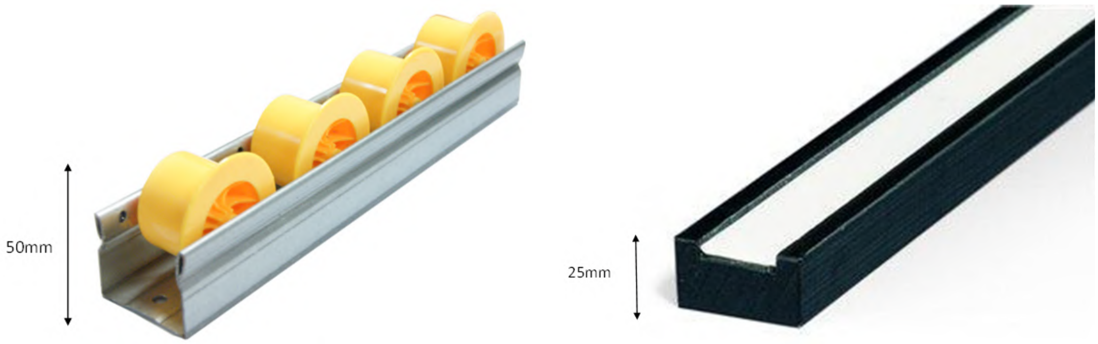

Figure 6.2: Difference between the roller profile 50mm high and the sliding profile 25 mm high

However, using the sliding profile throughout the cell was unnecessary since a sliding block was only needed where the cross beams were, as Figure 6.3 shows.

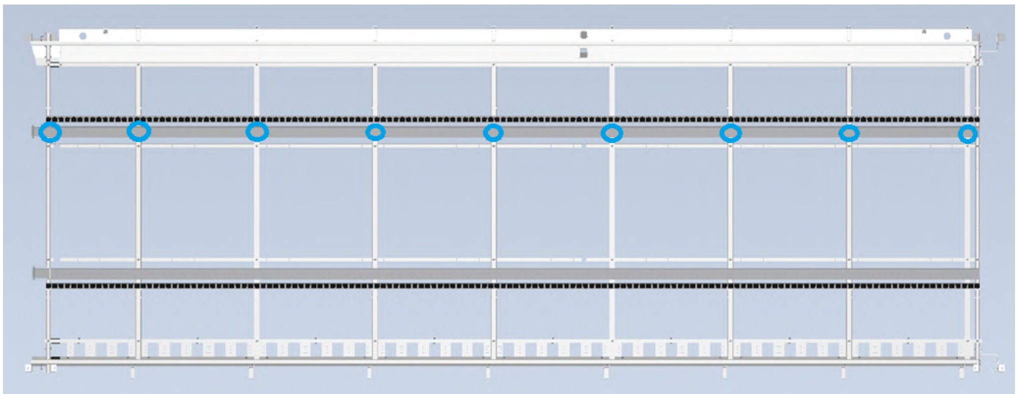

Figure 6.3: The blue circles represent the places for the sliding blocks

The last part of this design was how the notches would look. The idea was that the benches could move freely over the notches from the in-feed side while the notches would stop on the other side. The notches also needed to fall in position due to gravity. Therefore, the centre of gravity was on the right side of the hinge point. Figure 6.4 shows the design of the notch and the position of the centre of gravity.

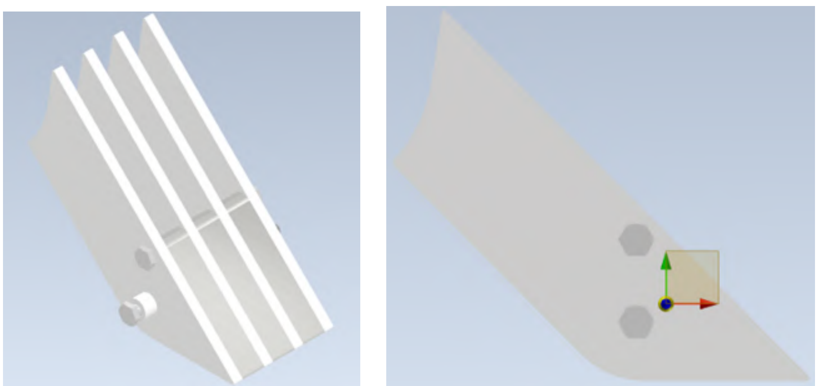

Figure 6.4: The notch consists of four plastic and three metal sheets to ensure that the centre of gravity is on the right side of the hinge point. The shape of the tip is rounded off to fit around the design of the bench perfectly.

Based on the combined concepts above, Figure 6.5 shows the CAD model of the pull track.

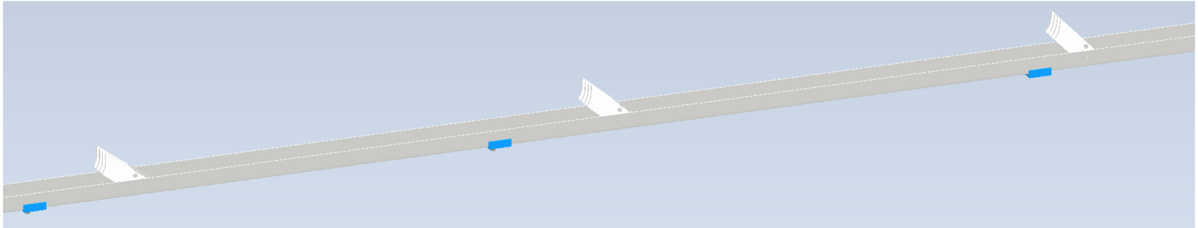

Figure 6.5: CAD model of the pull track

6.1.2. The Robot

The robot's function is to grab the pull track, pull it inside the lift, push it back into its starting position, and push the bench outside the lift onto the conveyor outside the cell. The idea was to use a telescopic arm for these functions. However, after some research and talking to specialised companies such as Eurofork, it became clear that with the strict dimensions of the climate cell, the complicated design for the telescopic arm moving up in both directions would be too complicated compared to the old design. After some brainstorming sessions, the idea arose of using the working principle of alternative 6, using gravity to lead the bench roll out of the lift onto the conveyor. This idea was possible in the elevator because the bench no longer contained so much water. The new schematic steps are shown in Figure 6.6.

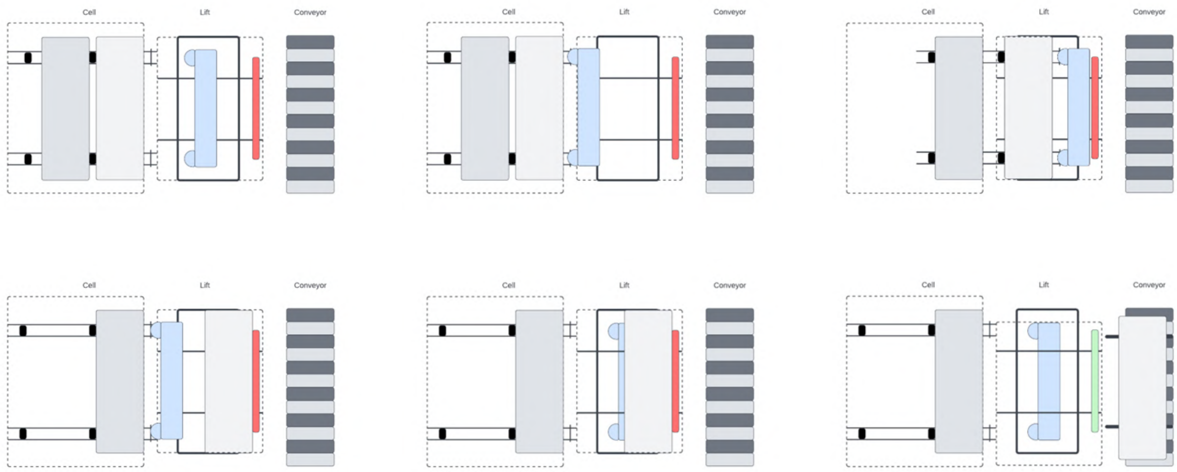

Figure 6.6: Steps 1 through 6 are shown for the final design. A stopper was placed to ensure the bench would not fall out of the lift. Red means the stopper is closed, and the bench is stopped. Green means the stopper is open, and the bench can move out of the lift.

A structure inside the conveyor needed to be built to cover the distance between the lift and the conveyor so that when the bench was ready to be removed from the lift, the structure would catch the container and guide it onto the conveyor. Thus, another main component was added: the receiver inside the conveyor, as seen in Figure 6.7.

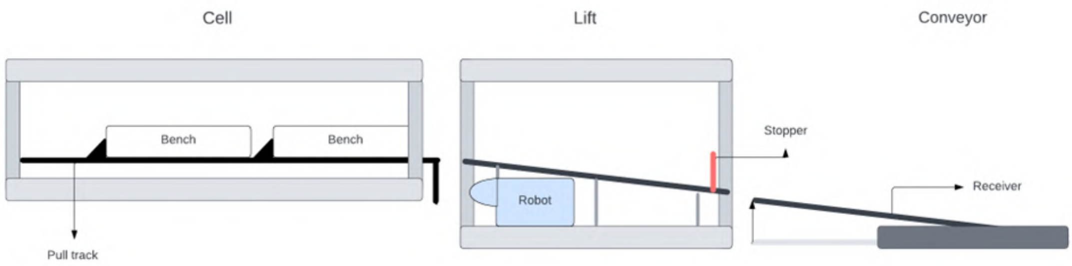

Figure 6.7: A roller profile that rises once the bench is ready to be removed from the lift

Finally, work began on the CAD model. First, the complete 3D model of the robot is shown, followed by the 3D model of the receiver. Each component is discussed in detail. The complete 3D model of the robot appears in Figure 6.8. All the welding and assembly drawings appear in Appendix D.

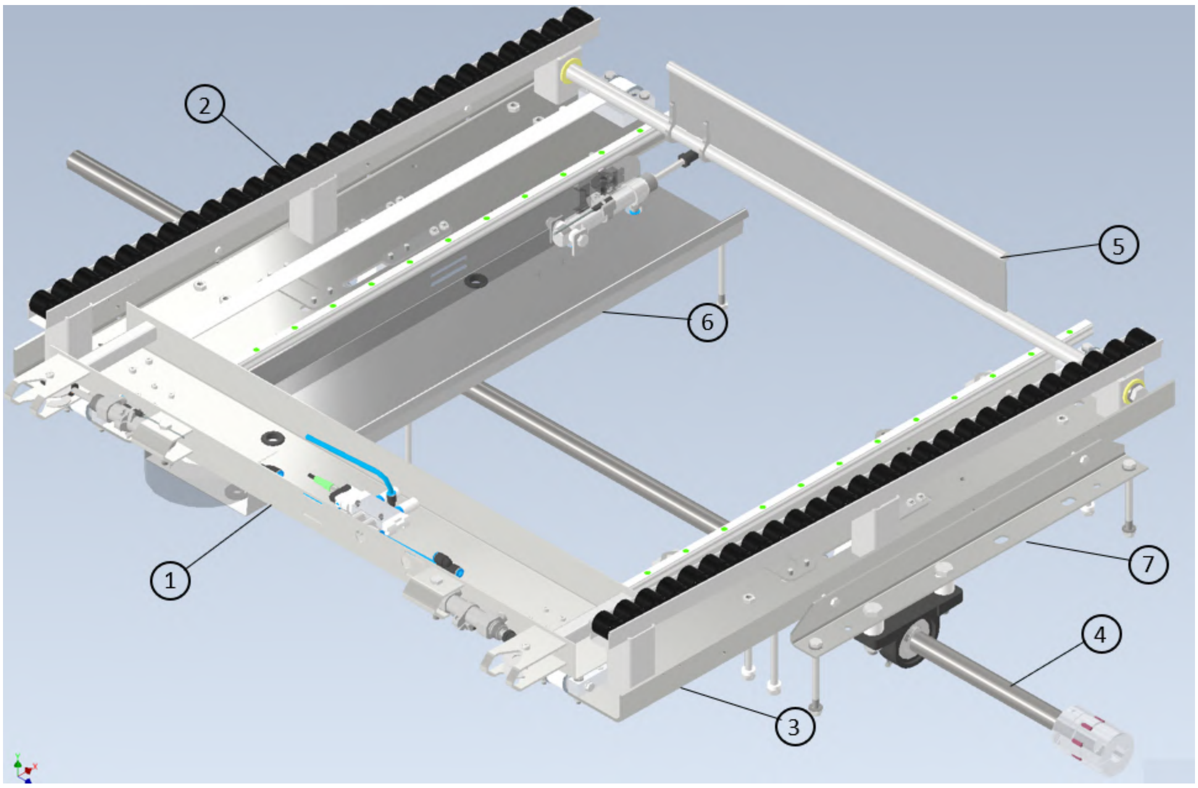

Figure 6.8: 1) Body of the robot, 2) right robot guidance, 3) left robot guidance, 4) engine shaft, 5) stopper, 6) cable caterpillar guidance, and 7) mounting plate

1.Body of the robot

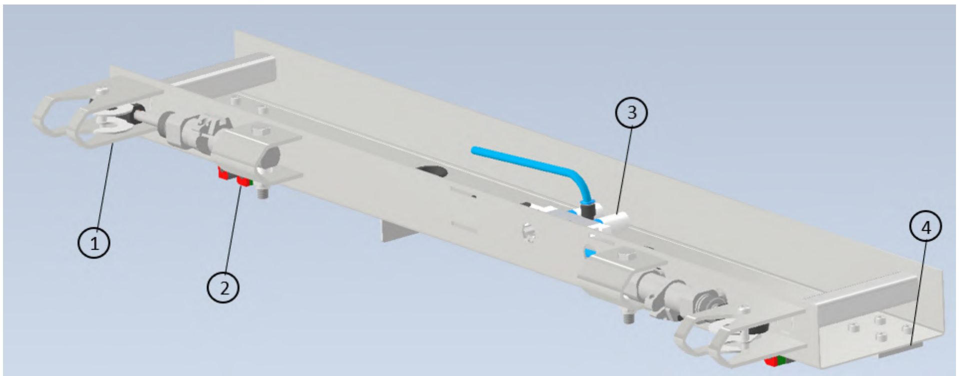

Figure 6.9: 1) Grabbing mechanism, 2) HIWIN cart, 3) air solenoid valve, and 4) clamping plate

The first component where the focus was on was the grabbing mechanism. Here still the idea mentioned in figure 5.11 is used, only now it only has to execute the hooking up. Because the mechanism only has to be open or closed a pneumatic cylinder is chosen. figure 6.10 & 6.11 show a CAD model top view of the open and closed situation.

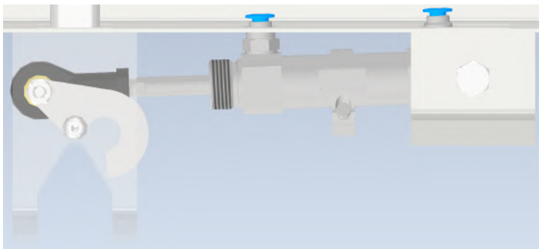

Figure 6.10: Hook on mechanism open

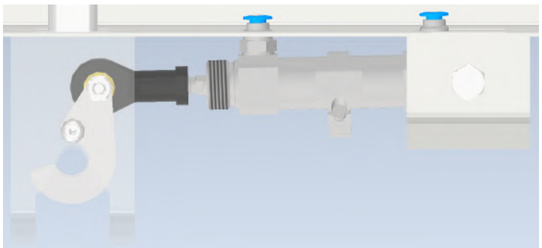

Figure 6.11: Hook on mechanism closed

The HIWIN cart, the clamping plate, the HIWIN rails, and the timing belt were used to ensure the robot could move back and forth. The air solenoid valve controlled the pneumatic cylinders.

