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Improving Egg Transfer in Hatcheries

A Redesign of Viscon's Selective Egg Transfer

Ewout Schokker (5118492)

Master Thesis

Improving Egg Transfer in Hatcheries

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By

E. Schokker

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Supervisor: Ir. W. van den Bos

Thesis committee:
Prof. Dr. Ir. D.L. Schott, TU Delft committee Chair, Mechanical Engineering
Ir. T.B. Keesom, TU Delft member, Mechanical Engineering
Ing. Coen Rombout, company supervisor, Viscon

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I acknowledge the use of AI tools in this work for grammatical editing and brainstorming purposes.

Abstract

This thesis delineates the redesign process of a very high-capacity selective egg transfer device. The device is used in hatcheries to selectively transfer eggs with living embryos from incubation trays into hatching baskets, while other eggs are left in the trays. Reliable and hygienic selective transfer is essential to achieve high hatchability and low mortality of embryos by preventing bacteria such as Salmonella from spreading, but this is compromised by problems encountered in the current design.

The research contains a comprehensive analysis of the current device and environment, which revealed several shortcomings, especially with the grabbing mechanism of the current device. Thorough literature and patent research was done to identify important design limitations and possibilities for handling eggs. Several designs were then constructed, which were assessed and compared using the weighted criteria method and defined design objectives.

The best-scoring design was then designed in detail. It consists of a removable vacuumbox with movable rods, which can avoid contact with eggs infected with bacteria. The removability of the vacuumbox enables thorough inspection and cleaning, theoretically eliminating most of the problems encountered with the prior art while improving its capacity.

The redesign described in this thesis was thus successful, contributing to a more effective and hygienic selective egg transfer process in industrial hatcheries.

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1 Introduction

This research shows the process of redesigning a device used in hatcheries, where eggs are incubated until they are hatched. This chapter gives some background on the company making these devices, Viscon, and hatcheries, together with the motivation and outline of this research.

1.1 Background

Viscon [1] is a Dutch company, based in ’s Gravendeel, The Netherlands. They are world leaders in designing and building automation solutions for several sectors, including (chicken) hatcheries, horticulture, and warehouses. Whereas many industries have automated many of their processes, the food and agri-industry is lagging due to the unpredictable and soft nature of many food products [2], even though global demand for products of this sector increases rapidly. Considerable efforts should thus be taken to increase the level of automation in these sectors.

Viscon has previously designed and deployed many automation solutions in the poultry industry, specifically in chicken hatcheries. One of these processes is the egg transfer process, in which eggs nonviable for hatching are ignored or transferred to a hopper, while the viable eggs are transferred from a tray to a basket. Viscon designed, among other machines, the Selective Transfer device (ST) for this purpose.

1.1.1 The journey of an egg in a hatchery

The journey of the egg in a chicken hatchery is a very static process, which, under correct conditions, takes approximately 21 days. Figure 1.1 gives an overview of the process.

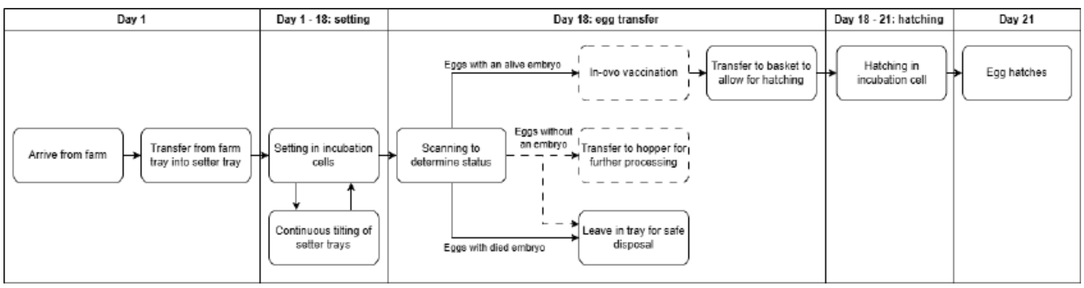


Figure 1.1: The journey of an egg in a hatchery. A dashed contour of a block indicates an optional step.

The eggs arrive at the hatchery from a farm on day 1, after which they are transferred to special setter trays, of which an example can be seen in Figure 1.2. They vary largely in diameter, height, and mass. The egg quality also varies, so the eggs are graded before transferring them to the setter trays. Very dirty eggs, eggs that are too small or too large, or eggs with cracks are removed in this process. After that, they are put in the trays with the sharp end of the egg pointing down. This orientation is the best for the chick’s head to get to the air chamber, which is at the blunt side of the egg. The eggs in the setter trays are then put on trolleys and incubated in an incubation cell, a process called 'setting'.

The setting process requires a continuous tilting motion of the eggs to prevent the pericarp within from sticking to the shell. An example of a setter incubation cell tilting the setter trays is shown in Figure 1.3. As shown, the tilting angle is almost acute. The sticking of the pericarp would stop the proper growth of the embryo and other vital processes required for hatching. In natural breeding, the hen does this by rotating the egg many times a day. The setter trays have a grid with a spot for every egg, preventing the eggs from touching and damaging each other, while also keeping the eggs in their spot during the tilting motion. Research pointed out that eggs that touch each other, even with very small forces below 5 N, can cause hair cracks in the shell that have a negative influence on the hatching outcome [3].

The temperature, humidity, and the O_2 and CO_2 concentrations during the setting process are precisely controlled by the incubation cell, allowing all eggs to have a similar development and all hatch around day 21. The temperature and humidity for setting the eggs should be around 37.6 °C and 52 %, respectively [4]. In natural breeding, the hen achieves this by sitting on the eggs.

After around 14 days of setting, the embryo has developed enough to allow for heartbeat and embryo detection. Embryo detection is done by detecting how much light an egg absorbs, which was done in the past using a candle, hence its name, candling. The egg's development, however, still requires continuous tilting motion until the 18th day. At that point, the growth of the embryo should be almost completed, and the eggs can be prepared for hatching.

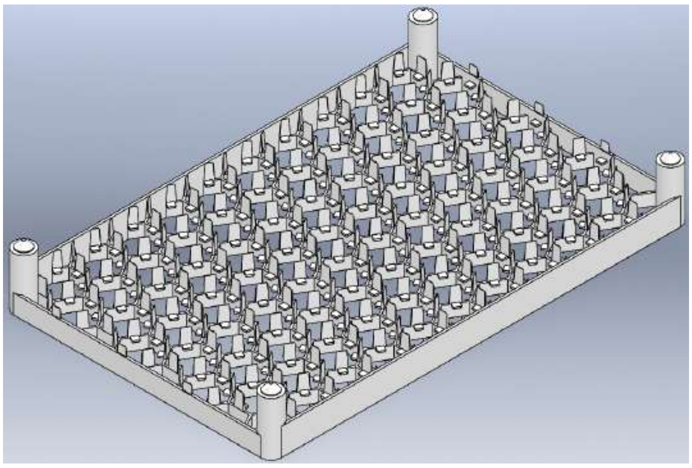


Figure 1.2: An example of a setter tray

Figure 1.3: An example of a setter incubation cell with tilted setter trays on trolleys [5]

Even though hygiene is considered very important and is highly regarded within hatcheries, eggs can get infected with microbes due to, e.g., dirty circumstances in the barn they originate from or from contaminated equipment in the hatchery. Infection can cause death and internal rotting of the embryo, and, by day 18, the rotten eggs have the potential to explode upon touch or even vibration due to a buildup of gases within the shell; hence their name, "banger" or "exploder". On day 18, three types of eggs can be distinguished, as listed below.

1. **Eggs with living embryos**, which have properly developed and are viable for hatching.
2. **Eggs with a dead embryo**, which were fertilized but died due to external circumstances, possibly due to microbes.
3. **Eggs without an embryo**, which were not fertilized at all. They are sometimes used for, e.g., cattle feed, or disposed of otherwise.

The setter trays in which the eggs are set for the first 18 days do not allow for hatching, as the chicks would get stuck in the grid, or they could walk off the setter trays. For that reason, hatcheries have to transfer the eggs to hatching baskets, an example of which is shown in Figure 1.4. A typical layout of such a transfer room is shown in Figure 1.5. The numbers in the layout figure show different machines in the egg transfer room, and the process steps are elaborated in the following list.

1. The setter trays with eggs are first put on a conveyor belt, the input line.
2. Empty hatching baskets are put on another conveyor belt, the output line.
3. A scanner, the so-called Live Embryo Detection (LED), then determines the status of the eggs on the input line.
4. In-ovo vaccination is then applied to the viable eggs on the input line, if required by the customer. Viscon uses their machine for this, called the Vinovo.
   Vaccination of chicks against diseases such as bird flu is often mandatory. This can be done before or after hatching. Vaccination before hatching, called in-ovo vaccination, is often considered the most efficient and animal-friendly [6]. Vaccination is done by pushing a tiny needle through the shell, after which the vaccine is injected into the amniotic fluid.
5. The viable eggs are then transferred from the setter trays on the input line to the hatching baskets on the output line using the ST, visible at point 5. *Some hatcheries can also use the eggs without an embryo to make, e.g., cattle feed. If required, the ST thus also transfers these eggs into a hopper located between the input and output line), after which they are further processed. In practice, between 5 and 95 % of eggs in a setter tray are to be transferred, depending on the egg quality and the customer's requirements.*
6. The hatching baskets on the output line are then transferred to trolleys, and further hatched in incubation cells in a separate hatching room.
7. The eggs remaining in the setter trays on the input line are disposed of, preferably in a separate room, to prevent contamination with microbes on viable eggs. The trays are tipped over with a tray tipper, after which they are transferred to trolleys and cleaned for reuse.

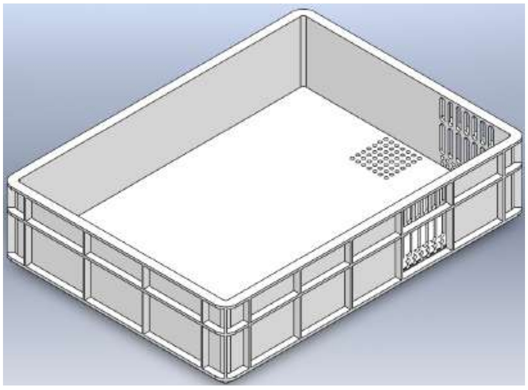


Figure 1.4: An example of a hatching basket

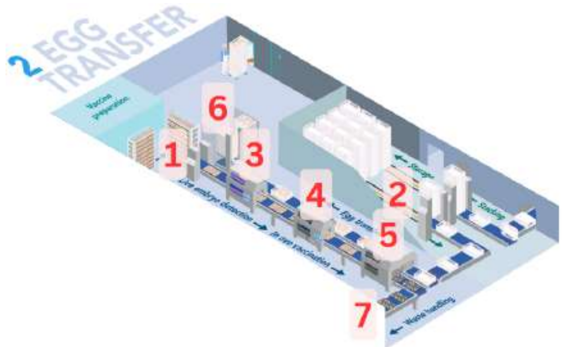


Figure 1.5: Typical layout of the egg transfer room in a hatchery

1.1.2 Hygiene in a hatchery

As stated before, hygiene is highly regarded in hatcheries. Any single microbe can grow to a visible colony within a few days, especially in the hot and humid environment required for hatching. Eggs contaminated before hatching can cause death to the embryo, as the porous shell allows bacteria to infiltrate the egg. Contamination in the egg can start a rotting process within, resulting in the banger eggs described before. Hatched chicks are also very vulnerable to microbes and can die from infection.