2 and 3.Robot guidance

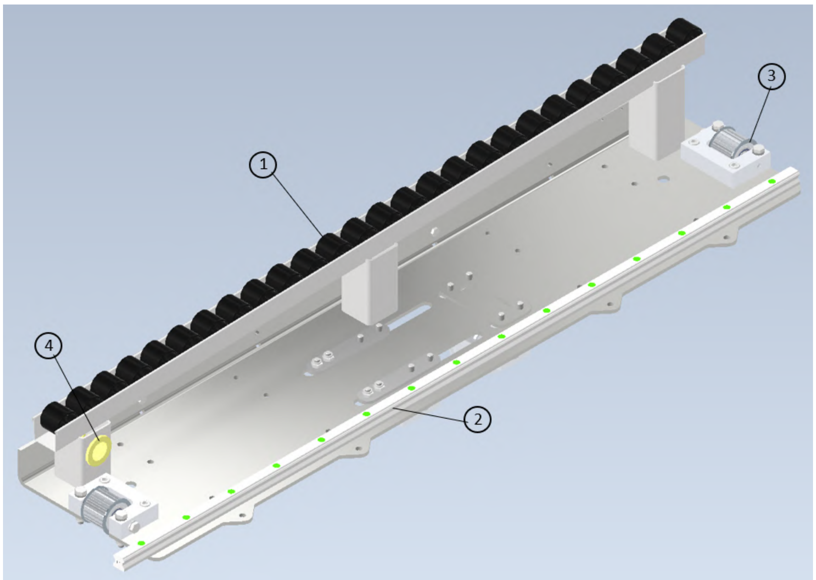

Figure 6.12: 1) Roller profile under a hook, 2) HIWIN rails, 3) timing belt pulley, and 4) stopper location

The design took advantage of gravity, so the roller profile was under a hook to ensure the bench moved from the top to the bottom by itself. A timing belt was chosen to move the robot's body because the robot had to be connected to the engine already there for the test setup to test the proof of concept. HIWIN rails were used for guidance because they worked well when tested in-house. Finally, the lowest pillar for the roller profile was used for the suspension of the stopper.

4.Stopper

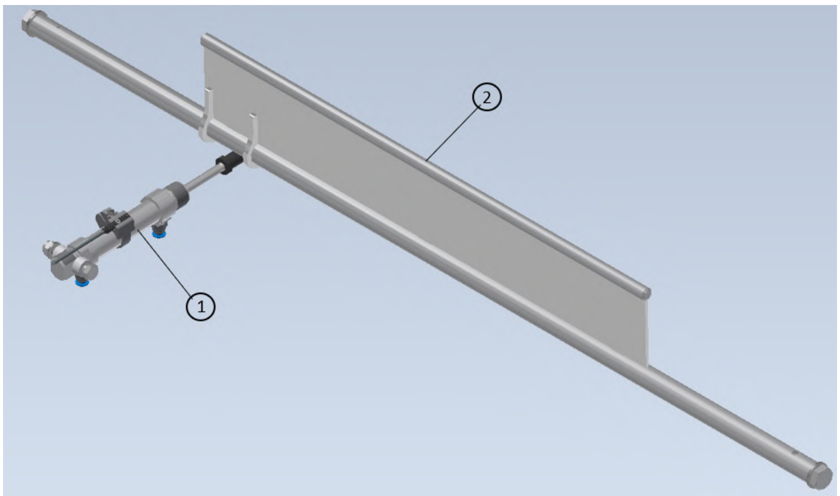

Figure 6.13: 1) Pneumatic cylinder and 2) stopper weld assembly

This in-house design was chosen because it has been used multiple times. The design was needed to stop the bench from falling out of the lift. Once the bench was ready to be removed from the cell, the pneumatic cylinder moved inwards, causing the stopper to open.

5.Cable caterpillar guidance

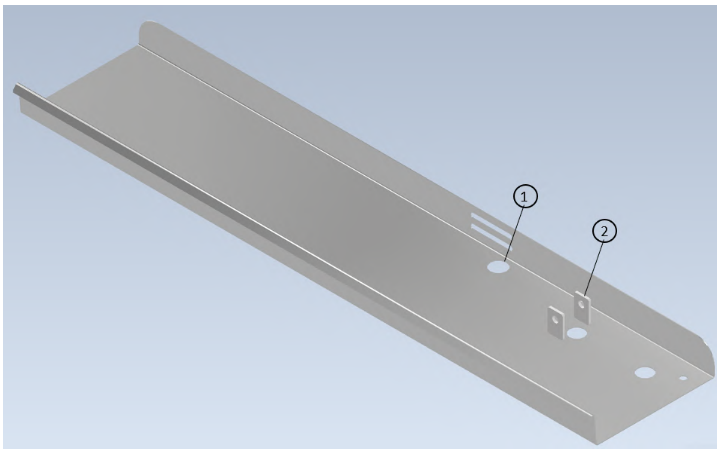

Figure 6.14: 1) Opening for the cables and 2) pneumatic cylinder location

Cable management was critical, so a cable caterpillar was mandatory so the cable would not become damaged or broken. Moreover, this component was used for the suspension of the pneumatic cylinder of the stopper.

6.Mounting plate

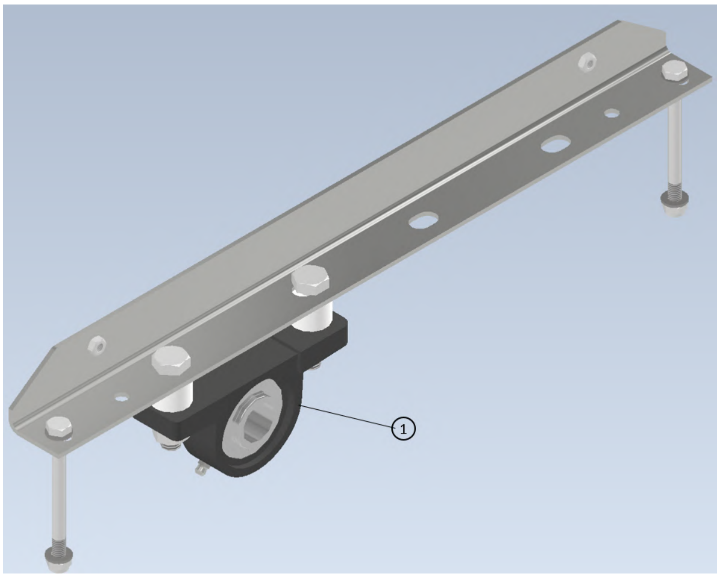

Figure 6.15: 1) Suspension of the engine shaft

The mounting plate allowed both robot guides to align perfectly so that the HIWIN carts did not break down over time. It also supported the engine shaft and kept it in place.

6.1.3. The Receiver

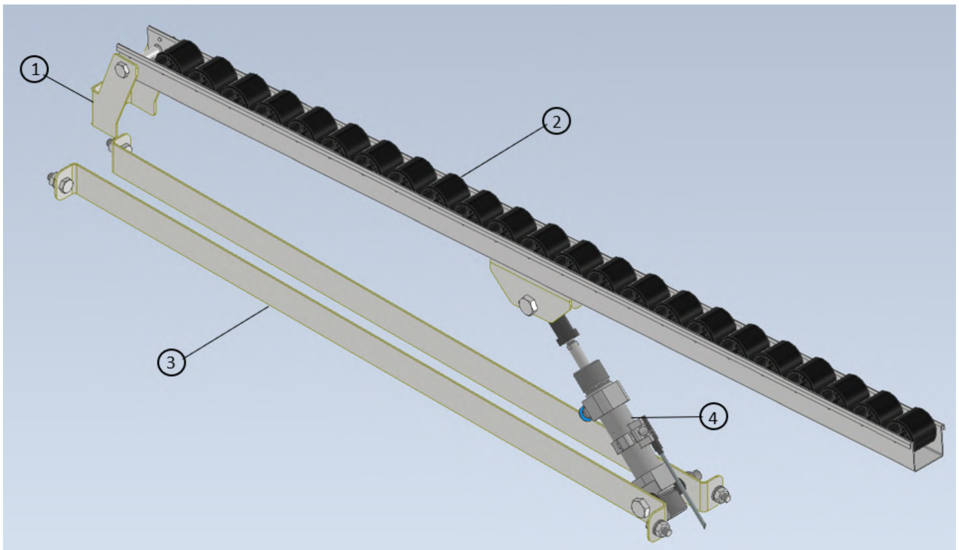

Figure 6.16: 1) Hinge point, 2) roller profile, 3) connection material to the conveyor, and 4) pneumatic cylinder

The receiver was connected to the conveyor. The pneumatic cylinder caused the roller profile to rise and end at an angle to receive the bench rolling out of the lift. Figures 6.17 and 6.18 show the closed and receiving positions of the receiver.

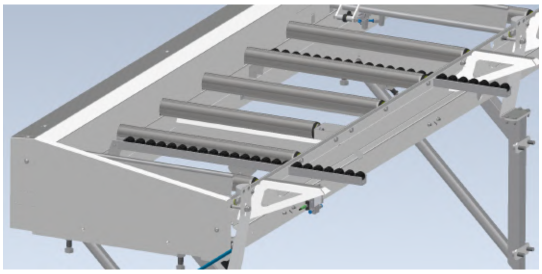

Figure 6.17: Closed position

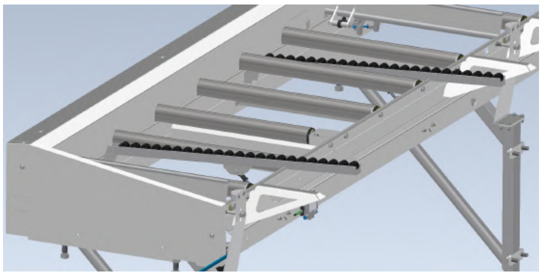

Figure 6.18: Receiving position

6.2. Selected means and material

This section substantiates why certain means and materials were used for this model.

6.2.1. RVS 304

AISI 304 stands out as a versatile type of stainless steel, widely used in various applications, especially in everyday items like household appliances. Its popularity comes from a blend of qualities: strong resistance to corrosion, great formability, and ease of welding [9]. In terms of its chemical makeup, 304 is often referred to as the 18/8 grade, denoting its composition of 18% chromium and 8% nickel. Typically, it contains 0.08% carbon, but newer production methods sometimes yield versions with as little as 0.04% carbon due to easier decarburisation through the AOD melting process. It offers excellent resistance against corrosion, although it can be sensitive to chlorides and acids. While primarily used indoors, 304 can also work out- doors in less aggressive environments. AISI 316 is better for more demanding corrosion conditions due to its higher resistance to chlorides, acids, and seawater. Moreover, the 304 grade is quite ductile, so it can be shaped into intricate forms due to the low yield strength and high ductility. It is also renowned for its superior weldability compared to other stainless steel grades. It welds well using various processes. Notably, it retains good toughness post-welding and typically does not require heat treatment afterwards, thanks to its non-hardenable structure upon cooling.

In summary, AISI 304 stainless steel is a go-to material in many industries due to its balanced properties, making it reliable for a wide range of applications, especially those that demand resistance to corrosion and easy shaping. Thus, it was the perfect material for this application.

6.2.2. HMPE

HMPE (short for high molecular polyethylene) derives its properties primarily from its molecular density of approximately 500,000 g/mol [6]. This density distinguishes it from standard PE (HD grade) and endows it with improved wear and impact resistance. Within the HMPE spectrum, the HMPE 500 variation specifically showcases superior wear and impact resistance compared to standard PE. Meanwhile, UHMPE (ultra-high molecular polyethylene), denoted by a molecular density of 1,000 or higher, is recognised for its exceptional abrasion resistance. UHMPE is interchangeably referred to as HMPE1000, signifying the same characteristics. HMPE boasts resistance to moisture, complies fully with the 10/2011 legislation for direct food contact, does not adhere to surfaces, and possesses a notably low coefficient of friction. This material was used primarily because of the last two advantages: the low coefficient of friction and legislation for direct food contact.

Once the 3D model was determined with the choice of its materials, all materials were ordered, ensuring this model would become a reality through a prototype. Because this prototype was an automated machine, other issues, including the mechanical power transmission and PLC, were addressed.

6.3. Electronic systems

6.3.1. Mechanical power transmission

Beforehand, the electrical engineers and the researcher examined what needed to be wired and whether there was enough room in the control panel. Two optical sensors were used to detect the position of the bench, two inductive sensors were used to detect the position of the robot, and three reed contacts were used to detect the position of the pneumatic sensors. Figure 6.19 shows the position of the optical and inductive sensors.

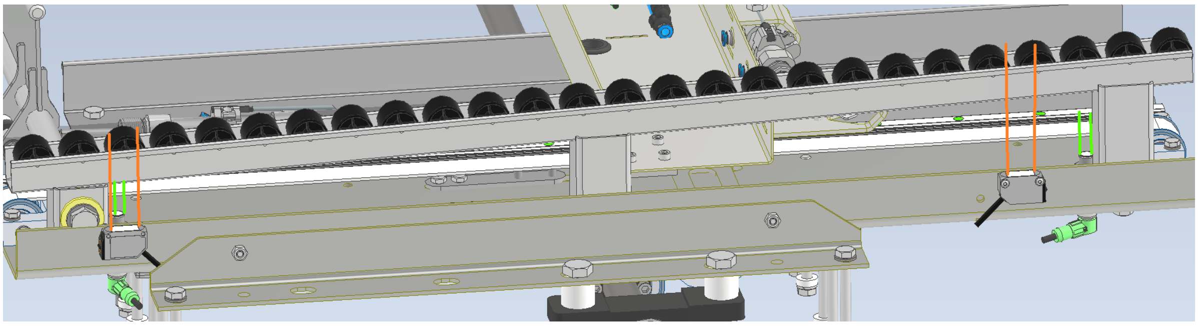

Figure 6.19: Position of the optical (orange) and inductive (green) sensors.

The following table summarises the electrical components:

Sensor name	Description	Sensor type
TR-02-01	Bench detection in front of the lift	Optical sensor: O6H301
TR-02-02	Bench detection at the stopper	Optical sensor: O6H301
TR-02-03	Robot detection at the front of the lift	Inductive sensor: IFT204
TR-02-04	Robot detection at the stopper	Inductive sensor: IFT204
TR-02-05	Left hook-up mechanism closed detection	Reed contact
TR-02-06	Right hook-up mechanism closed detection	Reed contact
TR-02-07	Stopper closed detection	Reed contact
SOV-02-01	Valve robot	Solenoid
SOV-02-02	Valve stopper	Solenoid

6.3.2. Programmable logic control

Next, a state machine was made since the steps needed to occur in succession. The sensors mentioned above ensured that a previous step was completed and the system continued to the next state. The state machine appears as follows in Figure 6.20:

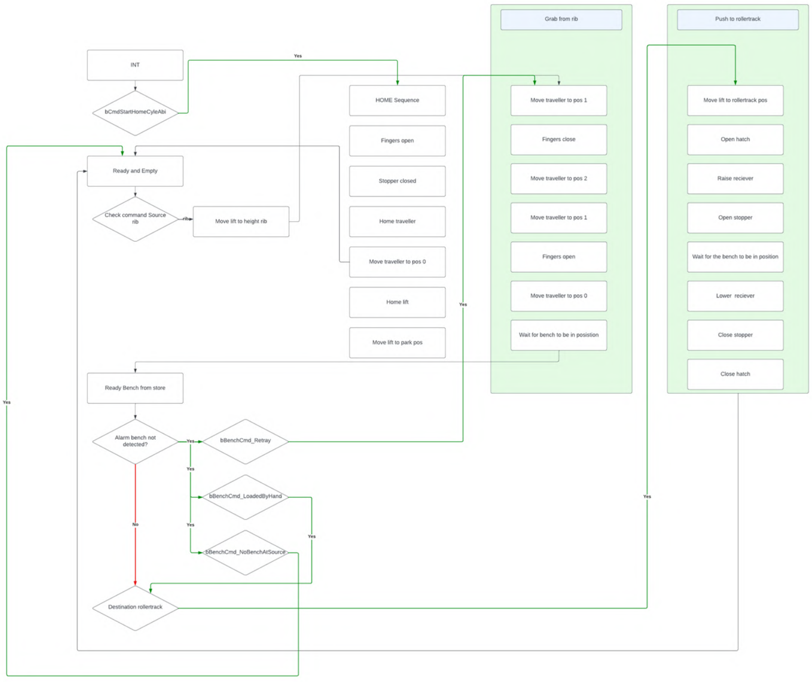

Figure 6.20: The green boxes show the states of the robot. *Grab from the rib* is the sequence to grab the bench from the cell. *Push to rollertrack* is the sequence to get the bench from the lift onto the conveyor outside the climate cell.

Finally, the prototype was built, implemented, and tested inside the climate cell (see Figure 6.21).

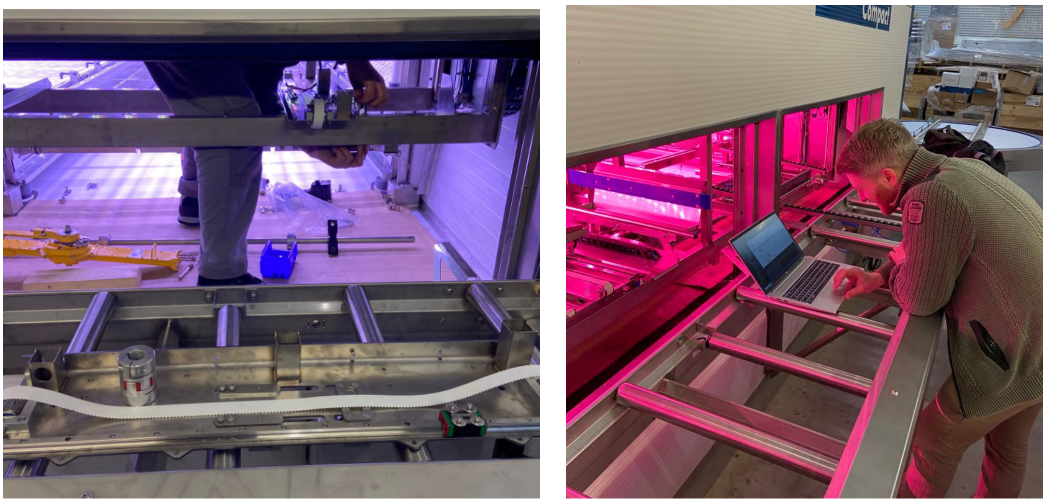

Figure 6.21: The prototype was built inside the climate cell located in the research centre with someone from the workshop. The programme was written with someone from the PLC department.

7

Implementation and Results

This chapter answers the fourth research sub-question:

Does the solution satisfy the requirements, and are the results what was desired beforehand?

As discussed in Chapter 6, , the design was separated into three main components: the pull track, the robot, and the receiver. First, the pull track was separately tested before everything was built inside the climate cell. Second, a test was executed where all three components worked together inside the climate cell. The goal of both tests was the proof of concept. Therefore, the test plan for both test setups was to execute the test between 20 and 50 times until the proof of concept was claimed. The proof of concept needed to be claimed for a range from 0 kg, representing an empty bench, to 60 kg, representing a bench full of crops. All other features, such as corrosion and soiling resistance, were secondary and were not tested.

7.1. Test setups

7.1.1. Pull Track test

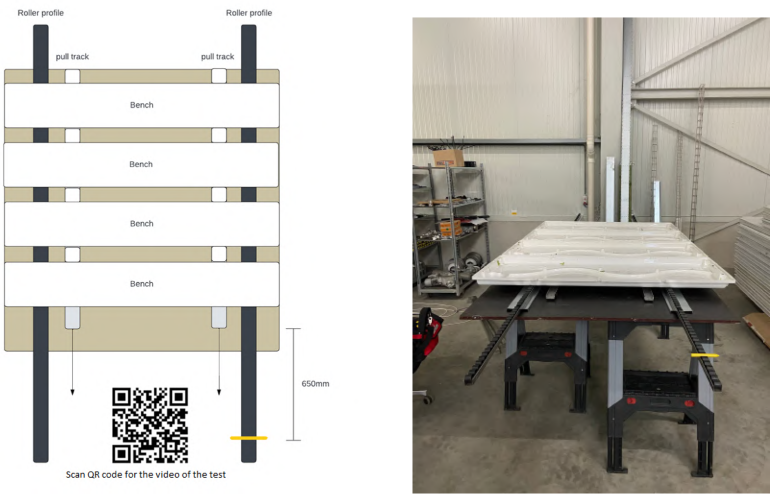

Figure 7.1: Pull track test setup.

The pull track was first tested separately to prevent failure before everything was built in the climate cell and had to be dismantled. Several issues were considered in advance. However, whether it works as imagined in real life remains to be seen. The issues were as follows:

- Q1: How well will the notches fall back in position due to gravity?
- Q2: How much resistance will the notches give if the benches move over the notches?
- Q3: Will each notch carry half the weight of the bench?
- Q4: Will the weight in the benches cause them to bend, leaving no more room for the notches?

Results
The results examined whether the system did better than expected on the questions created beforehand to determine if the system performed exactly as expected or less than expected. Subsequently, modifications to the model were considered.

	Performance	**Modification**
Q1	Better then expected	Smaller thicknesses of steel plates can be used
Q2	Exactly as expected	Nothing
Q3	Exactly as expected	Nothing
Q4	Worse then expected	Nothing because the effect was minimal yet mentionable

The pull track worked better than expected and was built into the climate cell for the final test.

7.1.2. Robot test

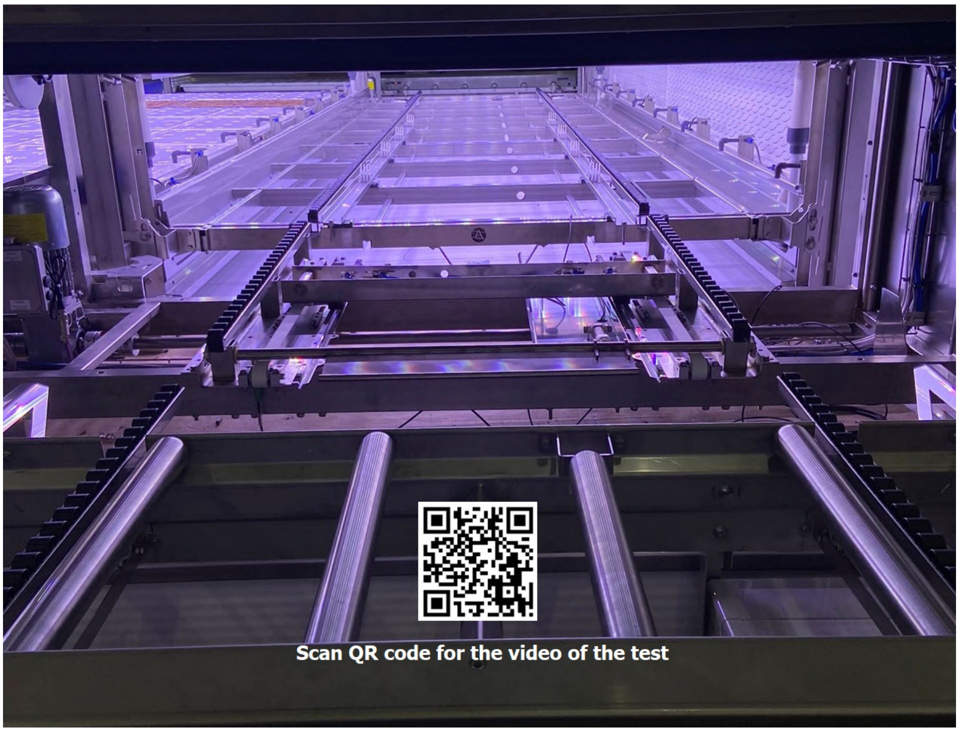

Figure 7.2: A full automation test of the pull track inside the cell, the robot inside the lift and the receiver inside the conveyor

Requirement verification

Index	Description	Fulfilment
R-1.0	The structure must grab the benches 99.95% of the time	87.5%
R-2.0	The structure must be less expensive than the previous version which cost €2500	€1,800
R-3.0	The part count must be less than the previous version which is 930 according to Inventor	677 parts
R-3.1	Fewer possible process steps than the previous version which is 12	8 steps
R-3.2	As few electronic features in the cell as possible	0 features
R-3.3	Easier to construct than the previous version, which is one week	3 days
R-4.0	The structure must be safe according to the ISO 13849-1:2023 standards [1].	fulfilled
R-4.1	The structure must not damage the plants, benches and trays.	fulfilled
R-4.2	Reasonably foreseeable misuses had to be considered per ISO 12100:2010 [3].	fulfilled
R-5.0	The structure must consider the design of the benches	fulfilled
R-5.1	The structure must compensate up to 10 cm position inaccuracy of the benches	fulfilled
R-6.0	The structure must be able to reach seven benches deep	fulfilled
R-6.1	The structure must have a capacity of at least 12.5 per hour.	60 per hour
R-7.0	The structure must fit in the design space. (Section 4.2.1)	fulfilled
R-8.0	The structure must have a lifetime of at least 219.000 cycles.	Not tested*.
R-9.0	Maintenance should be easier for wear parts then the previous version.	fulfilled
R-9.1	Protection from touch and water must have the IP value of 55 [7].	fulfilled
R-10.0	The structure must have a Food Grade [9]	fulfilled

*Duration test for future recommendations.

All critical movements were investigated separately, questioned, and answered as follows to better understand the reliability of the new vertical farm robot:
Q1: What is the robot's success rate for grabbing the pull track? **A1**: 100%.
Q2: What is the success rate of the bench not touching the sides? **A2**: 70%.
Q3: What is the success rate of the bench moving to the stopper by gravity? **A3**: 80%.
Q4: What is the maximum weight that the receiver can lift? **A4**: 40kg.
Q5: What is the success rate of the bench reaching the end of the conveyor? **A5**: 100%.

7.2. Conclusion

In the end, the full design worked, a proof of concept was established, and almost all requirements were met. However, a few minor issues caused the reliability to score slightly lower than preferred. First, the angle of the roller rails was too small because the exact angle of the slope test in Chapter 5 was used without any tolerance. Second, the lift had no side guidance, causing the bench to rotate and become stuck. Third, the pneumatic cylinders inside the receiver were too weak to withstand the load of a full bench (60 kg). Finally, because the pull track had to be attached to the transversal beams instead of integrated inside, the bench had to be lifted slightly into the lift instead of a smooth transition. Therefore, as a recommendation, these small adjustments must be incorporated into the new 3D model for the next revision.

8

Conclusion and recommendations

This chapter gives the outcome of this master's thesis and mentions possible next steps.

8.1. Conclusion

The analysis showed that the vertical farm robot had to be redesigned to grab seven benches deep to eliminate the system's shortcomings and significantly enhance its performance. Many ideas passed the revue by looking at competitors and other industries such as distribution centres. The pull track design was most likely to meet all requirements and constraints from many alternatives. It worked accordingly after building and testing the concept, and the concept's working principle was validated. However, to increase the new vertical farm robot's reliability and ensure a durability test, a few minor issues had to be resolved, such as increasing the slope angle, adding side guidance, and increasing the strength of the pneumatic cylinders. To answer the main research question, *'Can the system performance be improved by redesigning the vertical farm robot?'*, the answer with full conviction is yes, this new design of the vertical farm robot can enhance the system's performance. Therefore, this thesis is a success. The new and old robots were compared using the criteria mentioned in this thesis to validate this statement.

	Old Robot	New Robot
Price	€2500	€1800
Part count	930	677
Process steps	12	9
Construction time	1 week	3 days
Reachability	1	7
Reliability	95%	87,5%

Figure 8.1: Accomplishments of the new robot compared to the old robot.

Subsequently, recommendations are made to ensure the system's performance can increase even more.

8.2. Recommendations

This section presents recommendations collected throughout this report. They ensure that beyond this improvement, the company can continue to make further advancements, as follows:

- During the simulations in Chapter 2, it emerged that improvements to the simulation programme are needed. The programme adheres to the restrictions and decides based on them but does not consider future decisions.
- A conclusion in Section 2.4 was that it would be ideal to work with cycle times of seven days, meaning that some cycle times ideal for these plants should be changed. However, the impact is unknown. Therefore, this improvement involves experimenting with the cycle times and identifying the consequences.
- The out-feed robot was changed, while the in-feed robot still caused a small deviation in the position of the benches. Therefore, the in-feed robot also needs revision.
- The goal for Artechno is to have cell factories with ten climate cells. Hence, large-scale logistics imaging of the full factory can help better understand the process flow within the factory and identify bottlenecks to improve the system.
- During the design process, three robots were used instead of one moving in the y direction to ensure the design would be finished within the given time. An improvement would be to see how this design could be changed to move in the y direction, using only one robot to save costs.
- In the final design, a FEM analysis was used for the cross beams, which determined that the beams would be strong enough for construction in the cell. However, this issue must be investigated further to be 100% sure.
- Per the conclusion, three adjustments must be made to increase the reliability of the new robotade: increasing the slope angle, adding side guidance, and increasing the strength of the pneumatic cylinders.
- A duration test using 0, 20, 40 and 60 kg sought to determine if the new design would meet the requirement of a lifetime of at least 219,000 cycles.
- For implementation in a new project, a soiling test must be conducted to see if the new project would significantly damage the design and decrease the lifetime.
- Many decisions were made due to the benches' flexibility, resulting in many inaccuracies. Therefore, the bench design should be considered to eliminate these inaccuracies.

References

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[10] Art van Rijn. *ARTECHNO, fully automated vertical farming supplier*. 2000. URL: https://artechno-growsystems.com/.

A

Appendix A

A.1. Scientific paper

B

Appendix B

B.1. Test case 1

B.1.1. Number of different actions in sequence

For each day on the x axis the number of different actions in sequence can be found for different reachabilities of the m robot.

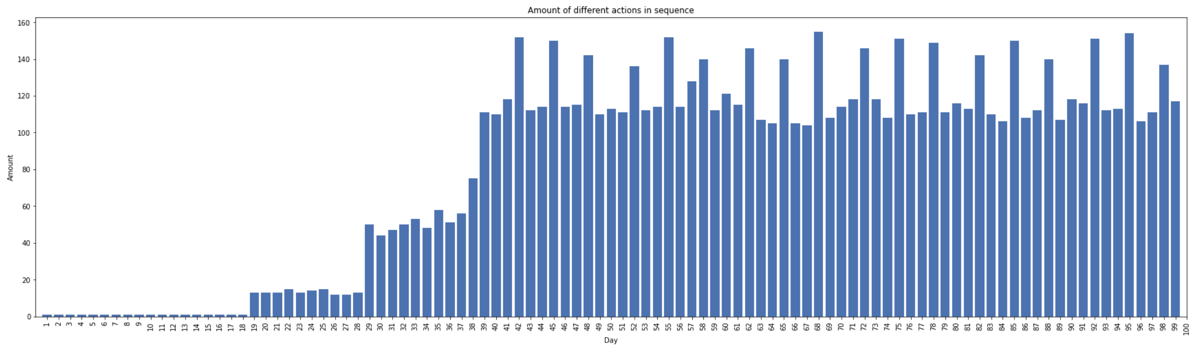


Figure B.1: Number of different actions in sequence for a reachability of 1.

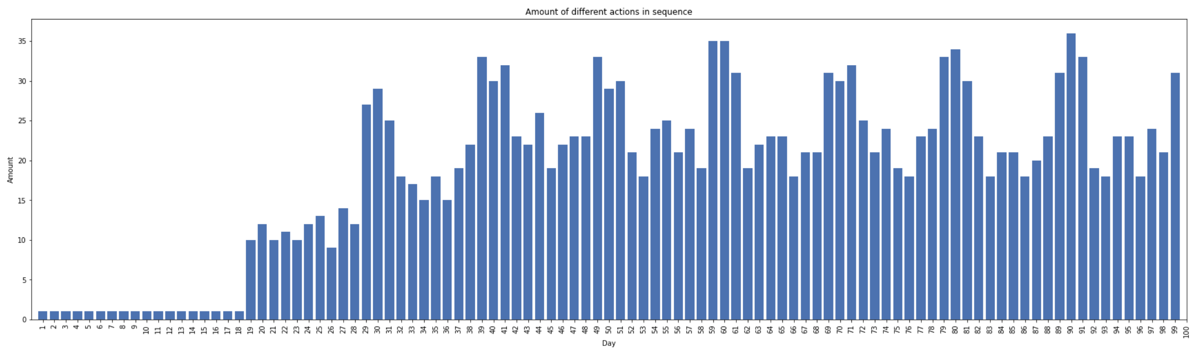


Figure B.2: Number of different actions in sequence for a reachability of 7.