Therefore, both the setting, transferring, and hatching in the hatchery are done in separate rooms. Air pressure differences between the rooms decrease the likelihood of microbes traveling from the dirtiest room, the hatching room, to the other rooms. Any traffic between the separate rooms, such as people, trays, baskets, and trolleys, is also decontaminated.

It should be noted that hatcheries work in batches. Every batch of eggs comes from chickens with different properties, and must thus be kept separate. As a certain type of eggs arrives as a batch at the hatchery, these are also set, transferred, and hatched in that same batch to ensure the eggs all hatch simultaneously.

After every day shift, after processing several batches of eggs, the complete hatchery is also cleaned with high-pressure water and detergents, which are cycled between alkaline and acidic to prevent the habituation of microbes.

1.2 Motivation

The current ST, however, has some fundamental shortcomings, which cause infection of costly viable eggs. Unreliability of the machine also causes undesired eggs to be picked up or left behind in the setter trays, which can cause contamination in the hatcher baskets or undesired disposal of eggs with living embryos, respectively. Extra cleaning of the system is also regularly needed due to exploding bangers, caused by touching them, which can clog the suction system or contaminate other eggs.

A lot of attention from operators is required due to these issues, which is economically undesirable. Besides, due to the contamination problems, hatched chicks or embryos can also die. As they cost upwards of €0.25 each, a loss of only one percent of the millions of eggs processed every week can cost thousands of euros every week.

Combined with ever-increasing customer demands for capacity, Viscon calls for a reconsideration of the current design of the Selective Transfer device, mainly to increase the hygiene, reliability, and capacity of the device.

1.3 Research outline

1.3.1 Objective

The objective of this research is to analyze the problems and potential improvements of the current ST. A new design will then be proposed to solve the problems and meet increasing customer demands.

1.3.2 Approach

To methodically solve the problem, the following research question is defined, which will be answered throughout this report:

> **To what extent can the Viscon Selective egg Transfer device be improved by a redesign?**

Different research sub-questions are defined as well:

1. How does the current system work, what are the problems with the current system, and how do these affect the system's performance?
2. What are the known properties of eggs that could limit the design, and how have others solved the problem of egg grabbing and selective egg transfer?
3. What solutions are possible, which is the most suitable, and what does the solution look like in detail?
4. How does the solution perform compared to the current system?

1.3.3 Research boundaries

The research in this report will be conducted within some boundaries. These boundaries are defined and presented in Table 1.1.

Table 1.1: Scope of the research

Boundary	
1	The research focuses on identifying problems with, and improving the current ST design made by Viscon, possibly eliminating its problems and meeting the increasing customer demands. The other machines in and the layout of the transfer process will be left as is.
2	Design of the conveyor belts that connect the different systems in the transfer room is left out of scope, but the design of the ST is constrained by and should work with existing conveyor belts.
3	As the design has to work in all hatcheries with only minor modifications, modularity of the design should be of high priority. However, the analysis and detailed design will only be made and elaborated for the most common setup, which transfers two HT88 trays into two HT88 baskets. This should not influence the concept, only configuration specific details such as dimensions.

1.4 Report outline

The remaining chapters of this research will be used to answer the different research sub-questions. In Table 1.2, the outline of this report is given. First, in **??**, the system and the problems will be analyzed in depth, and the effect of the problems on the performance of the system will be shown. Next, in Chapter 3, literature will be used to find solutions to similar problems, and the properties of eggs will be explored. In Chapters 4, 5 and 6, concepts will be made up, compared, and detailed. Finally, in **??**, the final concept will be compared to the current solution and will be checked against the requirements of the design.

Table 1.2: List of sub-questions and corresponding chapters

Sub-question		Chapter
1	How does the current system work, what are the problems with the current system, how do these affect the system's performance, and how can these problems possibly be solved?	Chapter 2
2	What are the known properties of eggs that could limit the design, and how have others solved the problem of egg grabbing and selective egg transfer?	Chapter 3
3	What solutions are possible, which is the most suitable, and what does the solution look like in detail?	Chapters 4 to 6
4	How does the solution perform compared to the current system, and does it satisfy the requirements?	Chapter 6

2
Process analysis

Before starting the process of redesigning the system, a thorough system analysis should be done. This is done by answering the first research question:

"How does the current system work, what are the problems with the current system, how do these affect the system's performance, and how can these problems possibly be solved?"

To answer this research question, the environment of the system will be analyzed in Section 2.1, as well as the system itself in Section 2.2. In Section 2.3, a summary will be given, which answers the research question.

As per scope, the most common configuration transferring two HT88 trays into two 2 HT88 baskets is used for the analysis.

2.1 The full transfer line

The current ST is a part of a larger transfer line, consisting of multiple machines. A schematic of the transfer line is presented in Figure 2.1.

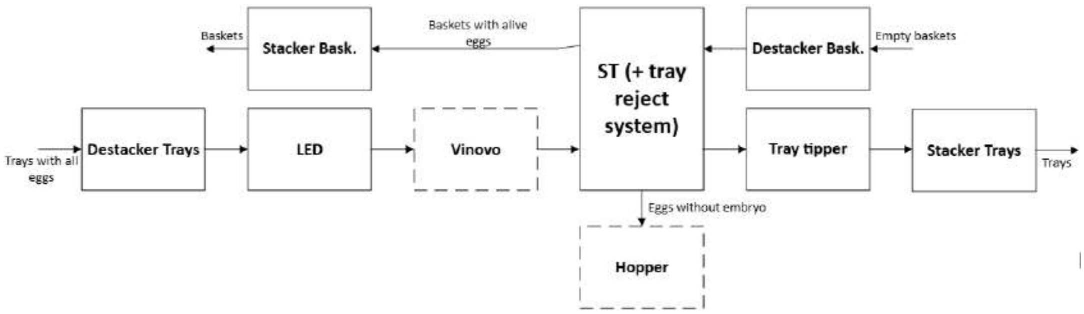


Figure 2.1: A schematic of the transfer process in a hatchery. The dashed outlines indicate optional processes.

The process above has been explained in steps before, in Section 1.1. As shown, multiple machines work together to achieve the transfer of viable eggs and empty eggs, with the ST fulfilling the main purpose of the transfer line.

The transfer line is usually placed in a special transfer room within a hatchery. In this section, several important details of the environment within the transfer room are analyzed and recorded.

2.1.1 The available space

The dimensions of the transfer room vary from hatchery to hatchery, and the rooms are usually built to accommodate the required machines. Sometimes, however, the transfer line is to be placed in an existing hatchery, which requires the line and machines to fit within an existing space.

The available space is thus case specific, and only the height of the space is constrained, as the smallest type of incubation cells requires at least 2680 [mm] of height.

Most access doors to transfer rooms, however, are only around 2500 by 2500 [mm] in size. It is best if the devices can fit through them without disassembly.

Minimizing the required area for the machines enables the increase of the number of transfer lines within the available space, which is why smaller machines are preferred if the capacity stays the same. Usually, most devices are made to handle a pitch of 1500 [mm] between the input and output line, but this can be decreased to 1000 [mm] for most of the machines in the transfer line if there is a lack of space.

2.1.2 Hygiene in the transfer room

As mentioned before, hygiene is highly regarded within hatcheries, due to the costs associated with infection of eggs and the quality of the hatched chicks. However, no specific hygiene standards exist for the design of devices in hatcheries, but several standards exist for machine hygiene, often based on Hazard Analysis and Critical Control Points (HACCP) [7] principles. In the past, these were considered guidelines, but starting from January 2027, these will become mandatory by European law [8]. The machines by Viscon should thus also conform to these principles.

In practice, HACCP requires machines in the (animal) food industry to have smooth and cleanable contact surfaces. All contact surfaces should be cleaned before every use, and cleaning detergents should not be able to stay behind. Non-cleanable parts should be sealed hermetically, and cleaning and usage instructions should be provided with the device. Accessibility is also of great importance to ensure that proper inspection can be done.

The materials used should also be non-toxic, smooth, and resistant to the chemicals used in hatcheries, such as Trisodium Phosphate, Sodium Hydroxide, Ethanol, and Chlorine. Most structural parts in devices in hatcheries are made from AISI 304 stainless steel, a very common, high tensile strength, weldable, and chemically resistant material. Other parts can also be made from plastics, such as POM, HMPE, FKM, or similar, as they are resistant to the chemicals used in a hatchery [9].

2.1.3 Trays and baskets

As stated before, many different types of trays and baskets are used in hatcheries. The system of trays, baskets, trolleys, and incubation cells is not made by Viscon; other companies that specialize in this equipment, such as HatchTech [5] and Petersime [10], design and deploy them in hatcheries. The trays and baskets are made to work in combination with the incubation cells of their respective company, and can vary largely in size, pitch, pattern, and egg count.

An overview of the most common trays and baskets is given in Table 2.1 and Table 2.2, respectively. The equipment in the hatchery, including in the transfer room, has to work with these trays and baskets. The type of tray and basket used does not vary within a hatchery; however, it can vary from hatchery to hatchery, calling for a tailored design for every hatchery.

Table 2.1: Most common setter trays used in hatcheries

Company	Name	Egg count	Dimensions $[mm]$	Smallest pitch $[mm]$	Pattern
HatchTech	HT88	88	626 x 306.5 x 34	48	Honeycomb
HatchTech	HT150 (= P150)	150	734 x 507 x 38	48.9	Square
Petersime	P84	84	505 x 373.5 x 33.8	47.6	Honeycomb
Petersime	P150	150	734 x 507 x 38	48.9	Square
Coopermaq	CP84	84	505 x 374 x 32	48	Honeycomb
Chick Master	CM132	132	892 x 307 x 31	47	Honeycomb
Chick Master	CM150	150	1045 x 305 x 43	46.8	Honeycomb
Chick Master	CM165	165	1164 x 307 x 27	47.8	Honeycomb
Jamesway	JW84	84	599 x 289 x 73.1	47.3	Honeycomb
Jamesway	JW168	168	1173 x 295.3 x 33.4	47.2	Honeycomb
Pas Reform	PR162	162	732 x 507 x 37	48.3	Honeycomb

Table 2.2: Most common hatching baskets used in hatcheries

Company	Name	Egg count	Dimensions $[mm]$	Usable area $[mm]$
HatchTech	HT88	88	670 x 350 x 166	642 x 322 x 149
Petersime	P84	84	600 x 400 x 166	572 x 372 x 149
Petersime	P150	150	795 x 565 x 130	762 x 530 x 110
Coopermaq	CP84	84	560 x 520 x 134	530 x 386 x 113
Chick Master	CM132	132	975 x 385 x 115	945 x 360 x 98
Chick Master	CM150	150	1115 x 378 x 117	1085 x 353 x 100
Chick Master	CM165	165	1227 x 422 x 116	1194 x 384 x 101
Jamesway	JW168	168	1250 x 381 x 120	1219 x 350 x 104
Pas Reform	PR162 (= P150)	162	795 x 565 x 130	762 x 530 x 110

2.1.4 The required capacity

The complete transfer line was analyzed to define the current and required capacity of the ST. All devices in the transfer line work by concurrently processing n number of trays or m number of baskets in a cycle. The amount of eggs that can be processed per unit of time, thus, depends on the egg count within a tray. n_{max} and m_{max}, however, also rely on the tray size, as the machines can only be scaled up to a certain point.