B.1.2. Number of executed benches of same kind in succession

On the x axis the number of executed benches of same kind in succession for different crops is visible with the number of time this occurs on the y axis. Reachability of the robot of 1 on the left and 7 on the right.

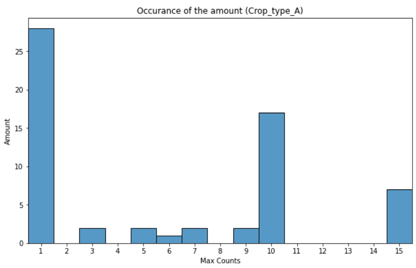


Figure B.3: Number of executed benches of same kind in succession of Crop A with a reachability of 1.

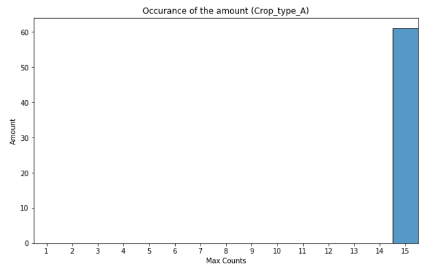


Figure B.4: Number of executed benches of same kind in succession of Crop A with a reachability of 7.

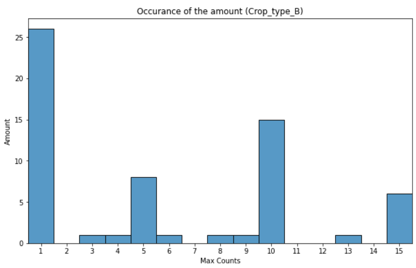


Figure B.5: Number of executed benches of same kind in succession of Crop B with a reachability of 1.

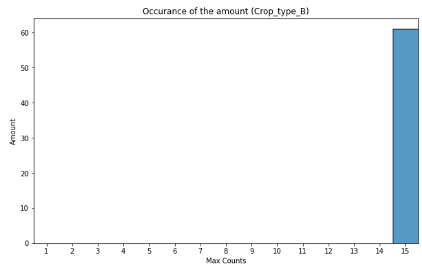


Figure B.6: Number of executed benches of same kind in succession of Crop B with a reachability of 7.

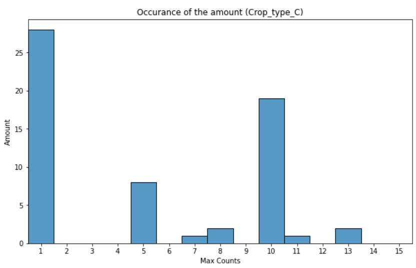


Figure B.7: Number of executed benches of same kind in succession of Crop C with a reachability of 1.

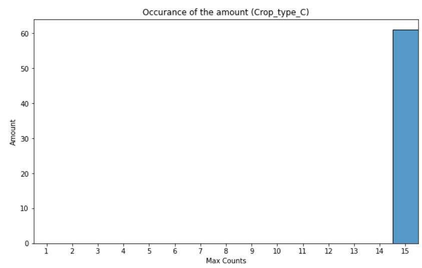


Figure B.8: Number of executed benches of same kind in succession of Crop C with a reachability of 7.

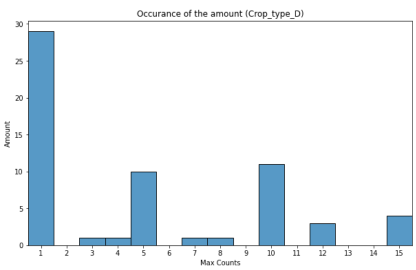


Figure B.9: Number of executed benches of same kind in succession of Crop D with a reachability of 1.

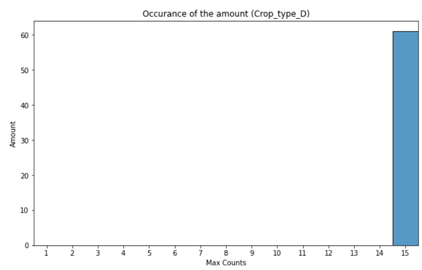


Figure B.10: Number of executed benches of same kind in succession of Crop D with a reachability of 7.

B.1.3. Number of empty benches appended

For each day on the x axis the number of empty benches appended on the y axis is visible for different reachabilities of the robot.

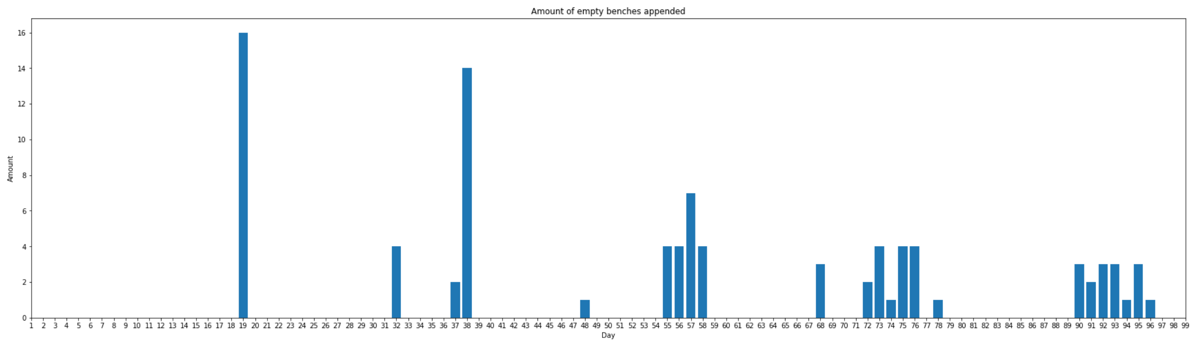


Figure B.11: Number of empty benches appended with a reachability of 1.

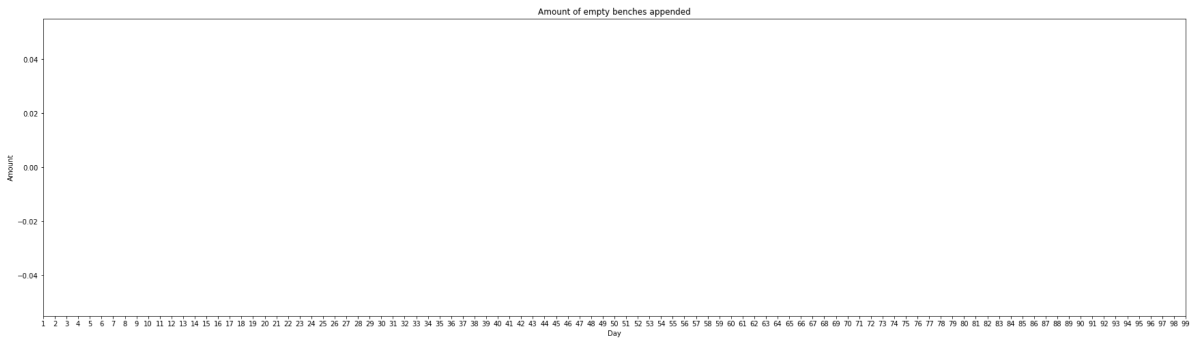


Figure B.12: Number of empty benches appended with a reachability of 7.

B.2. Test case 2

B.2.1. Number of different actions in sequence

For each day on the x axis the number of different actions in sequence can be found for different reachabilities of the vertical farm robot.

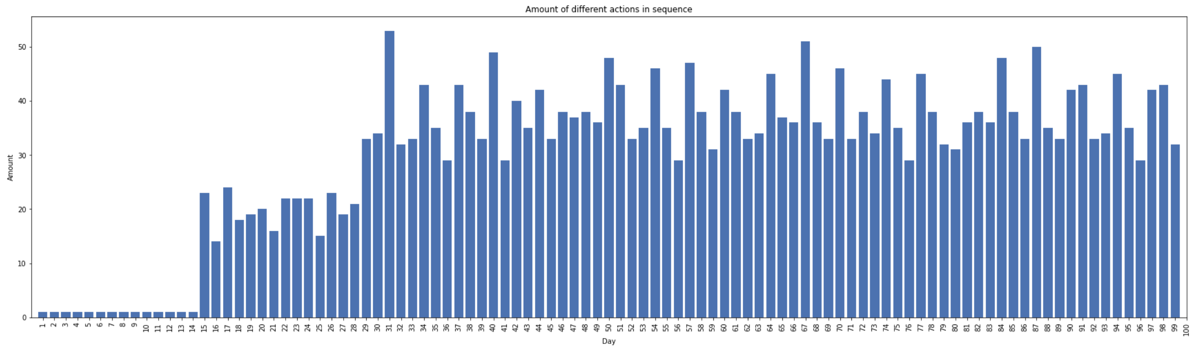


Figure B.13: Number of different actions in sequence for a reachability of 1.

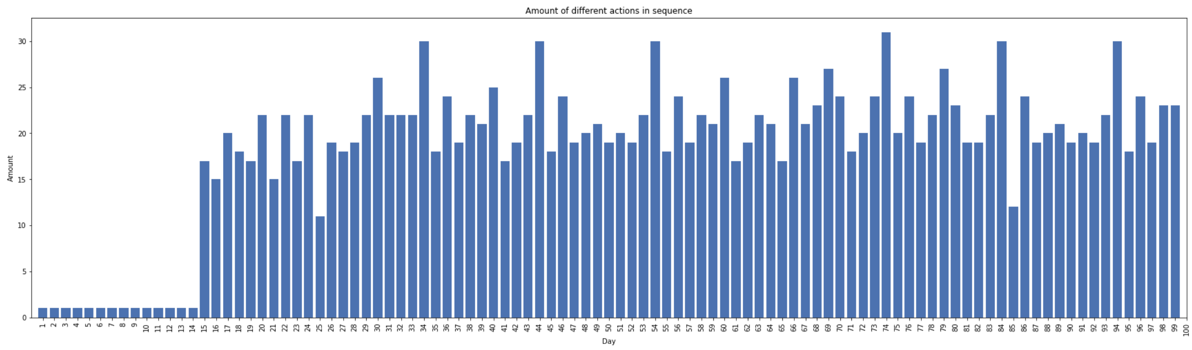


Figure B.14: Number of different actions in sequence for a reachability of 5.

B.2.2. Number of executed benches of same kind in succession

On the x axis the number of executed benches of same kind in succession for different crops is visible with the number of time this occurs on the y axis. Reachability of the robot of 1 on the left and 5 on the right.

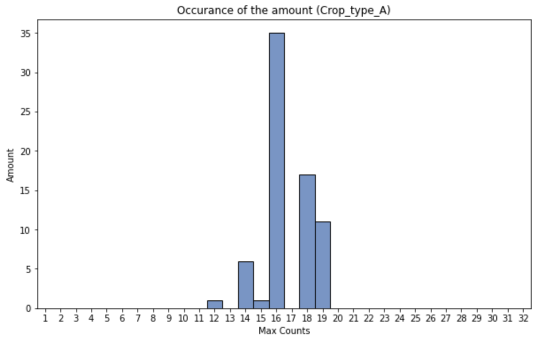


Figure B.15: Number of executed benches of same kind in succession of Crop A with a reachability of 1.

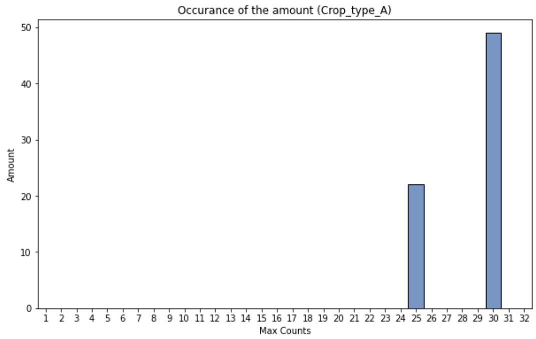


Figure B.16: Number of executed benches of same kind in succession of Crop A with a reachability of 5.

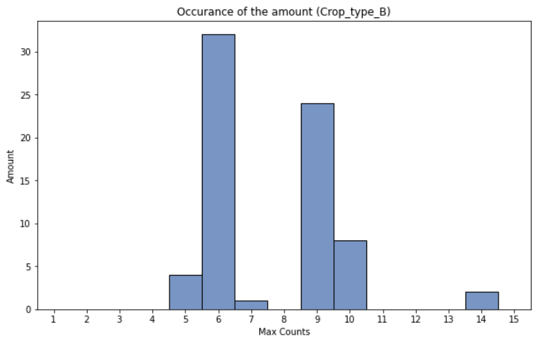


Figure B.17: Number of executed benches of same kind in succession of Crop B with a reachability of 1.

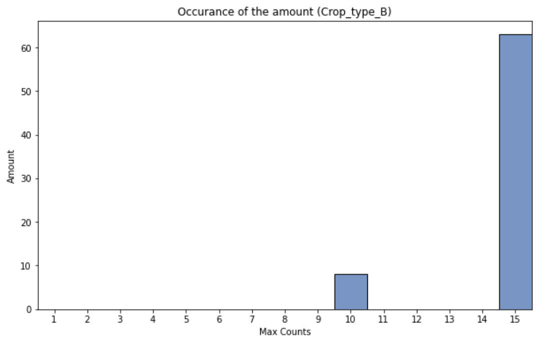


Figure B.18: Number of executed benches of same kind in succession of Crop B with a reachability of 5.

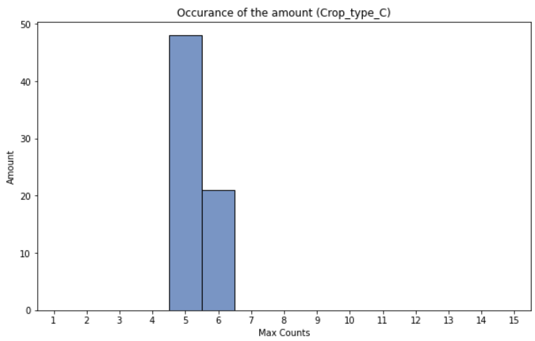


Figure B.19: Number of executed benches of same kind in succession of Crop C with a reachability of 1.

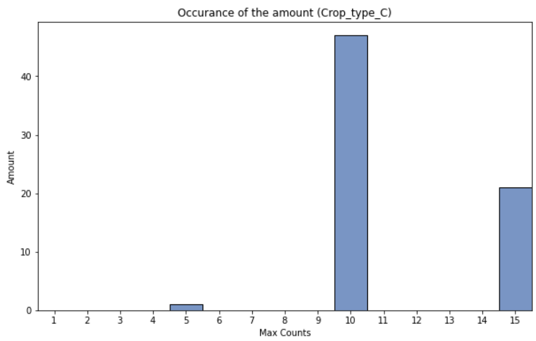


Figure B.20: Number of executed benches of same kind in succession of Crop C with a reachability of 5.

B.2.3. Number of empty benches appended

For each day on the x axis the number of empty benches appended on the y axis is visible for different reachabilities.