The density of eggs within a tray is around the same for every tray type. This means that the capacity of eggs per unit of time should be around the same for any tray type, since the maximum size of the ST limits n_{max} and m_{max}. For the sake of comparison, we will thus use the parameters of the transfer line for the most commonly used tray, with which the highest capacity is reached, the HT88 tray.

A schematic of the flow of trays and baskets with eggs is shown in Figure 2.2.

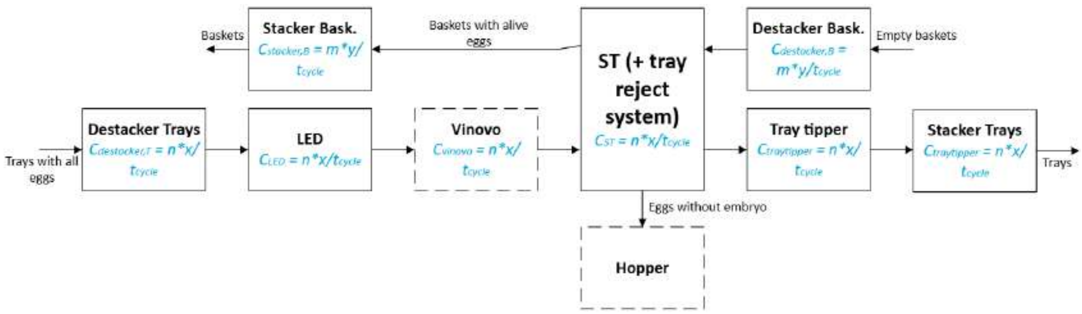


Figure 2.2: The capacities of the transfer process in a hatchery

In the image, some variables that define the capacity are shown. The maximum of n_{max} trays or m_{max} baskets a device can handle concurrently varies per device and type of tray or basket.

Multiplied by the number of eggs in them, x or y, the number of eggs processed in a single action is found. Dividing this by the time a single action at least takes, $t_{cycle,min}$, then gives the maximum capacity C_{max} of the machine, in eggs per second:

$$C_{max} = n_{max} \cdot x/t_{cycle,min} \text{ or } C_{max} = m_{max} \cdot y/t_{cycle,min} \tag{2.1}$$

The parameters were gathered for the devices in the transfer line and presented in Table 2.3, together with the resulting capacity.

Table 2.3: Capacities of the devices in the transfer process of HT88 trays and baskets. NB: the t_{min} of the (de)stackers includes the time required to change a trolley.

	Stacker (Trays)	**Stacker (Baskets)**	**Destacker (Trays)**	**Destacker (Baskets)**	**LED**	**Vinovo**	**ST**	**Tray tipper**
n_{max} / m_{max}	5	5	5	5	2	2	2	4
t_{min} [s]	17.5	17.5	17.5	17.5	8	8	8	8
C_{max} [eggs/s]	25.1	25.1	25.1	25.1	22	22	22	44

The table shows that the ST currently limits the transfer process in capacity to a maximum capacity of 22 [$eggs/s$], together with the LED and Vinovo machine.

It should be noted that in the past, Viscon has, in special cases, increased n_{max} to 4 on the ST to achieve double the capacity. This four-tray ST configuration was combined with multiple (de)stackers, 2 LEDs, and 2 Vinovos. This setup effectively means there are multiple transfer lines in the hatchery, except the ST is shared between two transfer lines. The default device, however, only allows for two HT88 trays to be handled concurrently due to the available space and motor power.

The ST should not bottleneck the transfer process and should therefore have a capacity of at least 22 [$eggs/s$], as this is the lowest capacity of any other device in the transfer line. For the redesign, however, Viscon wishes the device to become at least as fast as the (de)stacker devices for future-proofing, requiring an increase of capacity of 15 %.

2.2 Analysis of the current ST

In this section, the ST in particular will be analyzed to find the problems of the machine. First, the components of the ST will be shown in Section 2.2.1. The working principles and the problems encountered will then be analyzed in Section 2.2.2.

Some pictures of an ST are shown in Figure 2.3.

(a) Overview of the ST

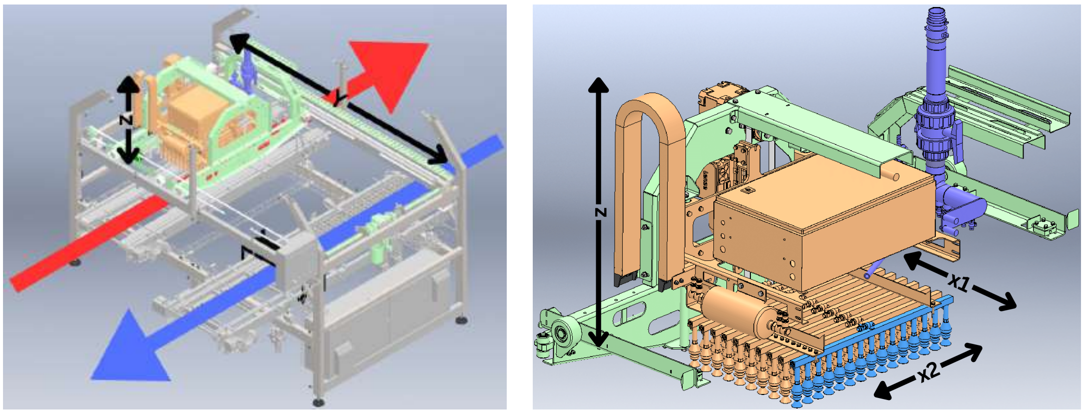
(b) Side view of the ST

Figure 2.3: Pictures of the ST

On the left, an overview of the ST can be seen. On the right, a side view of the ST is given, in which the suction cups used for transferring the eggs are visible.

2.2.1 The components

The ST has several components to achieve its selective egg transfer functionality, shown in the 3D models of the ST in Figure 2.4a. In Figure 2.4b, the green and orange assemblies are shown in more detail.



(a) Model of the full ST (b) Model of the driving assembly of the ST

Figure 2.4: 3D models of the ST

A list of the colored components is given hereafter:

- **Blue arrow:** The input lane, *on which setter trays with eggs arrive. The setter trays with the eggs remaining after the transfer leave the ST on this lane.*
- **Red arrow:** The output lane, *on which empty hatching baskets arrive. These hatching baskets are filled with viable eggs with living embryos, after which they leave the ST on this output lane.*
- **Orange assembly:** The lift assembly, *containing a set of manifolds with suction cups in the same pattern as the pattern of the setter trays. These suction cups are used to grab the eggs in the setter tray. Multiple transfer heads can be installed to process n trays simultaneously. The lift assembly can move along the z axis within the (green) driving assembly using a belt and motor system. It is moved along sliding rods.*
- **Purple assembly:** the vacuum distributor, *mounted on the lift assembly. This component is connected to a vacuum pump and the individual manifolds with suction cups, creating a vacuum in all of them.*
- **Blue assembly:** a manifold with suction cups, *mounted on the lift assembly. Every individual suction cup is connected to a valve box, which can enable a flow of pressurized air to any suction cup, called a blow-off. This flow cancels out the vacuum in the single suction cup and thus enables the machine to leave certain eggs in the setter trays. The flow comes from the customers' pressurized air system, and is buffered in a small buffer tank which is also mounted on the orange assembly as well.*

  Sometimes, adjustments in the spacing along either the x_1 or x_2 axes are required during the transfer process, if, e.g., one tray is to be transferred to two baskets. This is done by mounting certain blue assemblies on sliding rods with an electric cylinder for actuation.

- **Green assembly:** The driving assembly, *which moves the lift assembly along the y axis from the input to the output lane, and vice versa, using a belt and motor system. The green assembly has wheels that can drive on the gray frame.*
- Sometimes, a hopper is placed between the input and output lane, where the eggs without an embryo can be released. This hopper is not shown in the 3D models.

In total, the ST costs around €62k. This includes the components, assembly, programming, and testing in the workshop at Viscon. Economically, it is beneficial to decrease these costs, as Viscon can make a larger profit margin. If possible, this should thus be addressed in the redesign.

2.2.2 The working principle and encountered problems

Since the components of the system are now defined, the working principle of the ST can be analyzed. First, a single cycle of the ST during regular operation will be analyzed. After that, the cleaning methods for the ST will be shown.

Process steps of a normal operation cycle

Independent of the configuration of the ST, the operation of the ST is always the same. In Figure 2.5, a schematic of a single cycle of the ST during normal operation is shown. A cycle takes around 8 to 10 [s] during normal operation, depending on the required capacity. A total capacity of up to 80k [$eggs/hour$] can be achieved if two trays are processed simultaneously at the maximum speed.

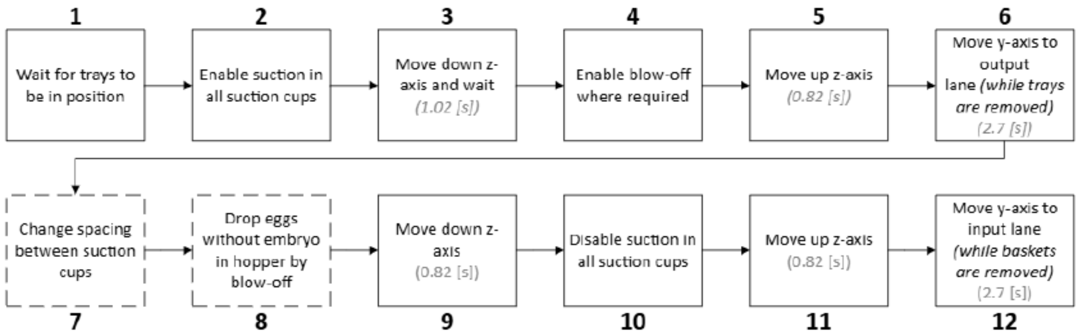


Figure 2.5: A schematic of a single cycle of the ST during normal operation. The required time for every step is also shown in grey.

The whole process cycle consists of 12 steps, as shown in the schematic. The required time for every step is also shown, and was measured on a built-up ST in the Viscon workshop, which has a total cycle time of 9.38 [s].

The details of the process steps and the problems encountered will be elaborated below.

1. First, the ST receives information about a tray and the eggs in it, and waits for the trays to arrive over the input lane. If the trays have arrived, a plate slides out to lock the tray from moving in the Z-direction due to stuck eggs being pulled out.
2. The ST then enables suction in all suction cups by switching on the vacuum pump.
3. The orange assembly is then moved down along the z-axis, as shown in Figure 2.6a.

   The suction cups are then pressed onto the eggs until the z-axis is in its lowest position, as shown in Figure 2.6b. When the cups touch the eggs, a vacuum is created by the suction, fixing the egg to the suction cup. The eggs vary largely in diameter (D = 40 - 48 [mm]), height (H = 50 - 68 [mm]), and mass (M = 25 - 75 [g]). Currently, all these egg sizes are supported by the suction cups, which should also be the case for the redesign. The variation in egg height is accounted for by the flexibility of the suction cups, which are compressed when pressed onto the eggs. For some batches of eggs, the hatchery knows the range of egg sizes beforehand, allowing for a software setting limiting the z-movement to decrease the exerted forces on the largest eggs.
   It is noticed from actual footage of the ST, that the suction cups get fully compressed when an egg is attached. As around 5 [N] is required to fully compress these suction cups, it can be concluded that at least 5 [N] of lifting force is applied by the vacuum system.

   → **Problem 1**
   This step is where problem 1 occurs. As all suction cups are pressed onto the eggs, the machine also touches the 'bangers'. These eggs can explode upon touch because of the accumulation of bacterial gases, as mentioned in Section 1.1. The amount of banger eggs depends on many factors, such as flock age and breed, but it is estimated by experts that upwards of 5 % of eggs can be bangers. The expelled egg contents are spread to other eggs and can be sucked up by the vacuum system, causing clogs, microbial contamination of eggs with living

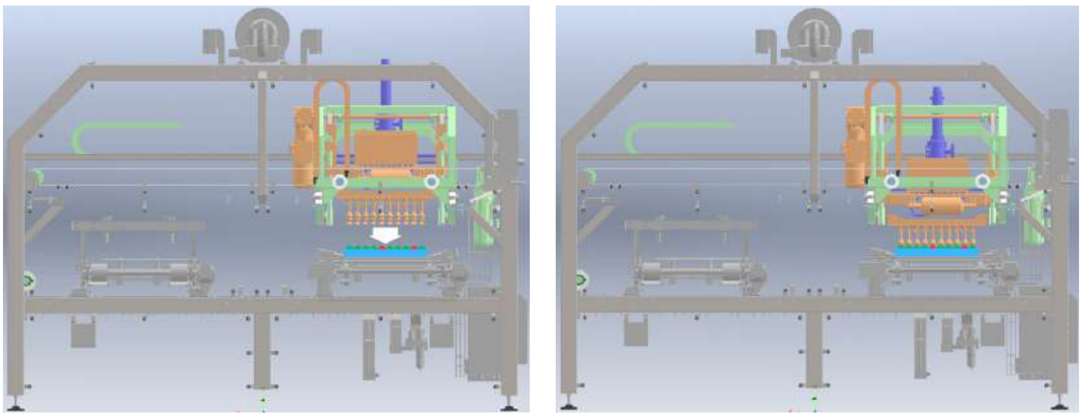
embryos, and a terrible smell for staff. The clogs occur in the suction cups themselves and in the hollow pillars on which they are suspended, as these only have a diameter of 1.75 [mm]. Clogs in the suction cups and egg contents on eggs can lead to bad seals with the vacuum cups, resulting in eggs being left in the trays when they should have been transferred. Other eggs can also get (micro)cracks because of the contact, which is bad for hatchability and can also cause sealing problems.

→ **Problem 2**
A second problem is also encountered here. Eggs can be dirty from feathers and egg contents before they arrive at the transfer line, which can cause a bad seal of the vacuum cups on the eggs, resulting in eggs being left in the trays when they should have been transferred. It is estimated that about 0.5 % of the eggs are dirty, but this depends on many factors.

4. While moving down, the blow-off is enabled in the individual suction cups corresponding to the eggs that should not be picked up.

→ **Problem 3**
This, however, is where problem 2 occurs. Between 5% and 95% of eggs usually have to be transferred. Especially with eggs of older flocks, up to 95% of eggs should be left in the trays, requiring a blow-off for 95 % of the suction cups. This requires a high average airflow, resulting in a deficit. Viscon gives customers a debit requirement, but available pressurized air systems in hatcheries limit this. This problem results in the vacuum not being canceled out by the blow-off system, which in turn causes undesired eggs to be transferred when they should have been left in the trays. The lack of blow-off above bangers also allows for more easy clogging and microbial contamination of the system, as the egg contents are sucked up.

→ **Increase of problem 1**
The first problem is also made worse because of the blow-off system. The suction cups in which blow-off is enabled are also pressed onto an egg, applying 6 bars of pressure on the eggshell, theoretically equaling over 30 [N] of force.

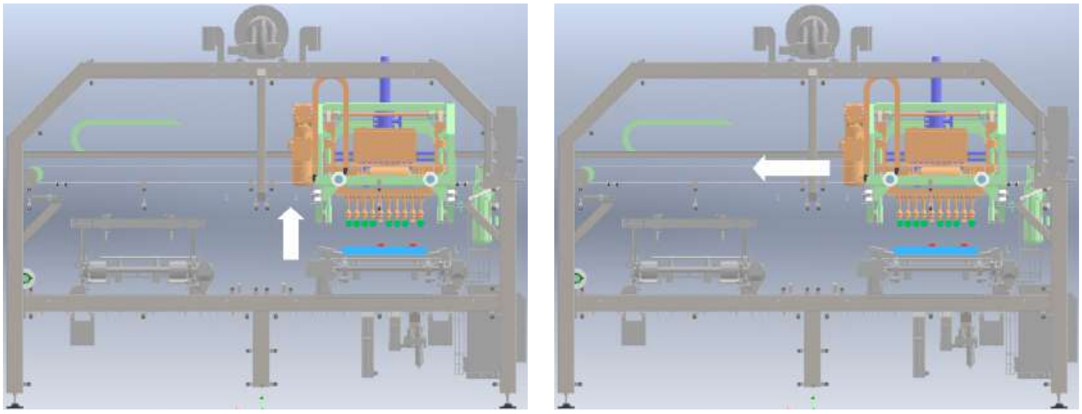


(a) The orange assembly moves down above the trays on the input lane.

(b) All suction cups are lowered to the eggs.

Figure 2.6: Steps 1 through 4 of a cycle of the ST. The blue block indicates the tray with all types of eggs, green and red, desired and undesired.

5. The orange assembly is then moved up again along the z-axis, until its highest position, as shown in Figure 2.7a.
6. After that, the green assembly is moved along the y-axis, towards the output lane, as shown in Figure 2.7b. The trays with the remaining eggs are simultaneously removed from the input lane and sent towards the tray reject system.
Usually, a pitch of 1.5 [m] is used between the input and output lane, as some machines in the transfer line require this space. However, this pitch should be variable, as some hatcheries' layouts require a different pitch distance.

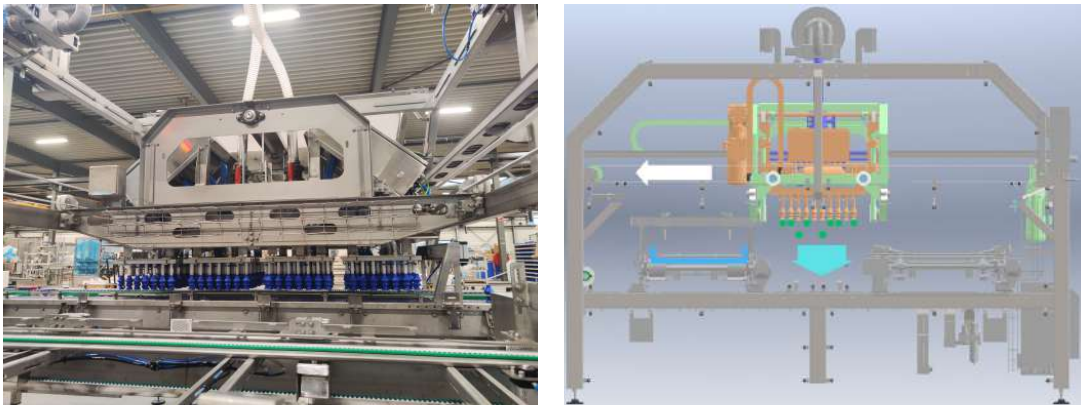


(a) The orange assembly moves up.

(b) The green assembly is then moved towards the output lane.

Figure 2.7: Steps 5 and 6 of a cycle of the ST. The green eggs indicate the desired eggs that should be lifted, and the red eggs indicates the eggs that should be left in the tray.

7. During the movement towards the output lane, the spacing between sets of suction cups can be changed along either the x_1 or x_2 axis. This is only required, e.g., if multiple trays are to be transferred into multiple baskets that differ in size compared to the trays. In Figure 2.8a, it can be seen that there is a space between the sets of suction cups, which is adjusted if required by the configuration. The spacing is achieved by sliding the sets of suction cups over sliding rods using a pneumatic actuator.
8. While driving towards the output lane, the eggs without an embryo are dropped.

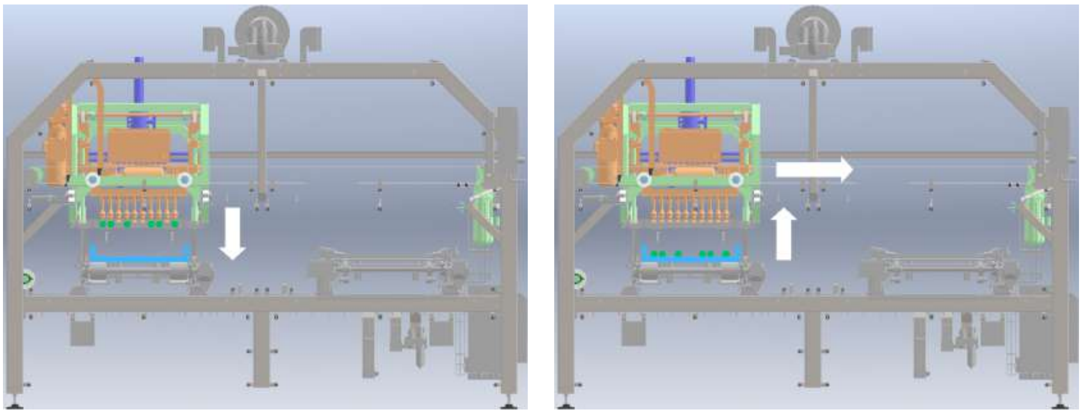


(a) The space that can be seen between the sets of suction cups can be adjusted, if required by the configuration.