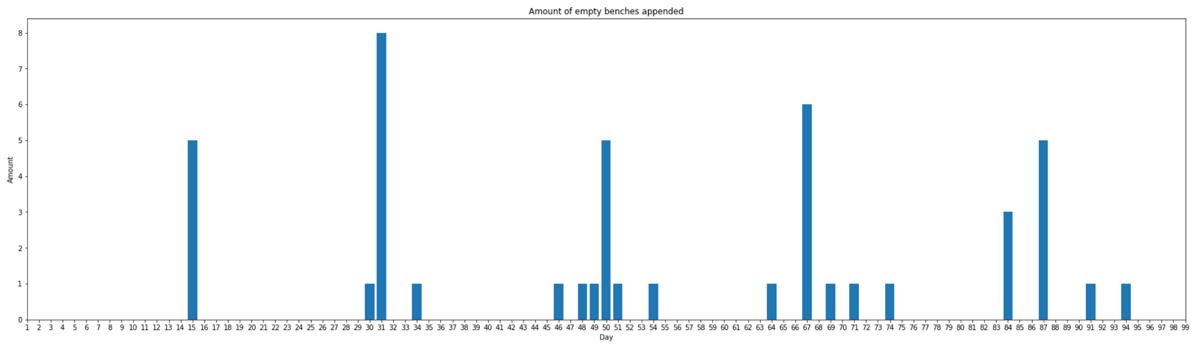


Figure B.21: Number of empty benches appended with a reachability of 1.

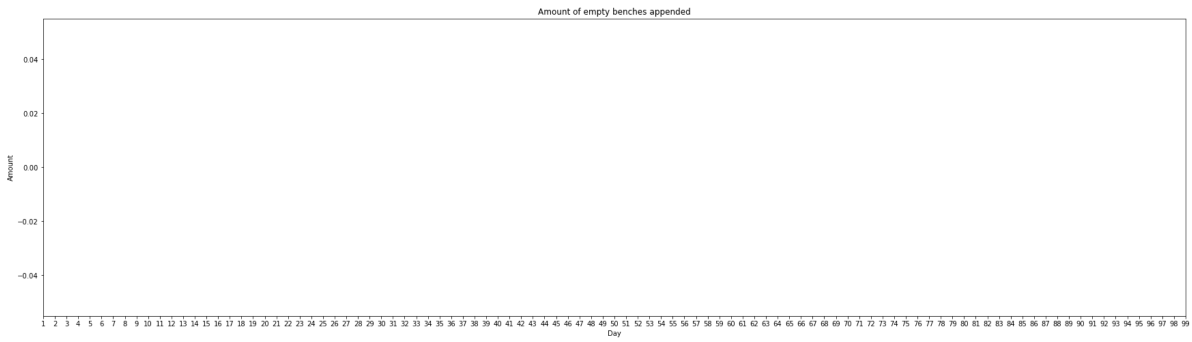


Figure B.22: Number of empty benches appended with a reachability of 1..

B.3. Test case 3

B.3.1. Number of different actions in sequence

For each day on the x axis the number of different actions in sequence can be found for different reachabilities of the vertical farm robot.

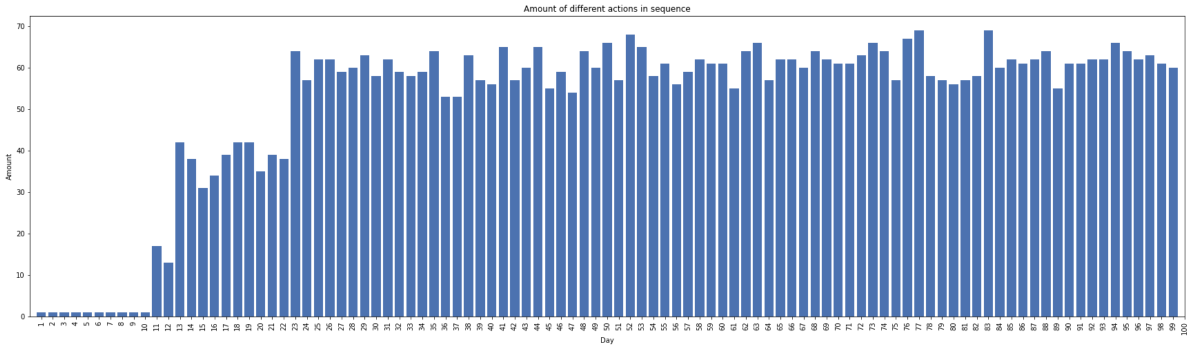


Figure B.23: Number of different actions in sequence for a reachability of 1

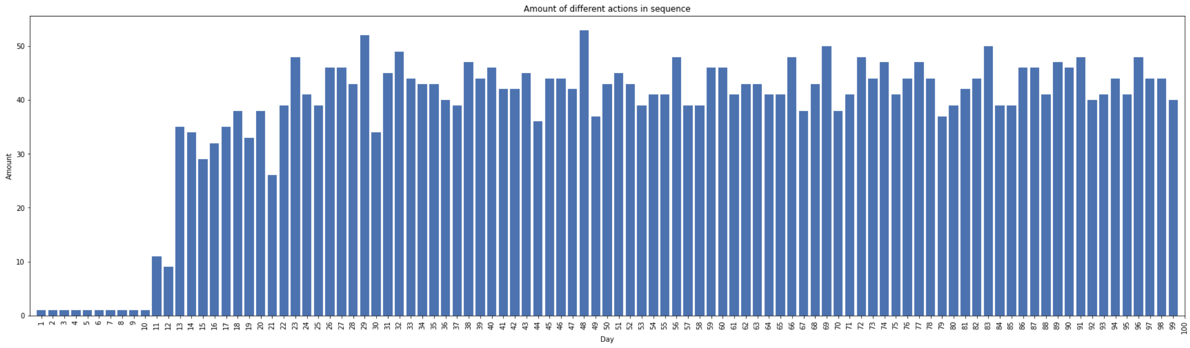


Figure B.24: Number of different actions in sequence for a reachability of 6

B.3.2. Number of executed benches of same kind in succession

On the x axis the number of executed benches of same kind in succession for different crops is visible with the number of time this occurs on the y axis. Reachability of the robot of 1 on the left and 6 on the right.

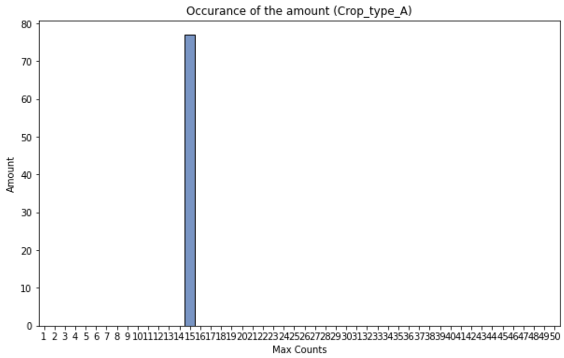


Figure B.25: Number of executed benches of same kind in succession of Crop A with a reachability of 1.

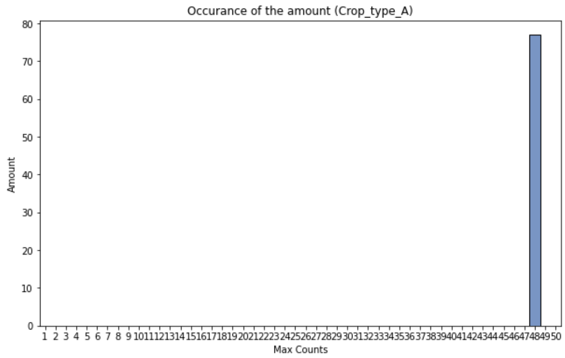


Figure B.26: Number of executed benches of same kind in succession of Crop A with a reachability of 6.

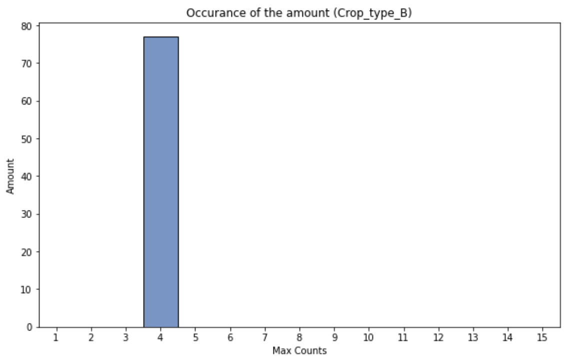


Figure B.27: Number of executed benches of same kind in succession of Crop B with a reachability of 1.

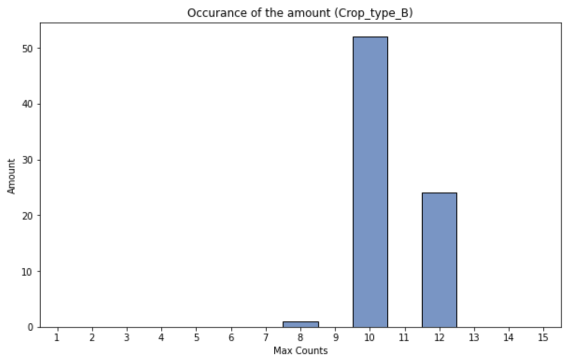


Figure B.28: Number of executed benches of same kind in succession of Crop B with a reachability of 6.

B.3.3. Number of empty benches appended

For each day on the x axis the number of empty benches appended on the y axis is visible for different reachabilities.

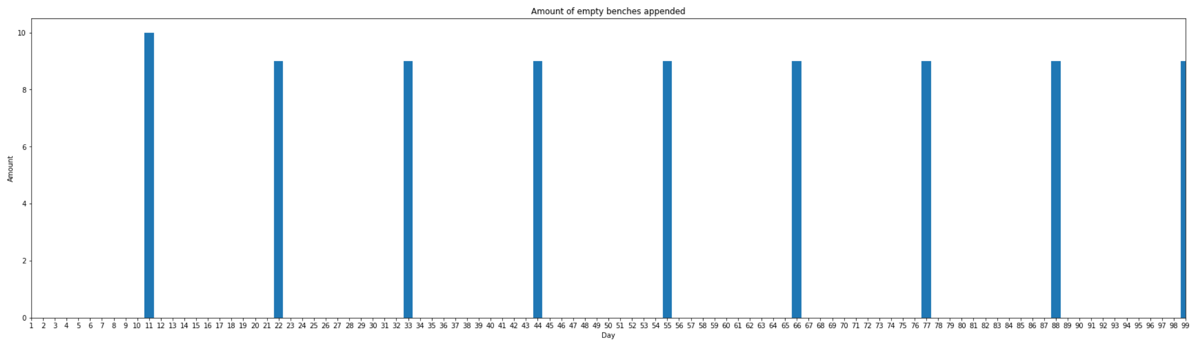


Figure B.29: Number of empty benches appended with a reachability of 1.

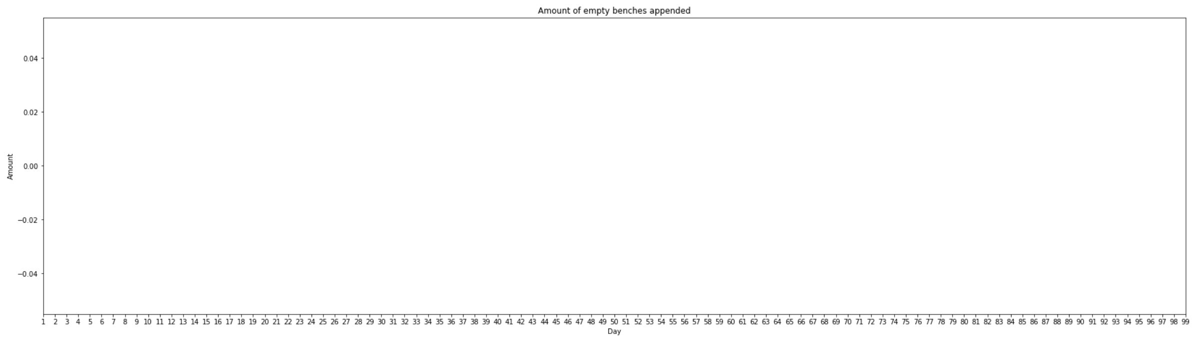


Figure B.30: Number of empty benches appended with a reachability of 6.

B.4. Test case 4

B.4.1. Number of different actions in sequence

For each day on the x axis the number of different actions in sequence can be found for different reachabilities of the vertical farm robot.

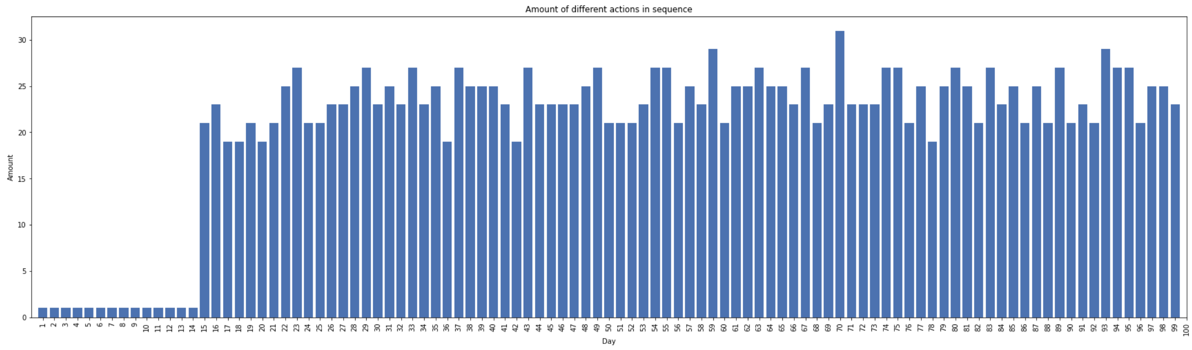


Figure B.31: Number of different actions in sequence for a reachability of 1

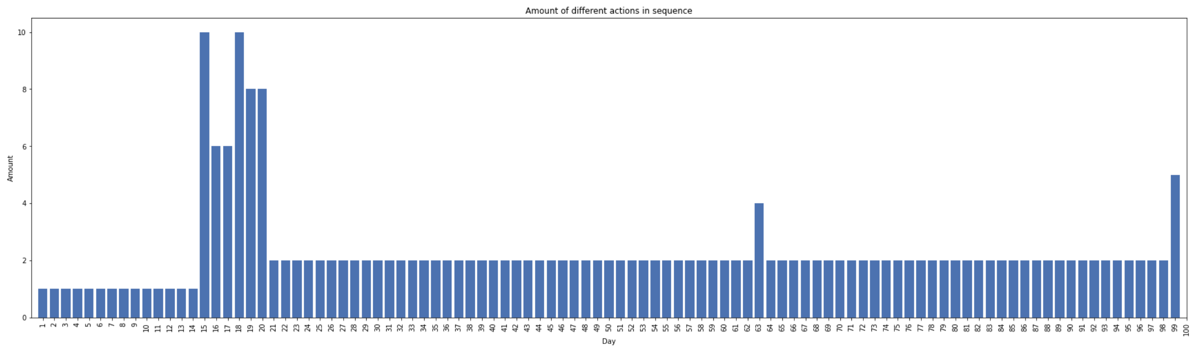


Figure B.32: Number of different actions in sequence for a reachability of 3

B.4.2. Number of executed benches of same kind in succession

On the x axis the number of executed benches of same kind in succession for different crops is visible with the number of time this occurs on the y axis. Reachability of the robot of 1 on the left and 3 on the right.

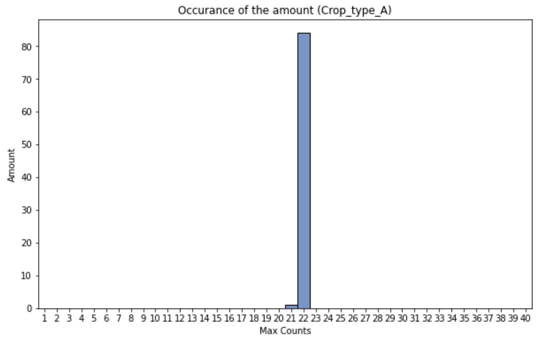


Figure B.33: Number of executed benches of same kind in succession of Crop A with a reachability of 1.

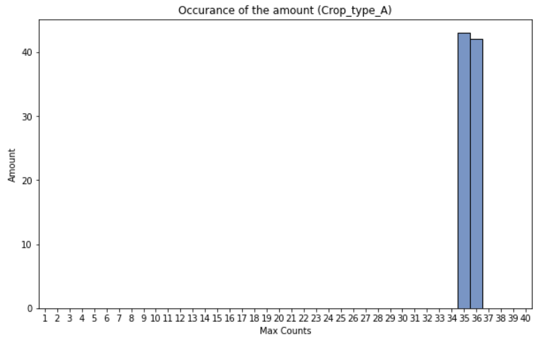


Figure B.34: Number of executed benches of same kind in succession of Crop A with a reachability of 3.