(b) While moving towards the output lane, the eggs without an embryo are dropped.

Figure 2.8: Step 7 and 8 of a cycle of the ST. The turquoise arrow indicates the dropped eggs without an embryo

9. The green assembly then arrives at the output lane, above the baskets. The orange assembly is moved down along the z-axis, as shown in Figure 2.9a.
10. After that, the ST turns off the vacuum in all suction cups by switching off the vacuum pump. This makes sure all eggs are left in the baskets.
11. The orange assembly is then moved up again along the z-axis, until its highest position.
12. The green assembly then moves back to the input lane. The baskets with eggs that have a living embryo are simultaneously removed from the output lane. These final three steps are shown in Figure 2.9b.



(a) The orange assembly is moved down above the basket on the output lane, after which the vacuum is disabled.

(b) The orange assembly is moved up after the eggs are dropped, and the green assembly is moved back to the input lane.

Figure 2.9: Steps 9 through 12 of a cycle of the ST.

Cleaning of the suction system

After each day shift, having processed multiple batches of eggs, the entire hatchery is cleaned using high-pressure water and detergents. In addition to this, the suction system of the ST has to be cleaned as it can get dirty on the inside, at places that are hard to access using the aforementioned cleaning methods.

This cleaning is done in two steps. First, a hose can be connected to the vacuum distributor, allowing the system to be flushed by cleaning detergents and water. Secondly, an automated cleaning method was designed by Viscon to clean the insides of the suction cups, shown in Figure 2.10. This so-called bubble bath is required as the suction cups and the system behind it are inaccessible for the cleaners.

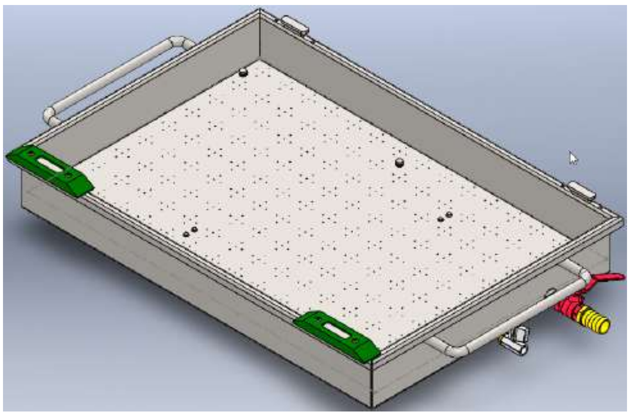


Figure 2.10: 3D model of the bubble bath, used for cleaning the vacuum cups

The bubble bath is connected to both pressurized air and water. This creates bubbles, which are intended to loosen the soil on the suction cups when placed into the bubble bath.

→ **Problem 4**

However, the current automated bubble bath cleaning method proves to be unreliable in practice, which is problem 3. Bacterial testing systematically shows this system is the most unhygienic in the process. The suction cups are often still dirty after the cleaning process, and they are often pointed out as one of the dirtiest parts in the egg transfer process. It is hard to inspect and access them, so they cannot be manually cleaned afterwards.

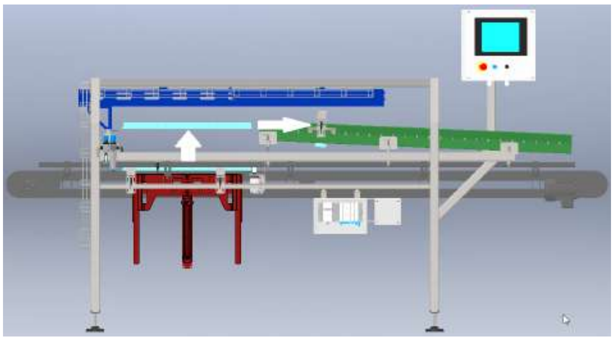
The manifolds to which the suction cups are attached are not cleaned by this method either, even though they also have a high chance of contamination.

Some of the unreliability could be caused by the operator of the bubble bath, e.g., if the wrong water or air pressure is applied.

Tray reject system

As mentioned in step 6 in Section 2.2.2, the trays from the input line continue to the tray reject system. This system is installed in the transfer line because of the unreliability of the ST, as up to 1 % of the trays contain eggs that should have been transferred, per estimation of the engineers in charge of the ST. Leaving the viable eggs in the trays is too costly, but the reject system is also expensive. The tray reject system is shown in Figure 2.11.

(a) Picture of the tray reject system



(b) Sideview of the tray reject system

Figure 2.11: The tray reject system used after the ST

The device scans the trays and checks whether eggs are still in the positions of viable eggs. If this is the case, the red mechanism in Figure 2.11b pushes up the tray, after which it is pushed onto the green buffer lane by the dark blue assembly. An operator then manually corrects the error.

Building this system costs around €5.7k, of which the scanner costs €3.5k. Due to the many rejected trays, the operator needs up to 0.5 FTE to manually correct the errors. The system also occupies around 3 m^2 space in the transfer room.

→ **Problem 5**

The large unreliability creates the fifth problem; the requirement of this tray reject system. It is undesired as it costs a lot to operate and build, and takes up space in the transfer line.

2.2.3 Problem overview and preliminary solutions

Especially the reliability of the machine is compromised by the problems described in the previous section. Some preliminary solutions were identified and listed in Table 2.4. The problems that the solution can affect and possibly solve are also listed.

Table 2.4: Preliminary solutions to the identified problems. Problems that are affected but not completely solved are shown in brackets.

Solution		Solved problems
1	Prevent using vacuum cup system	1, 2, 3, (4), (5)
2	Increase low egg strength	1, 4, 5
3	Prevent touching banger eggs	1a - e, (4), (5)
4	Lower impact of touch	1, (4), (5)
5	Prevent clogging and contamination of suction cups and vacuum system by dirt / egg contents	1b, 1d, (4), (5)
6	Prevent touching desired eggs	1f, 2, (4), (5)
7	Clean eggs before transfer	2, (4), (5)
8	Prevent blow-off requirement	3, (4), (5)
9	Increase efficiency of blow-off system	3, (4), (5)
10	Prevent use of customer air system / increase system efficiency	3, (4), (5)
11	Prevent bubblebath requirement	4, (5)
12	Improve bubblebath efficiency	4, (5)
13	Clean eggs after transfer	(1a), (1c), (3b)
14	Lower costs and space required of tray reject system	5
15	Prevent bad smell from spreading or accessing staff	1e

As can be seen from the table, some solutions are focussed on a single problem, while others possibly solve multiple problems. Solutions 1 and 2 have the potential to solve most of the problems, depending on the details of the solution, and should thus be considered in the redesign.

2.3 Conclusion

In the sections before, the ST was analyzed, the required capacity, the available design space, and the main issues were identified, which should be addressed in the redesign. This answers the first research question, "How does the current system work, what are the problems with the current system, and how do these affect the system's performance?".

From the analysis, several things can be concluded, listed below:

- The **size of the ST** is restricted to the minimum height of 2680 [mm] a hatchery has. Besides that, the footprint should be minimized where possible, without compromising the capacity. This allows for scaling up of the system, increasing the capacity of the full transfer process (Section 2.1.1). The machine is also part of a larger transfer line, and increasing the size of the machine could require changes to the system when implemented in an existing transfer line (Section 2.1.1).
- The device has to be designed with cleanability and hygiene in mind, as contamination can have negative consequences (Section 2.1.2)
- The ST should never **bottleneck** the transfer line. To achieve this, at least 22 [$eggs/s$] should be processed, which is currently reached. Viscon also wishes the system to be future-proofed by a margin of 15%, requiring 25 [$eggs/s$] to be processed. (Section 2.1.4).
- **Egg sizes** ranging from with D = 40 - 48 [mm], H = 50 - 68 [mm] and M = 25 - 75 [g] should be supported (Section 2.2.1). For some batches of eggs, the range of egg sizes is known by the hatchery. Different tray and basket types should also be supported by the ST (Section 2.1.3), without major modifications.
- Around **5 - 95% of eggs** should be transferred from a tray (Section 2.2.2).
- The current device, including the tray reject system, **costs** around €66k. If possible, this should be decreased for economical reasons (Section 2.2.1).

The current device achieves its selective transferring function by pressing a suction cup on an egg, and blowing it off it the egg should not be transferred. Moving the suction cups vertically is achieved through a belt and pulley system, just like the transfer motion.

Five main problems were identified with the system, which mainly affect the reliability of the device. The problems are listed below, and how they affect the ST is also mentioned; the red text means the problem decreases the performance, and the green text means the problem increases the performance.

1. All vacuum cups are pressed against an egg
   Affects reliability

   All vacuum cups are moved down when the rigid transfer head is moved down, to pick up desired eggs. The undesired eggs are in the same tray at the same level, which is why all eggs are touched simultaneously.

   (a) Bangers are also touched, always. It is estimated that upwards of 5 % of eggs can be bangers, depending on many factors. When a banger is touched, it often explodes. This causes the rotting contents to be spread, infecting the environment and other eggs. This poses a problem, especially in combination with the in-ovo vaccination system, which leaves a hole in the shell and breaks the natural protection of the embryo.
   (b) The rotting contents cause clogs in the vacuum system, which causes malfunctioning of the suction cups.
   (c) The rotting contents increase the possibility of infecting viable eggs and small chicks through contamination of the egg shells.
   (d) The rotten contents are spread to multiple eggs and can cause the vacuum cups to seal badly on the eggs, resulting in malfunctioning of the suction cups.
   (e) The rotting contents cause a terrible smell, which is unpleasant for staff.
   (f) Pressing the suction cup on eggs can cause (micro)cracks, which is bad for hatchability and the seal with the suction cup.
   (g) Blown-off suction cups are also pressed onto an egg, and the blow-off pressure can destroy eggs and spread their contents.

2. Eggs that arrive can be dirty
   Affects reliability

   Eggs can be dirty from feathers and egg contents before they arrive at the transfer line. It is estimated that about 0.5 % of the eggs are dirty, but this depends on many factors.

   (a) The dirty eggs can cause a bad seal of the vacuum cups on the eggs, resulting in eggs being left in the trays when they should have been transferred.
   (b) The rotting contents cause clogs in the vacuum system, which causes malfunctioning of the suction cups.
   (c) The rotting contents increase the possibility of infecting viable eggs and small chicks through contamination of the egg shells.

3. Vacuum blow-off deficit can cause wrong eggs to be picked up
   Affects reliability

   Especially with eggs of older flocks, many eggs have to remain in the setter trays. This requires a high average airflow for blowing off the vacuum in the vacuum cups. Viscon gives customers a debit requirement, but available pressurized air systems in hatcheries limit this.

   (a) The deficit can cause undesired eggs to be picked up. This increases the possibility of microbial infection of chicks after hatching, as they tend to peck anything.
   (b) The deficit can cause the rotten contents of bangers to be sucked up instead of being blown away by the blow-off (which should be activated when touching a banger). This causes malfunctioning of the suction cups and increases the possibility of infecting viable eggs and small chicks.

4. Cleaning of the system is unreliable
   Affects reliability, OPEX

   Because the vacuum cups suck up the dirt they get in contact with, they can get relatively dirty inside. The system is inaccessible for cleaners, and thus an automated cleaning method was designed. However, the current automated bubble bath cleaning method proves to be unreliable in practice. It also depends on critical external factors, e.g., water pressure and correct use by the operator. Accessibility to the suction cups is low, leaving no options for thorough cleaning. Currently, the suction cups and vacuum system of the ST are often pointed at as one of the dirtiest parts in the egg transfer process.

(a) The bad cleanability can lead to suction cup malfunctioning due to clogs and increases the possibility of infecting viable eggs and small chicks.

5. Requirement of the tray reject system
Affects reliability, OPEX, space efficiency

Malfunctioning of the suction cups is quite common, it poses serious reliability issues. This is often due to clogging, when dirt, dust or egg contents from bangers are sucked into the vacuum cups. To increase the reliability of the ST, an expensive tray reject system is installed after the ST. The scanner in the tray reject system detects whether all desired eggs are removed or not, together with a reject system requiring costly manual labor (up to 0.5 FTE). Currently, an average of 1 % of trays has to be rejected, which, even though it might not seem too much, is very costly due to the scale of the process.

(a) The requirement of the tray reject system leads to extra (operational) costs
(b) The requirement of the tray reject system leads to extra space used

3
Literature Research

In this chapter, literature and patent research will be done to prepare for the redesign process. The answer to the second research question will be answered therewith:

"What are the known properties of eggs that could limit the design, and how have others solved the problem of egg grabbing and selective egg transfer?"

Firstly, a brief literature research on the mechanical properties of eggs will be conducted in Section 3.1, to identify known parameters that could aid or limit the redesign.

Then, in Section 3.2, literature and patents will be consulted to identify useful mechanisms for grabbing and transferring eggs. In the previous chapter, some preliminary solutions were identified. The most promising solution involves a change in the gripping mechanism, which is complex and can be achieved in many ways. The options may be narrowed down by conducting a thorough literature and patent research on gripping mechanisms.

3.1 Physical and mechanical properties of eggs

Eggs are known to be fragile and delicate objects; therefore egg handling should be done with care. In this section, literature is consulted to find important physical and mechanical properties of eggs, which should be dealt with when handling eggs. Studies regarding the following properties were consulted in more detail in the following sections:

- **Rupture force**, which is the compressive force an egg can withstand before cracking. This can be important when designing grippers or suction cups for gripping eggs, as the applied forces should not result in the cracking of the eggs. This measure is often used instead of shell strength, as it is easier to measure.
- **Rupture energy**, which is the area under the force-deformation curve. This measure shows the energy an egg can absorb before cracking, which can be used as the maximum allowable impact energy by, e.g., a drop or a grabbing device.
- **Embryonal acceleration force**, which is the acceleration force an embryo can withstand before being damaged. This parameter will be important when designing the transfer movement, as this movement should not have an effect on the hatchability of the egg.
- **Static friction coefficient**, defined as the ratio between a normal force on an object and the resulting friction force. This coefficient could also be useful when gripping eggs using friction.

3.1.1 Rupture force

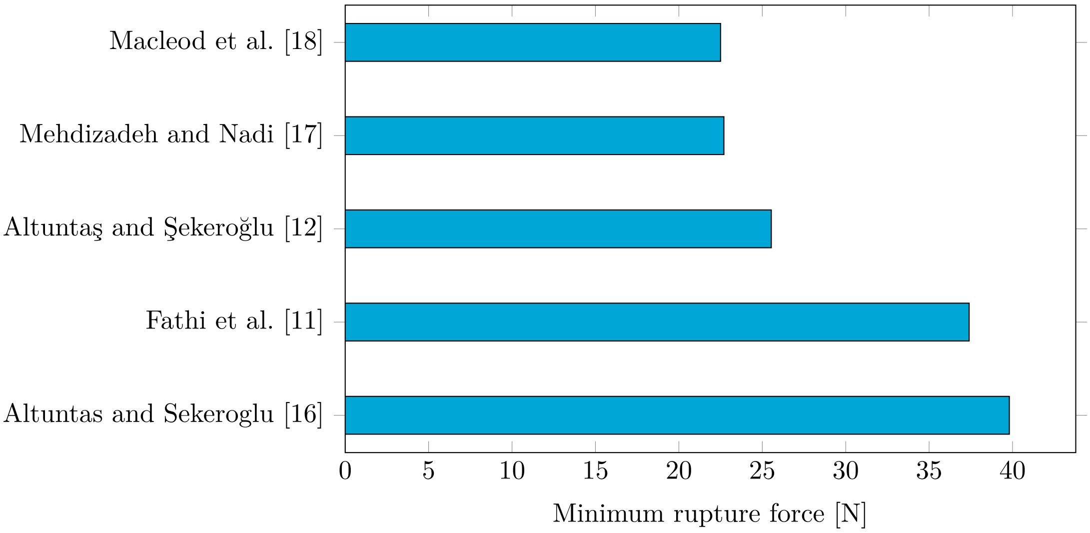
The rupture force of an egg is defined as the compressive force needed to introduce cracks in an egg, by means of a point load. This egg property is often studied, as it is easier to measure than the stress in the egg's shell. The rupture force correlates with several (physical) properties of eggs, listed in Table 3.1.

Table 3.1: Correlation of rupture force with other properties of eggs. *The Shape Index is defined as the ratio between the height and the width of an egg

Property	Correlation	Source
Eggshell thickness	+	[11]
Egg Shape Index*	+	[12]
Eggshell percentage	+	[12]
Egg size	-	[13]
Storage time	-	[14]
Chicken breed	None	[15]

From the table, it can be seen that increases in eggshell thickness, Shape Index (SI), and shell percentage also increase the rupture force of the eggs. The numerical values for rupture force can also be found in the literature, of which some values are shown in Figure 3.1.

Figure 3.1: Minimum rupture force of eggs by a point load



The range of rupture force values differs significantly across studies, with the minimum value being 22.7 $[N]$. Using a distributed load made of rubber, as researched by Hahn et al. [19], increases the rupture force of chicken eggs to around 750 $[N]$. Using this measurement method, they could also determine a maximum allowable stress of 21.9 to 30.9 $[MPa]$, depending on egg size and chicken breed. Similar values of 17.4 to 22.4 $[MPa]$ were found by Liu et al. [20]. They also loaded the egg in reverse, from the inside, resulting in a 20 times lower rupture force, showing that the dome shape of the egg contributes a lot to its strength.

However, it should be noted that even though the eggs do not break below a certain rupture force, haircracks in the eggshell can occur and negatively affect the hatchability of an egg at contact forces as low as 5 $[N]$ [3].

3.1.2 Rupture energy

The rupture energy is the amount of energy an egg can absorb before cracking occurs. This measure mainly depends on the compression speed, SI value, and compression axis of the egg [16, 12]. Results for rupture energy in compression tests are shown in 3.2.

Table 3.2: Rupture energy of eggs measured at different compression axes and different compression speeds

Compression axis	**Speed** $[mm/s]$	**Minimum value** $[mJ]$	**Maximum value** $[mJ]$
Major	0.33	1.90 [12] - 4.04 [16]	3.64 [12] - 5.10 [16]
Major	0.99	3.14 [12] - 5.32 [16]	4.77 [12] - 6.35 [16]
Minor	0.33	3.15 [12] - 4.47 [16]	3.76 [12] - 4.90 [16]
Minor	0.99	3.66 [12] - 6.29 [16]	3.88 [12] - 6.68 [16]

It can be seen that a high compression speed yields a higher rupture energy, and the minor axis has the highest rupture energy. When grabbing an egg, the impact energy should be kept below the minimum values.

These values also imply that the eggs should not be dropped intentionally. Assuming the highest measured rupture energy, an egg weight of 75 $[g]$, and rupture energy equal to potential energy upon release, results in an allowable egg drop height of around 9 $[mm]$ without rupture. This is confirmed by Cohen [21], who showed that over 50% of twenty dropped eggs ruptured from only 8 $[mm]$ of height on a surface with a stiffness much greater than that of an egg, while over 75% of twenty eggs ruptured when dropped from a 10 $[mm]$ height. The slight nuance of an egg rupturing at a 9 $[mm]$ drop could be attributed to the compression speed upon landing being orders of magnitude larger.

3.1.3 Embryonal acceleration force

Acceleration forces on embryos can have an effect on the hatchability of fertile eggs, by causing broken yolk sacs and ruptured blood vessels [22]. The quantitative effects of acceleration have not been studied extensively yet, but Olsen and Byerly [23] found in their 1938 study that persistent accelerations of 1.8G cause a 25% lower hatchability.

However, egg quality and methods might have changed much since then. Besch et al. [22] found in a more recent study that a 2G threshold should be maintained to prevent damage to fertilized eggs. This study was, however, done on eggs before incubation, and the effects of accelerations are known to change during the incubation period, increasing in severity until around day 7, after which they decrease [23].

In the past, Viscon has developed machines together with HatchTech [5], who claim to have done internal research on this subject for fertilized eggs at day 9 of the incubation, showing that accelerations of at least 1G do not affect hatchability. Even though this internal research cannot be accessed, its results were successfully implemented in previous Viscon machines handling 9-day-old eggs. They can be used as a safe benchmark for this redesign, especially considering the decreased effect of accelerational forces after day 7 of the incubation.

3.1.4 Static friction coefficient

The friction coefficient of eggs was also found to be dependent on several factors, including egg size and SI value. An overview of the static friction coefficients from literature is shown in Table 3.3.

Table 3.3: Static friction coefficients of several materials on eggs

Material	**Minimum value**	**Maximum value**
Galvanized metal	0.01 [16] - 0.059 [12]	0.09 [16] - 0.160 [12]
Plywood	0.024 [16] - 0.058 [12]	0.145 [16] - 0.291 [12]
Rubber	0.048 [16] - 0.100 [12]	0.152 [16] - 0.280 [12]
Chipboard	0.027 [16] - 0.060 [12]	0.127 [16] - 0.160 [12]
Glass	0.015 [16] - 0.033 [12]	0.069 [16] - 0.148 [12]

From the table, it can be seen that the static friction coefficients vary widely. Galvanized metal has the lowest friction coefficient, ranging from 0.01 to 0.160. Either rubber or plywood can be used to achieve the highest coefficient of friction.

3.2 Suitable grippers and gripper classes

Much scientific attention is allocated towards robotic end effectors for handling and manipulation of objects. Egg handling, as done by the ST, also involves object handling using some sort of end effector. Because the grabbing mechanism is a crucial part of the ST, it should be researched and considered in much detail.