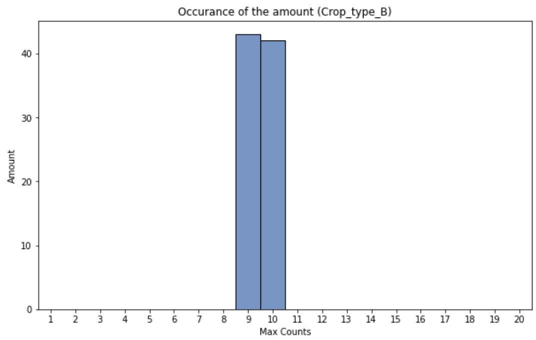


Figure B.35: Number of executed benches of same kind in succession of Crop B with a reachability of 1.

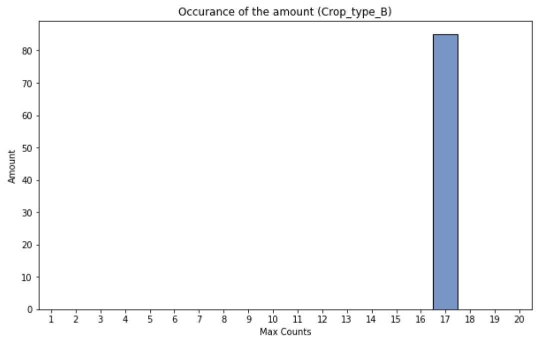


Figure B.36: Number of executed benches of same kind in succession of Crop B with a reachability of 3.

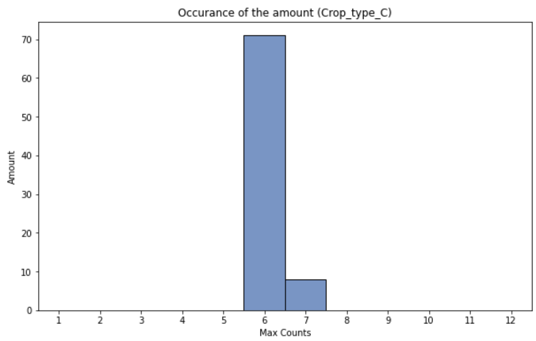


Figure B.37: Number of executed benches of same kind in succession of Crop C with a reachability of 1.

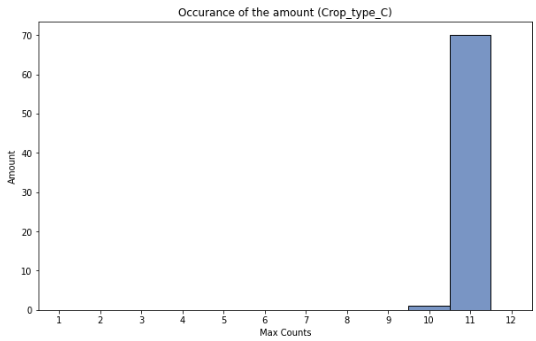


Figure B.38: Number of executed benches of same kind in succession of Crop C with a reachability of 3.

B.4.3. Number of empty benches appended

For each day on the x axis the number of empty benches appended on the y axis is visible for different reachabilities.

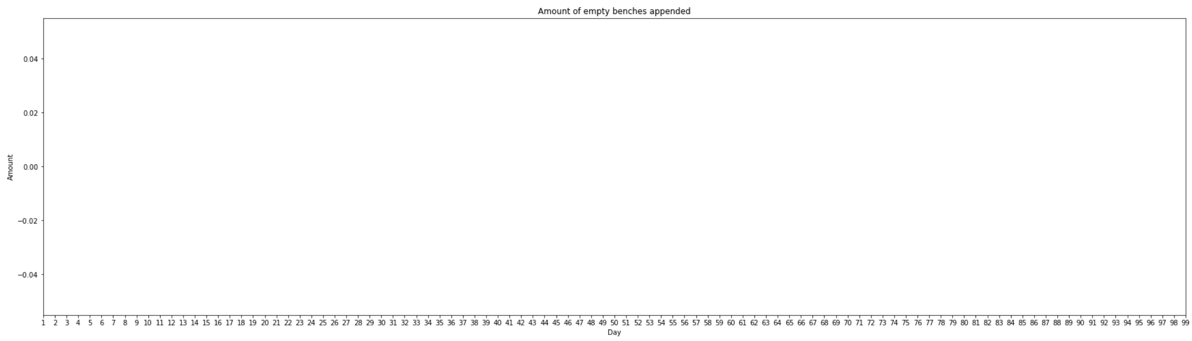


Figure B.39: Number of empty benches appended with a reachability of 1.

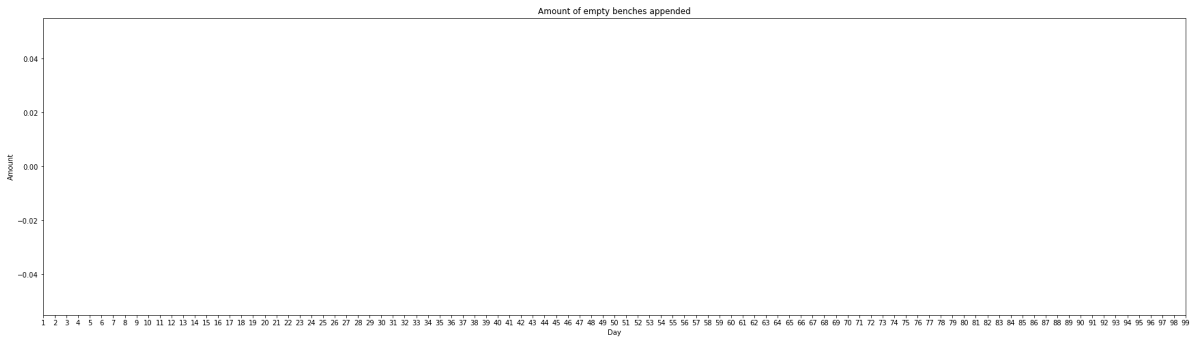


Figure B.40: Number of empty benches appended with a reachability of 6.

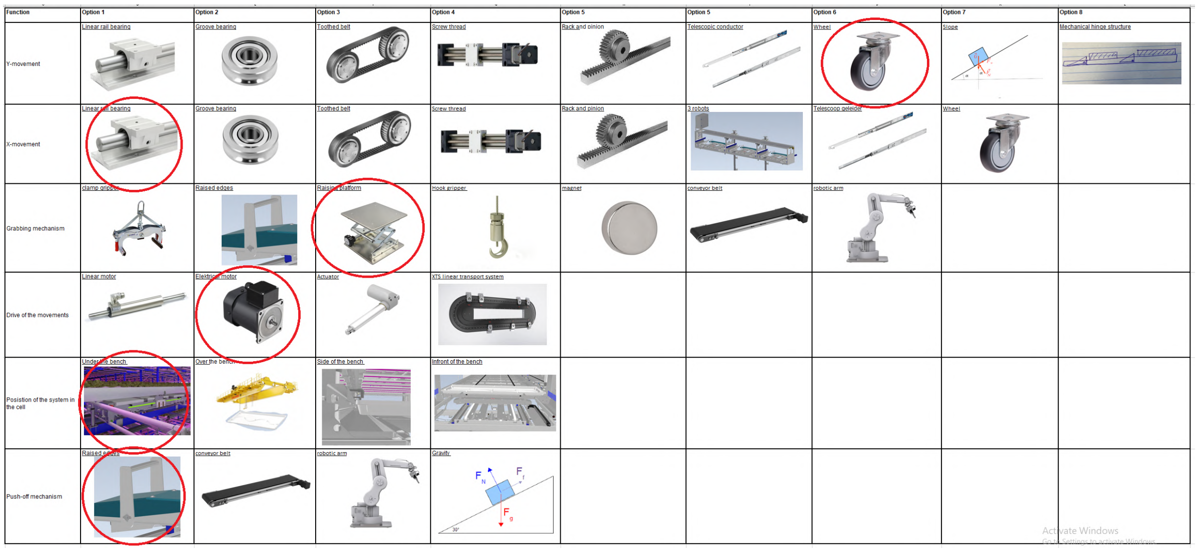
Appendix C

C.1. Morphological chart

Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 5	Option 6	Option 7	Option 8
Y-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	Telescopic conductor	Wheel	Slope	Mechanical hinge structure
X-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	3 robots	Telescoop geleider	Wheel	
Grabbing mechanism	clamp gripper	Raised edges	Raising platform	Hook gripper	magnet	conveyor belt	robotic arm		
Drive of the movements	Linear motor	Elektrical motor	Actuator	XTS linear transport system					
Posistion of the system in the cell	Under the bench	Over the bench	Side of the bench	Infront of the bench					
Push-off mechanism	Raised edges	conveyor belt	robotic arm	Gravity					

Figure C.1: Morphological chart.

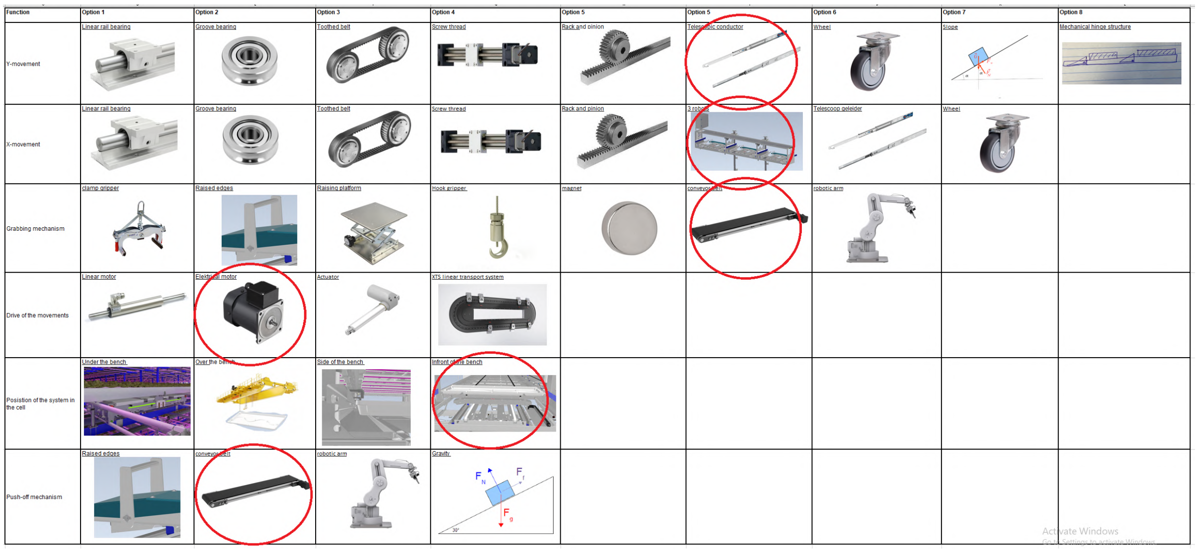
C.1.1. Alternative 1.



Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 5	Option 6	Option 7	Option 8
Y-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	Telescopic conductor	Wheel	Slope	Mechanical hinge structure
X-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	3 robots	Telescoop geleider	Wheel	
Grabbing mechanism	clamp gripper	Raised edges	Raising platform	Hook gripper	magnet	conveyor belt	robotic arm		
Drive of the movements	Linear motor	Elektrical motor	Actuator	XTS linear transport system					
Posistion of the system in the cell	Under the bench	Over the bench	Side of the bench	Infront of the bench					
Push-off mechanism	Raised edges	conveyor belt	robotic arm	Gravity					

Figure C.2: Alternative 1.

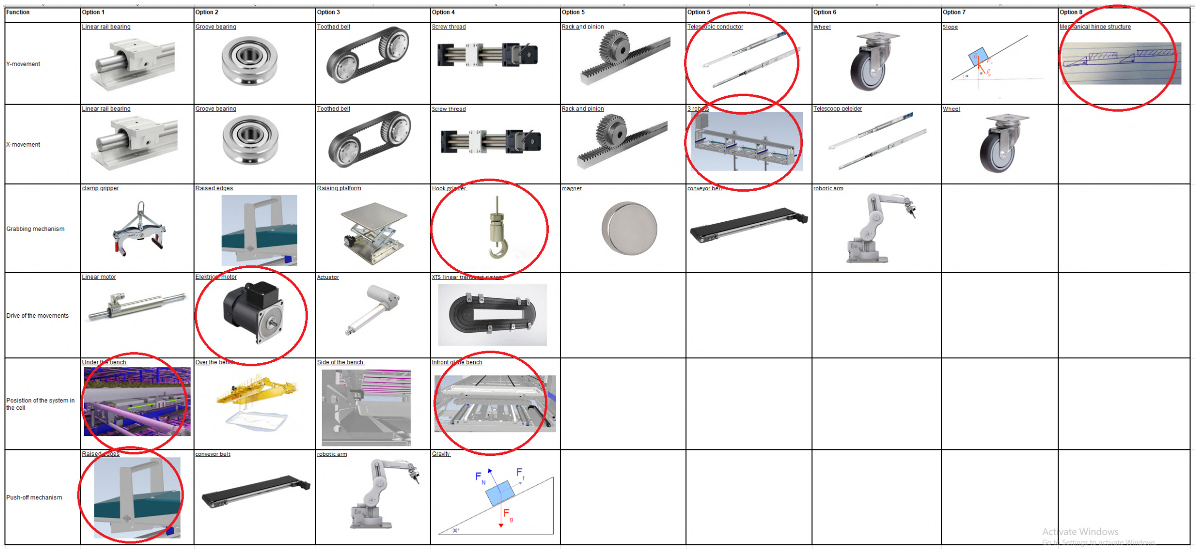
C.1.2. Alternative 2.



Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 5	Option 6	Option 7	Option 8
Y-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	Telescopic conductor	Wheel	Slope	Mechanical hinge structure
X-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	3 robots	Telescoop geleider	Wheel	
Grabbing mechanism	clamp gripper	Raised edges	Raising platform	Hook gripper	magnet	conveyor belt	robotic arm		
Drive of the movements	Linear motor	Elektrical motor	Actuator	XTS linear transport system					
Posistion of the system in the cell	Under the bench	Over the bench	Side of the bench	Infront of the bench					
Push-off mechanism	Raised edges	conveyor belt	robotic arm	Gravity					

Figure C.3: Alternative 2.

C.1.3. Alternative 3.



Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 5	Option 6	Option 7	Option 8
Y-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	Telescopic conductor	Wheel	Slope	Mechanical hinge structure
X-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	3 robots	Telescoop geleider	Wheel	
Grabbing mechanism	clamp gripper	Raised edges	Raising platform	Hook gripper	magnet	conveyor belt	robotic arm		
Drive of the movements	Linear motor	Elektrical motor	Actuator	XTS linear transport system					
Posistion of the system in the cell	Under the bench	Over the bench	Side of the bench	Infront of the bench					
Push-off mechanism	Raised edges	conveyor belt	robotic arm	Gravity					

Figure C.4: Alternative 3.

C.1.4. Alternative 4.

Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 5	Option 6	Option 7	Option 8
Y-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	Telescopic conductor	Wheel	Slope	Mechanical hinge structure
X-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	3 robots	Telescoop geleider	Wheel	
Grabbing mechanism	clamp gripper	Raised edges	Raising platform	Hook gripper	magnet	conveyor belt	robotic arm		
Drive of the movements	Linear motor	Elektrical motor	Actuator	XTS linear transport system					
Posistion of the system in the cell	Under the bench	Over the bench	Side of the bench	Infront of the bench					
Push-off mechanism	Raised edges	conveyor belt	robotic arm	Gravity					

Figure C.5: Alternative 4.

C.1.5. Alternative 5.

Figure C.6: Alternative 5.

C.1.6. Alternative 6.