The following sections will be dedicated to identifying useful grippers and gripper classes (Section 3.2.2) for egg handling and gripper designs that satisfy all criteria required for egg handling, from scientific literature. Patents on grippers for egg handling are presented in Section 3.2.3.

3.2.1 Gripper classification

Grippers are often subdivided into classes. Several classifications have been proposed in literature, and they are often based on the working principle of a gripper. The gripper classification systems by Monkman et al. [24] and Shintake et al. [25] are combined to include most grippers found in the literature, resulting in the gripper classification listed below. Gripper classes that imply ingression of the object or some form of glue or freezing adhesion were excluded from the search, as these cannot be used on eggs. These classes are also not mentioned in this classification.

- **Impactive** grippers control objects based on the physical effects of classical (Newtonian) mechanics, such as friction or reaction forces due to envelopment. This class includes the classical grippers with fingers, but can also consist of a web, sphere, or cylinder. In this class, a few subclasses are found in the reviewed papers:
  - **Soft Pneumatic Actuator** (SPA), soft grippers that are actuated pneumatically, e.g., by inflating the fingers of the gripper.
  - **Passive Structure with External Motor** (PSEM), soft or rigid grippers that are actuated externally. These are either tendon-driven or contact-driven, the latter being driven by physical contact with the fingers of the gripper, while the former has some sort of tendon going through the fingers.
  - **Dielectric Elastomer Actuator grippers** (DEA) have fingers that change in shape when an electric field is applied to them.
  - **Shape Memory Alloy grippers** (SMA) use thermally driven shape shifting to drive the fingers of the gripper.
- **Controlled stiffness** grippers are soft grippers that can be stiffened up using external stimuli to achieve higher gripping strengths or lower energy usage. They often approach objects in the soft state after which they are stiffened, applying interlocking and friction to lift the objects. In this class, a few subclasses are found in the reviewed papers:
  - **Jamming grippers**, based on the effect of change of packing observed in granular and layered materials when a change in pressure is applied. This effect can be used to stiffen a gripper by applying a pressure change.
  - **Electro- and Magnetorheological grippers** use either electric fields or magnetic fields to stiffen a special ER/MR-sensitive fluid.
  - **Shape Memory Polymer grippers** use external stimuli, such as temperature variations or electric impulses to change the elastic modulus of the gripper. This enables them to temporarily conform to an object but recover their original shape when stimulated.
- **Astrictive** grippers apply some form of attractive force to the object's surface to achieve retention. In this class, a few subclasses are found in the reviewed papers:
  - **Vacuum grippers** use some method to develop a vacuum with which the object can be lifted. This includes vacuum cups, but other methods are employed as well
  - **Electro-Adhesion grippers** (EA) are highly controllable adhesive grippers. A high electric potential is applied to an electrode, which polarizes dielectric materials in its electric field. These polarized materials, in turn, are attracted to the electric field, creating the required adhesive forces.
  - **Gecko-adhesion grippers** exploit van der Waals forces using microfibers on the contact surfaces, just like geckos do. The adhesive is sensitive to the direction of the applied load; a small normal force will disengage the adhesive, but it can handle large shear forces when pressed on a surface.

– **Bernoulli grippers** are based on the Bernoulli principle. The gripper does not physically contact the object, but a high-pressure stream of air is blown on the object when the gripper is very close. The air leaving the nozzle changes from linear to radial flow, creating a region of very low pressure just above the object, which in turn lifts it.

3.2.2 Suitable grippers from literature

Thousands of gripper designs in multiple gripper classes are presented in the literature. As eggs are delicate objects, only grippers designed for such objects are of interest. Using review papers about grippers for delicate object handling [2, 26, 27, 28, 29, 30, 31, 32], specifications for grippers and gripper classes were analyzed and compared in a previous effort by Schokker [33]. All grippers and references in these papers were analyzed, and data about the object shapes, required workspace, (maximum) grabbing force, and (minimum) grabbing time were collected.

To find suitable grippers, criteria are set up to which the grippers should conform, as presented in Table 3.4.

Table 3.4: Criteria for selecting gripper and gripper classes from literature

Data	**Value**	**Source**
Object shape	Convex	Shape of an egg
Required workspace	$\leq$ 110% of object size	To account for the small available space in trays/baskets (Section 1.1.1)
Grabbing force	$1 \leq F_g[N]$	To enable egg lifting and a high travel acceleration of 3.33 m/s^2 (Section 2.2.1). It is assumed that no criteria for maximum grabbing force should be applied, as grippers can often be scaled down
Grabbing time	$t[s] \leq 10$	To reach high capacity (Section 2.1.4)

Table 3.5 shows the summarized specifications of the grippers found in scientific literature, grouped by their subclass.

Table 3.5: Gripper subclass support for convex shapes, grabbing time, grabbing force, required workspace, and possibly suitability for egg handling

Subclass (Class)	Entries	Convex shapes [%]	Grabbing time [s]	Grabbing force [N]	Required workspace [%]	Possibly suitable
SPA (I)	43	51	0.05 - 30.0 (Mean: 6.18)	0.05 - 200.0 (Mean: 19.26)	100.0 - 500.0 (Mean: 151.0)	Yes
PSEM contact-driven (I)	33	63	0.5 - 30.0 (Mean: 5.42)	0.25 - 86.3 (Mean: 16.54)	105.0 - 275.0 (Mean: 152.0)	Yes
Vacuum (A)	15	63	1.0 - 18.0 (Mean: 6.54)	0.3 - 330.0 (Mean: 29.68)	100.0 - 150.0 (Mean: 107.0)	Yes
PSEM tendon-driven (I)	12	67	1.0 - 30.0 (Mean: 7.44)	0.68 - 200.0 (Mean: 25.87)	119.0 - 222.0 (Mean: 143.0)	No
Jamming (CS)	7	54	1.0 - 5.0 (Mean: 2.31)	1.5 - 110.0 (Mean: 65.6)	130.0 - 200.0 (Mean: 160.0)	No
Electro-Adhesion (A)	6	33	0.2 - 65.0 (Mean: 45.03)	0.0 - 164.6 (Mean: 30.23)	100.0 - 108.0 (Mean: 101.0)	Yes
Bernoulli (A)	4	43	5.0 - 5.0 (Mean: 5.0)	0.05 - 0.69 (Mean: 0.37)	100.0 - 182.0 (Mean: 152.0)	No
SMP (CS)	4	60	3.0 - 180.0 (Mean: 68.75)	0.17 - 14.7 (Mean: 3.84)	125.0 - 150.0 (Mean: 133.0)	No
Other (CS)	3	50	4.0 - 10.0 (Mean: 6.33)	4.3 - 43.0 (Mean: 21.9)	148.0 - 178.0 (Mean: 161.0)	No
SMA (I)	3	75	15.0 - 30.0 (Mean: 25.0)	0.15 - 10.8 (Mean: 4.15)	109.0 - 183.0 (Mean: 144.0)	No
Gecko-adhesion (A)	2	100	0.4 - 3.0 (Mean: 1.7)	0.35 - 50.0 (Mean: 25.18)	100.0 - 120.0 (Mean: 110.0)	Yes
Magneto-Rheological (CS)	2	100	5.0 - 5.0 (Mean: 5.0)	1.47 - 100.5 (Mean: 50.98)	214.0 - 300.0 (Mean: 257.0)	No
Other (I)	2	50	3.0 - 32.0 (Mean: 17.5)	0.39 - 4.8 (Mean: 2.6)	113.0 - 133.0 (Mean: 123.0)	No
DEA (I)	1	0	0.5 - 0.5 (Mean: 0.5)	0.02 - 0.02 (Mean: 0.02)	100.0 - 100.0 (Mean: 100.0)	No

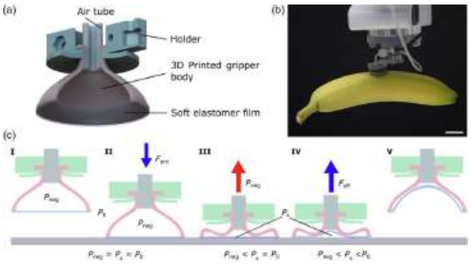
The table shows that the subclasses SPA, contact-driven PSEM, Vacuum, Electro-Adhesion, and Gecko-adhesion have the potential for egg handling in this specific situation, as their properties conform to the set criteria. Eleven grippers in particular were found to tick all boxes, of which the most interesting working principles are introduced and further investigated in the following list, to check for their suitability.

1. **Suction cup effect gripper** by Koivikko et al. [34], can lift up to 7.4 [N] with a 6 [s] cycle time and 100 % workspace requirement. The novel design and the working principle are shown in Figure 3.2a. It consists of a suction cup with a film over it, creating an internal suction chamber. The suction cup is put on the object, after which around 10 [mL] of air is evacuated from the internal chamber, creating a vacuum of around -55 [KPa]. When the gripper is moved, the suction cup effect enables the object to stay on the gripper. As the vacuum cup is closed off, it could prevent clogs from happening at all. The cycle time should be improvable; the paper did not focus on that.

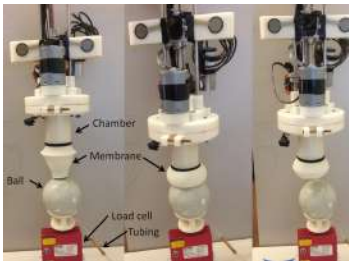
   The same suction principle is applied by Krahn et al. [35], depicted in Figure 3.2b. It can lift up to 10.1 [N] with a 5 [s] cycle tim and 100 % workspace requirement. The design has a flexible pouch that is connected to a plunger, which has a switch on the end. When the switch contacts an object, the plunger retracts while the gripper is moved down at the same time. This first molds the pouch around the object and creates a vacuum if the plunger is moved further up, and the object is again lifted using the same suction cup effect.

   Tahir et al. [36] also created a similar gripper, combining the suction cup effect with friction based pinch gripping. Their modular cubed gripper, called PASCAV, is shown in Figure 3.2c.

The design would need to be scaled down to apply it on eggs.