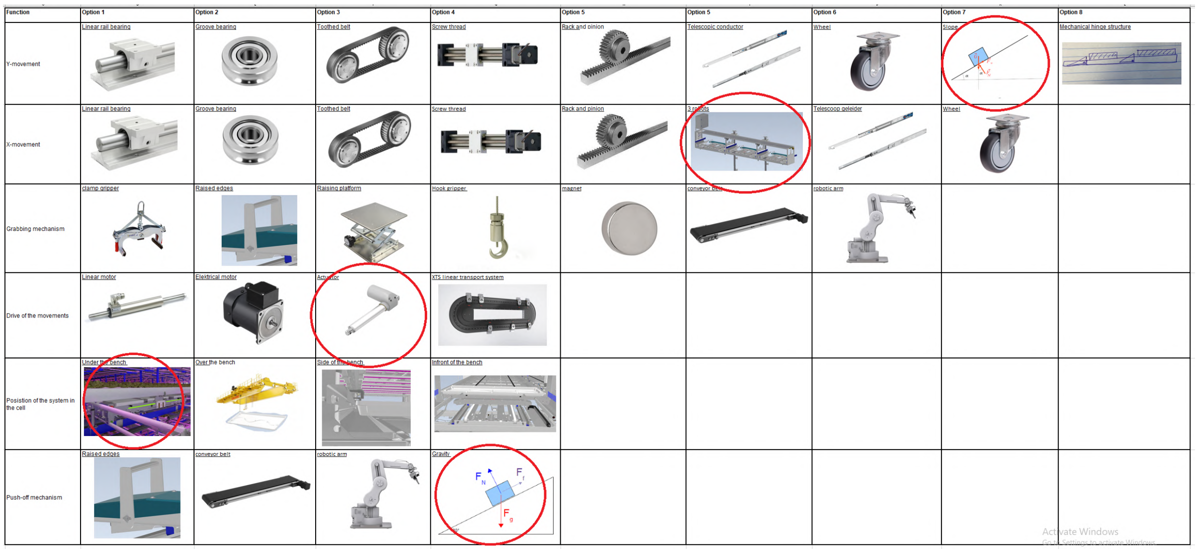
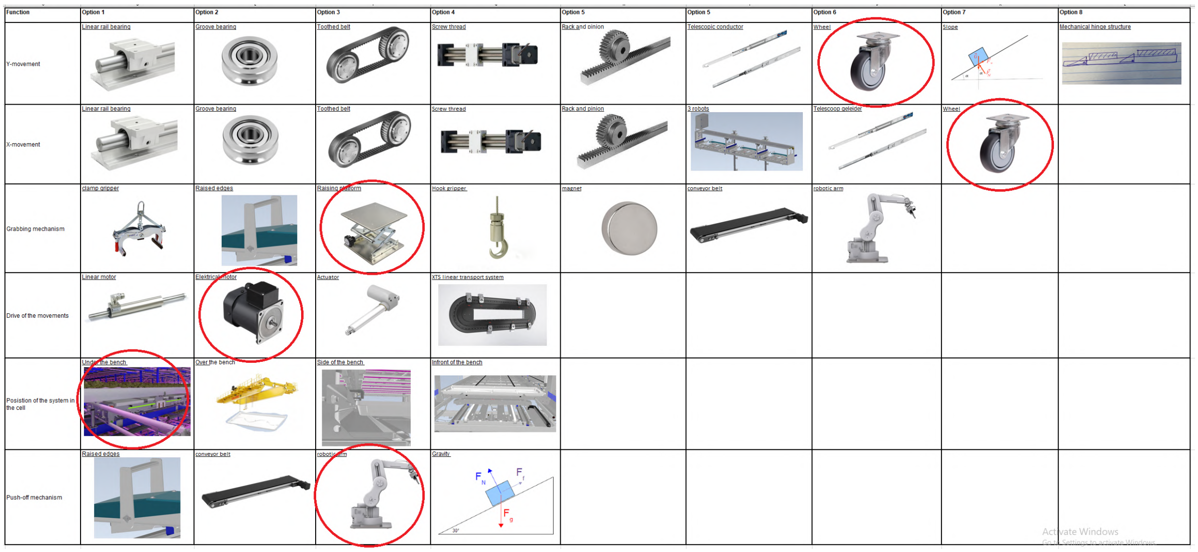


Figure C.7: Alternative 6.

C.1.7. Alternative 7.



Function	Option 1	Option 2	Option 3	Option 4	Option 5	Option 5	Option 6	Option 7	Option 8
Y-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	Telescopic conductor	Wheel	Slope	Mechanical hinge structure
X-movement	Linear rail bearing	Groove bearing	Toothed belt	Screw thread	Rack and pinion	3 robots	Telescoop geleider	Wheel	
Grabbing mechanism	clamp gripper	Raised edges	Raising platform	Hook gripper	magnet	conveyor belt	robotic arm		
Drive of the movements	Linear motor	Elektrical motor	Actuator	XTS linear transport system					
Posistion of the system in the cell	Under the bench	Over the bench	Side of the bench	Infront of the bench					
Push-off mechanism	Raised edges	conveyor belt	robotic arm	Gravity					

Figure C.8: Alternative 7.

Appendix D

D.1. Welding drawings

D.1.1. Body of the robot

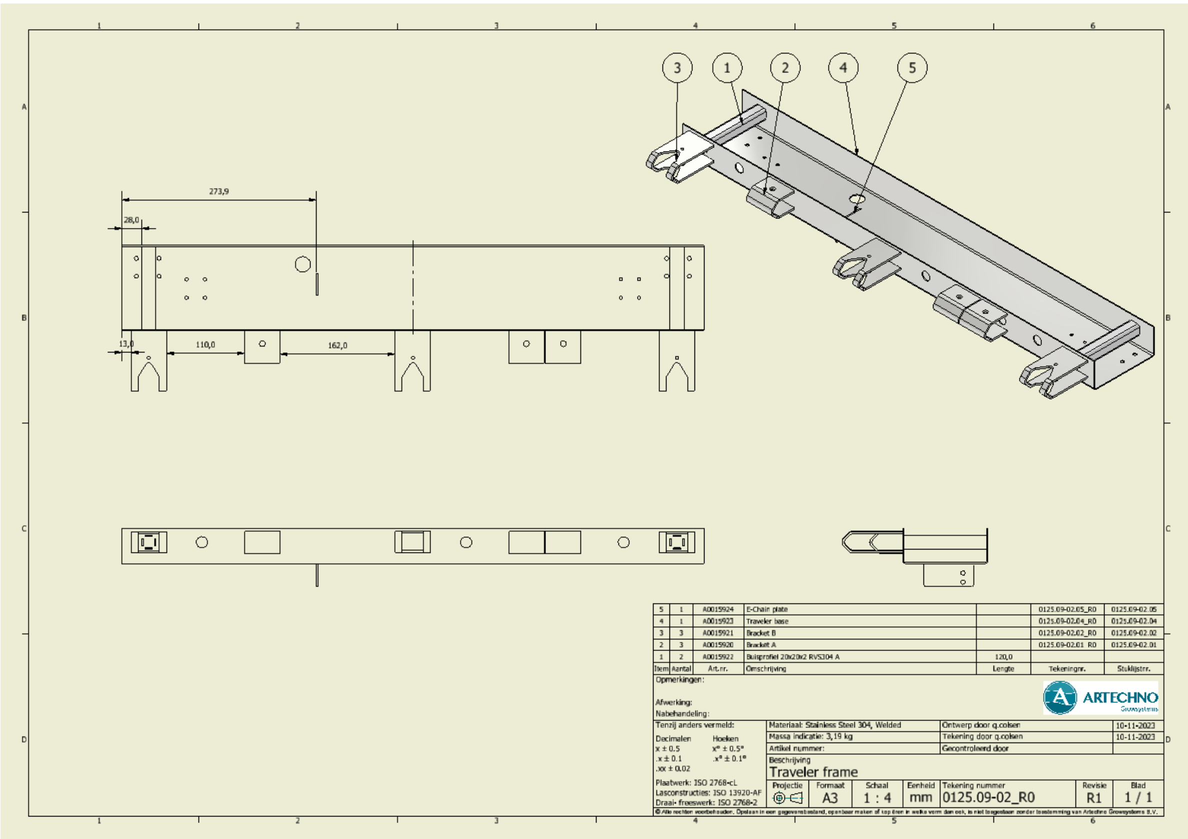


Figure D.1: Welding drawing of the body of the robot.

D.1.2. Right robot guidance

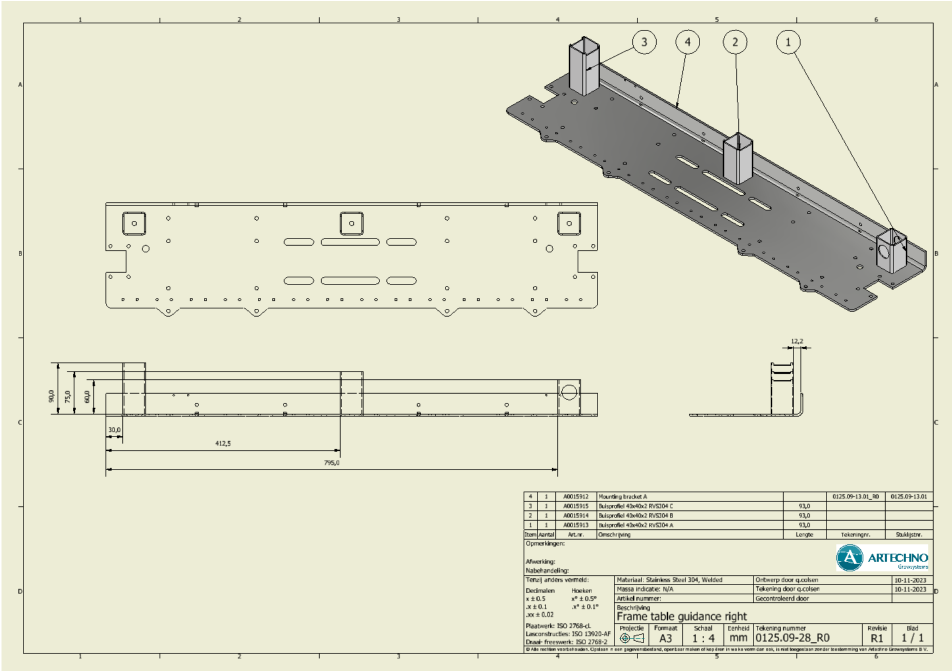


Figure D.2: Welding drawing of the right robot guidance.

D.1.3. Left robot guidance

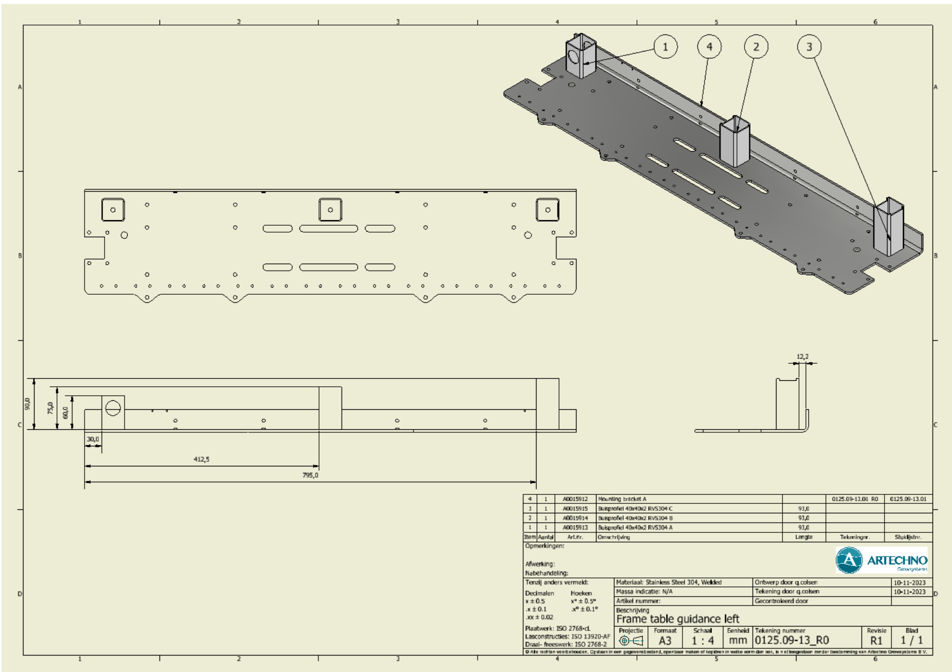


Figure D.3: Welding drawing of the left robot guidance.

D.1.4. Stopper

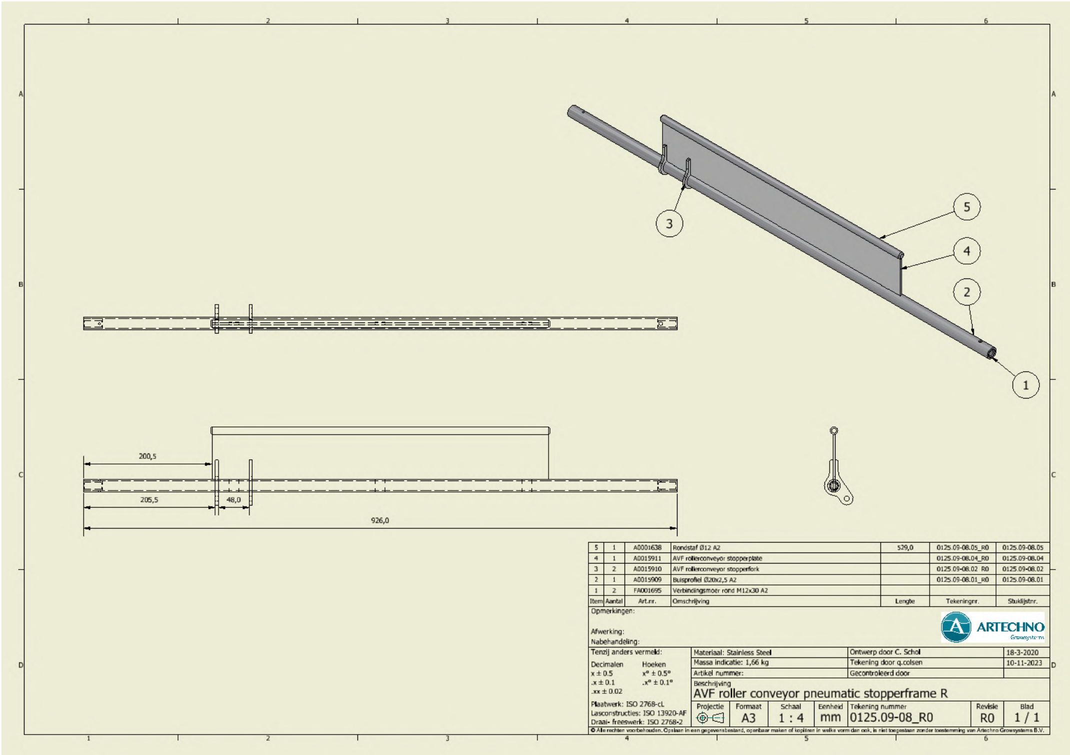


Figure D.4: Welding drawing of the Stopper.

D.1.5. Cable Caterpillar guidance

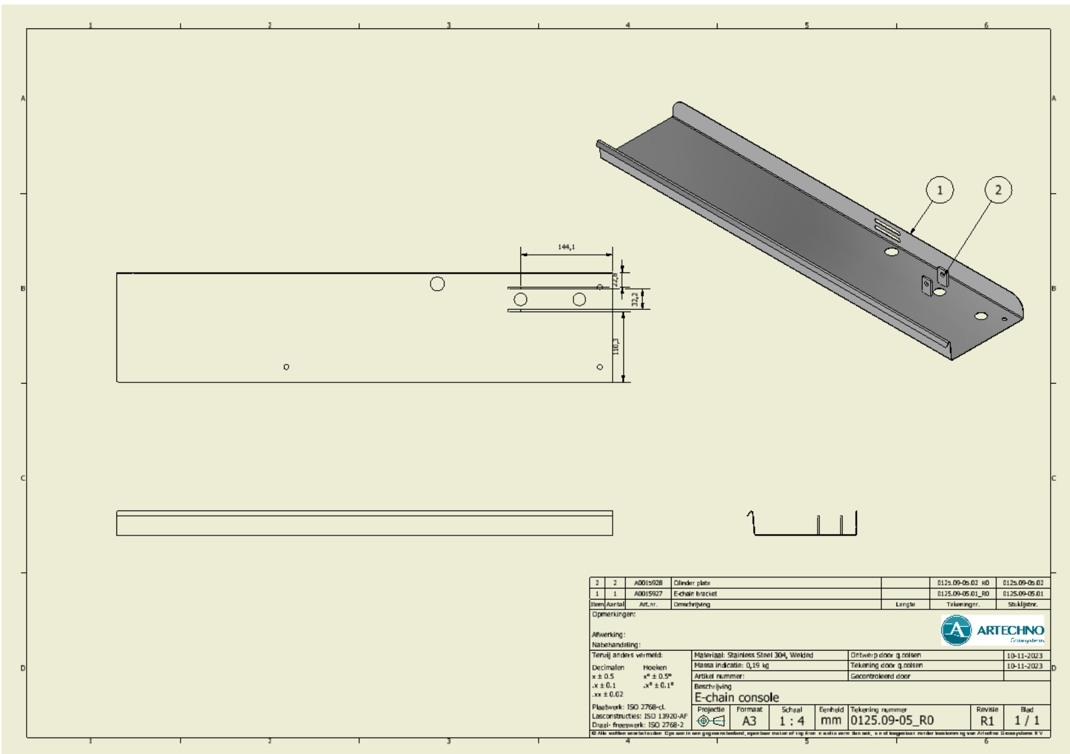


Figure D.5: Welding drawing of the cable caterpillar guidance.

D.2. Assembly drawings

D.2.1. Full vertical robot assembly

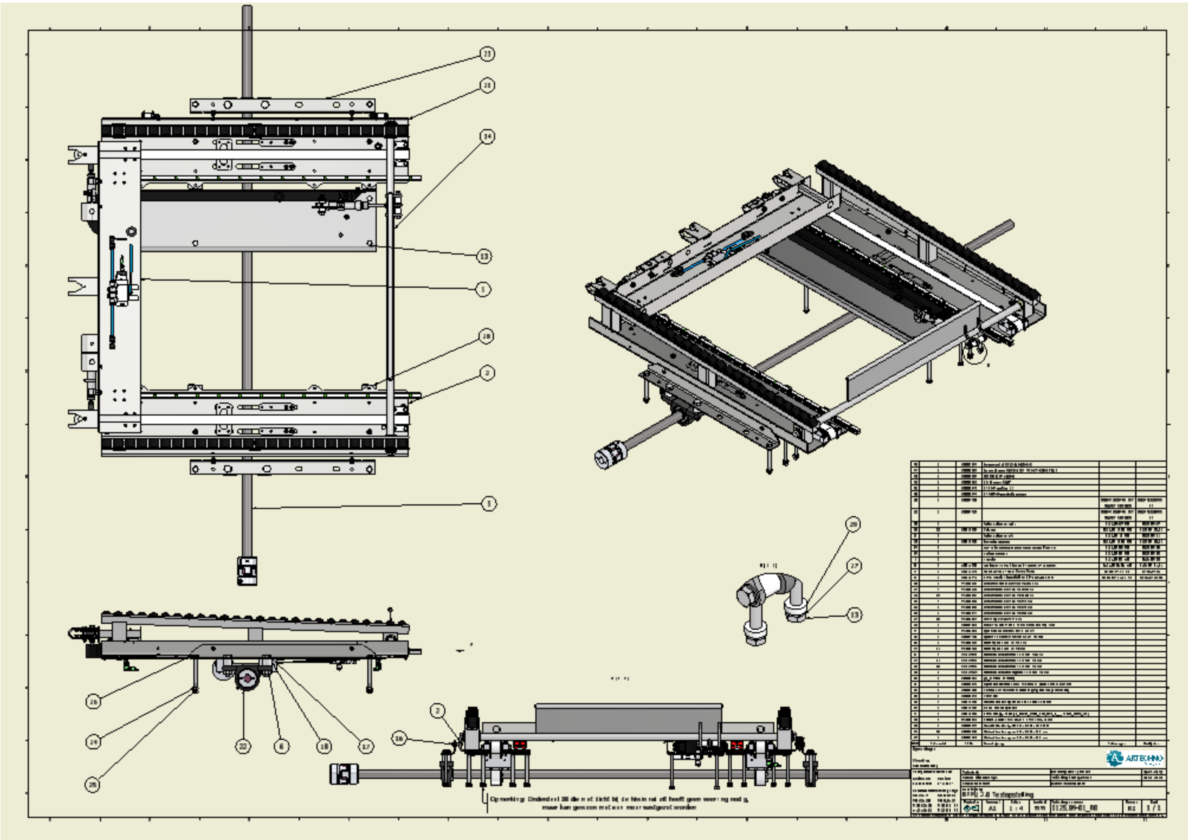


Figure D.6: Assembly drawing of the vertical farm robot.

D.2.2. Body of the robot

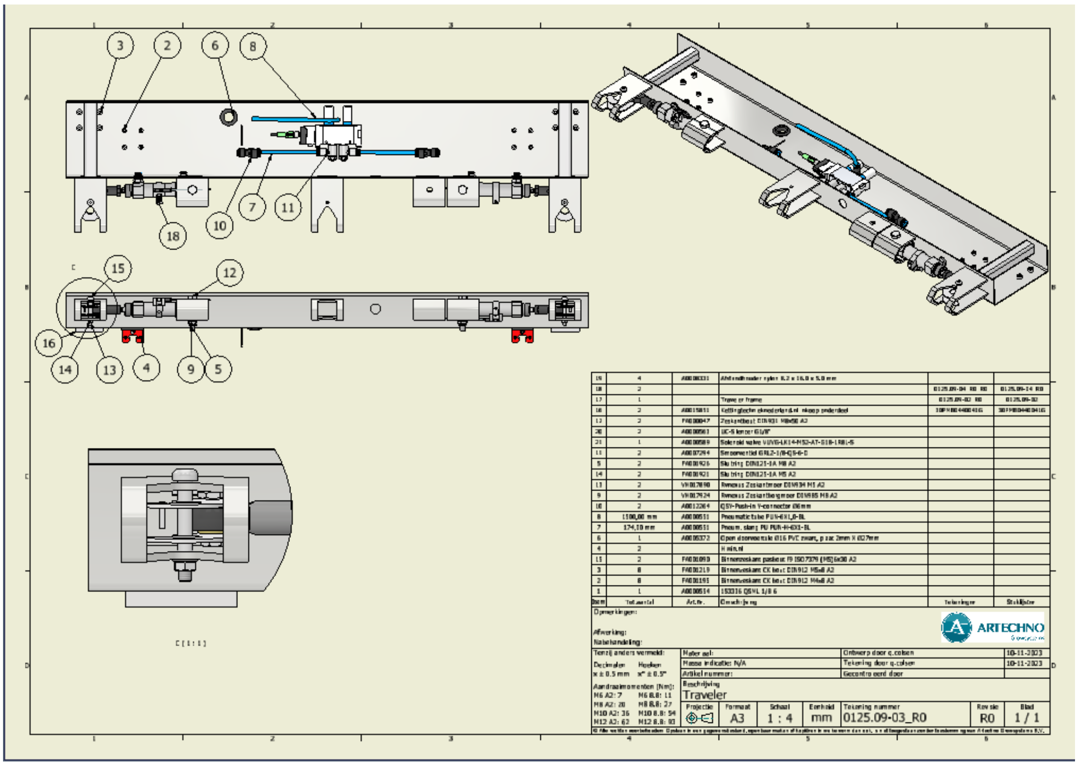


Figure D.7: Assembly drawing of the body of the robot.

D.2.3. Right robot guidance

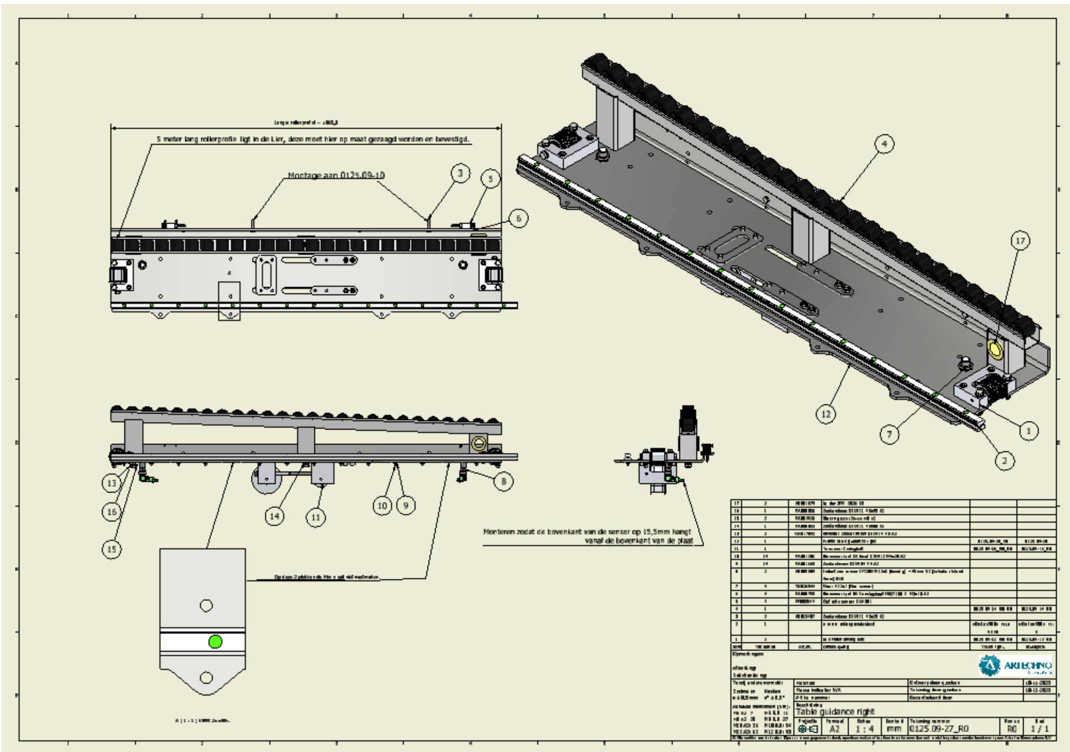


Figure D.8: Assembly drawing of the right robot guidance.

D.2.4. Left robot guidance

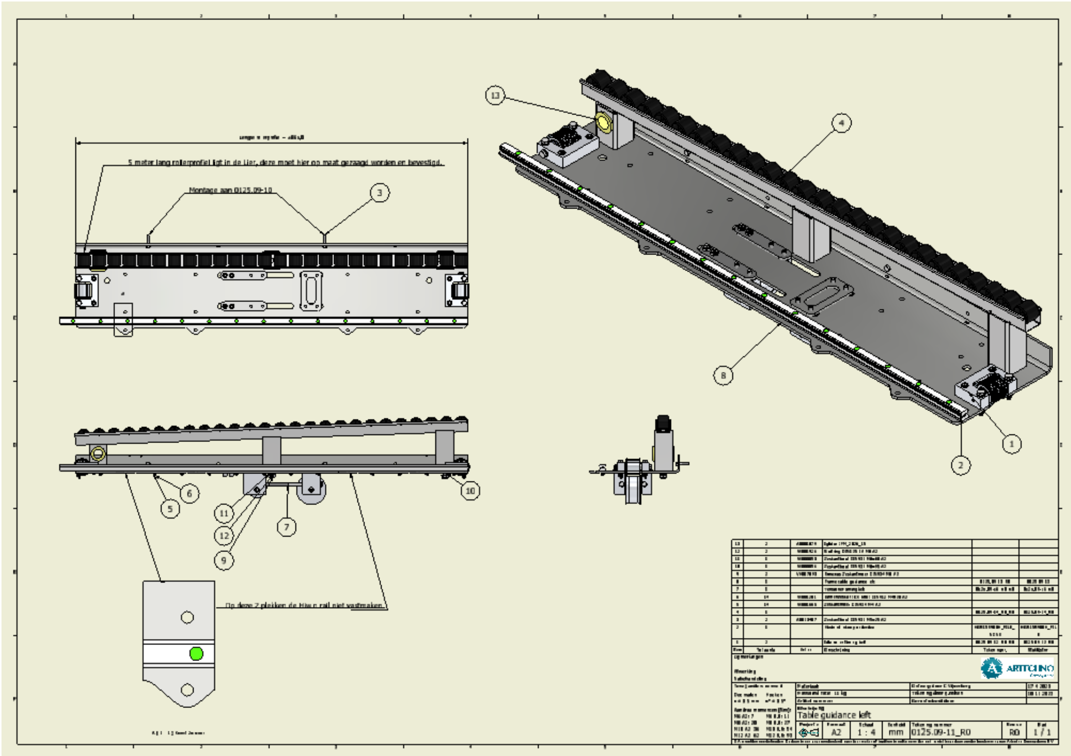


Figure D.9: Assembly drawing of the left robot guidance.

D.2.5. Stopper

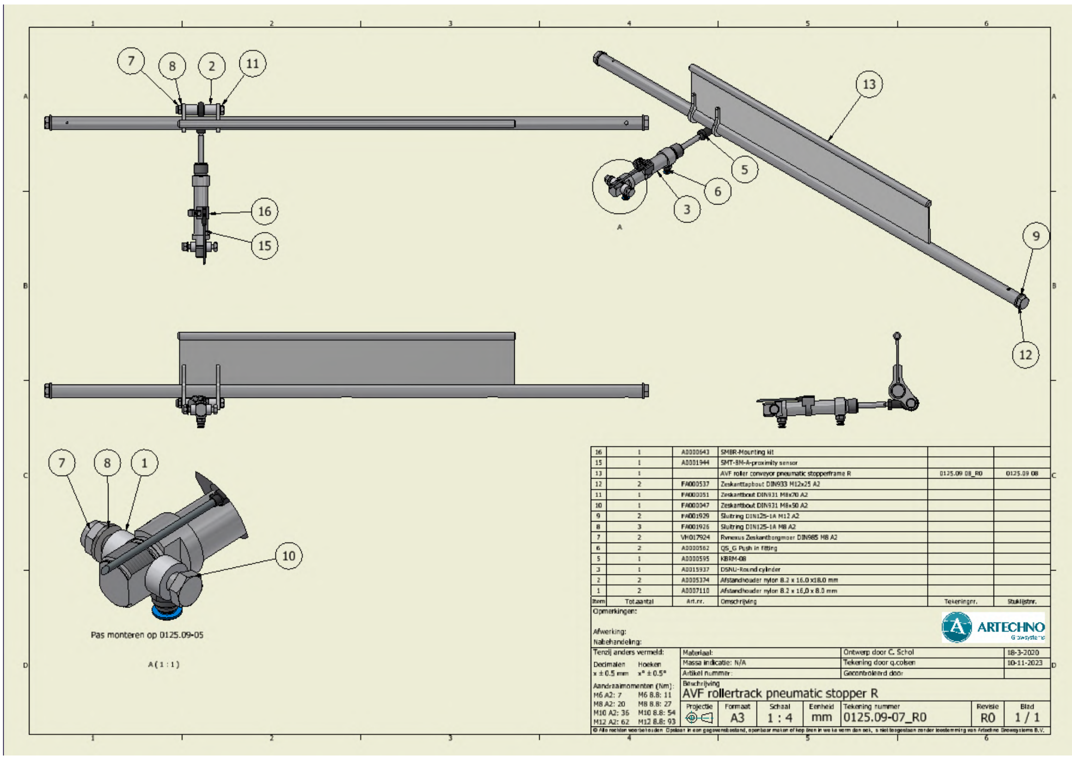


Figure D.10: Assembly drawing of the Stopper.