(a) Vacuum cup with film and the working principle [34]



(b) Vacuum gripper with plunger, showing three steps [35]

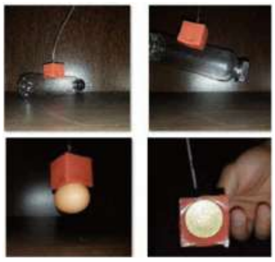
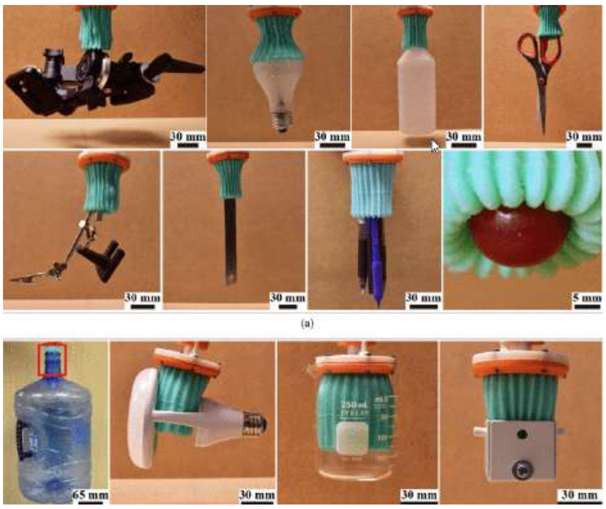

(c) PASCAV gripper [36]

Figure 3.2: Different suction cup effect grippers

2. **SPA skirt gripper with gecko-padding** by Hao et al. [37]. This gripper has an origami structure which can be inflated and deflated. The gripper achieves holding forces through a combination of friction and the gecko-padding, which imitates the adhesive forces of gecko feet by van der Waals forces. The lighbulb shown in Figure 3.3a perfectly resembles the gripping situation of gripping an egg from the top. However, from the paper, it is unclear whether the lightbulb is lifted through friction of by the gecko-adhesion. The gecko-adhesion effect performs poorly in dirty environments, which would make it inapplicable for our situation.
3. **Di-Electric Actuator with Electro-Adhesion** by Shintake et al. [38]. This gripper consists of two Di-Electric Elastomers, which create a pinching motion by applying high voltages. At the same time, the electric field is used to create Electro-Adhesive forces on the object. However, the Electro-Adhesion effect performs poorly in dirty environments, which would make it inapplicable for our situation.



(a) SPA skirt gripper by Hao et al. [37]

(b) DEA gripper [38]

Figure 3.3: Different gripper designs

From all the compared grippers, not many seem applicable for egg handling in a tight, dirty environment. Vacuum grippers are currently applied in industry for this purpose, and the only left alternatives seem to be suction cup effect and contact-driven PSEM grippers.

Contact-driven PSEM in particular are very commonly found, such as the topology optimized grippers made by Liu et al. [39, 40, 41]. These grippers were optimized for specific gripping situations, by using FEM simulations. These Fin Ray based grippers are all required to envelop the egg, which might be complex for eggs located in trays.

3.2.3 Patents on grippers for eggs

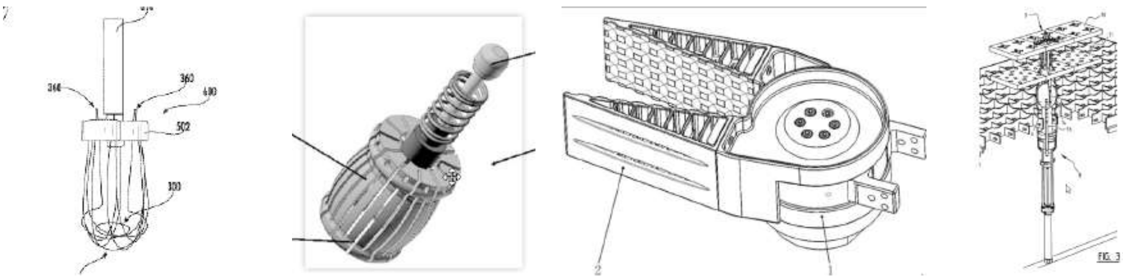
Many patents have also been filed for lifting eggs from trays and for lifting egg-shaped objects. Using patent classifications, many relevant patents were consulted on Espacenet [42]. The most interesting grippers from each gripper class found in the database are introduced in the following list:

1. **PSEM grippers**, such as patent US10946995B2 [43] shows a gripper made of metal wire loops, with a push-out unit. The gripper is used in almost the same application and promises low-contact egg handling. The estimated speed of this gripper.

   A similar approach, using flexible fingers and a push-out mechanism, is shown in Figure 3.4b [44]. The fingers are passive in this design, meaning the egg is gripped by pishing the gripper over it, just like in the previous patent. The device is used for injecting and vaccinating eggs, but can be adapted for the egg transfer application. The flexibility of the fingers allows for different sizes of eggs to be handled.

   The patent shown in Figure 3.4c [45] shows a Fin-Ray PSEM, which is commonly found in scientific literature as well. The design is made from rubber and is specifically made for fragile objects as it forms around them.

   Viscon has previously patented a gripper design for the ST as well, shown in Figure 3.4d. Their design featured a push-up mechanism, which pushed the egg up from the tray. The gripper was then closed using a moving plate. The gripper design, however, had many issues, such as broken or rotated eggs due to the stiff fingers.



(a) Flexible prongs gripper with push-out [43]

(b) Flexible finger gripper with push-out [44]

(c) Fin-Ray gripper patent [45]

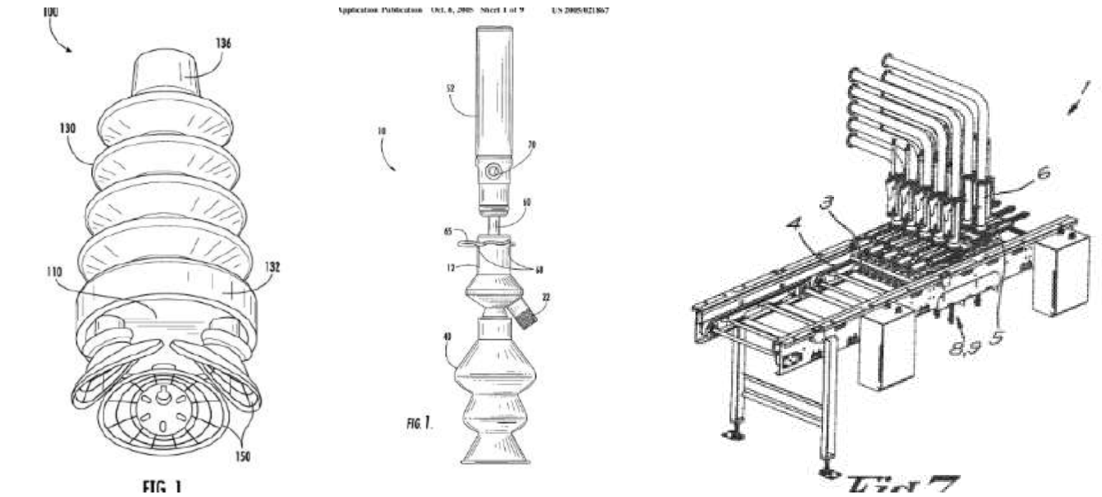
(d) Viscons gripper with push-up mechanism [46]

Figure 3.4: Different gripper designs

2. **Vacuum grippers** were also found in the patent database, such as the optimized suction cup shown in Figure 3.5a. It has three small suction cups on it, made to reduce the risk of infecting vaccinated eggs, as the vaccination hole is not touched. As these small suction cups act as independent suction cups, they also increase the chance of a successful sealing.

   Figure 3.5b shows a suction cup in which the suction is created by a Venturi nozzle. This design supposedly decreases the chances of contamination of the vacuum system, as any dirt is blown out of the Venturi nozzle. However, clogging of the nozzle might become an issue because of the small hole required for the Venturi effect.

   In Figure 3.5c, a design is shown which is intended for removing fragile banger eggs. The design consists of hollow tubes connected to a vacuum pump. Banger eggs in trays are released from below using compressed air, after which they are sucked into these tubes.



(a) Flexible prongs gripper with push-out [43]

(b) Venturi [47]

(c) remove bangers[48]

Figure 3.5: Different gripper designs

3.3 Conclusion

The literature research will be concluded by answering the second research question, "What are the known properties of eggs that could limit the design?", using the information from prior sections.

Several known properties of eggs were found that could have an effect on the design. Firstly, the rupture force of an egg, which is the point load needed to introduce cracking in an egg, is found to be above 22.7 $[N]$. When using a distributed rubber load, this can increase to around 750 $[N]$. However, haircracks in the eggshell can already occur at $5[N]$ of force, and can negatively affect the hatchability of an egg.

From the rupture energy of eggs, it can be concluded that eggs should never be dropped on purpose, e.g., in a basket. Compressing at higher speeds yields a higher rupture energy, and compressing the minor axis also yields a higher rupture energy.

Accelerational forces on eggs should be considered when designing machines that handle them, as they can decrease hatchability. Accelerations of up to 1G should not affect the hatchability and can thus be used as a safe limit.

The static friction coefficient depends on the contact material, and values between 0.01 on galvanized metal and 0.291 on plywood were mentioned in the literature. Plywood or rubber should be used as a contact material to achieve the highest friction coefficient.

Next, the prior art was investigated, resulting in numerous findings. Several grippers from patents and scientific literature were methodically compared and analyzed in the previous effort by Schokker [33], to narrow down the gripping methods to be considered for the redesign.

In specific, grippers in the subclasses SPA, vacuum, and PSEM can theoretically be applied for egg handling. Specific gripper concepts were also presented in the literature or in patents, which indeed all belonged to the aforementioned gripper subclasses.

4 Conceptual design

Now knowing the egg properties and viable grippers and gripper types from Chapter 3, the conceptual design phase can start. In this chapter, the first steps will be made towards a redesign, by answering the first part of the third research question:

"What solutions are possible, which is the most suitable, and what does the solution look like in detail?"

First, the design methodology for finding the possible and most suitable solutions will be explained in Section 4.1, after which requirements, constraints, and main and subfunctions are determined in Sections 4.2 and 4.3. Finally, in Section 4.4, concepts for all functions are made and arranged in a morphological chart, answering the first part of the fourth research question.

4.1 Design methodology

Designing is an incredibly complex process that is highly unpredictable and iterative. To grasp this unpredictable process, a design methodology can be applied. For the redesign of the ST, the design methodology prescribed by Roozenburg and Eekels [49] was used as a guide. Their model is based on the method developed by Pahl and Beitz [50], which is a proven design methodology. It comprises six main steps or phases delineating essential design tasks, as shown in Figure 4.1. Though in practice, these phases are not static, and continuous feedback within and between phases is required to ensure the design process is still correct.

Orientation and analysis The first phase encompasses orientation and analysis. Chapters 1 to 3 describe this in detail, and in Section 4.2 the information was translated into design requirements and constraints. The main and sub-functions should also be determined, which is described in Section 4.3. The results were used as input for the next phase.

Conceptual design The second phase explores the design space and experiments. In this phase, a morphological chart was created, with solutions for every sub-function. Results from scientific literature and patents found in Section 3.2 were used for this as well (Section 4.4).

Preliminary design In the third phase, preliminary designs were developed by combining several solutions into complete devices. In this thesis, as described in Chapter 5, concepts were developed for two sets of functions, as they can be seen as individual designs that hardly influence each other. The performance of the concepts on specific design objectives was then calculated or predicted, and a final concept was chosen for each set of functions, using the weighted criteria method. This method allows for comparing concepts on various criteria with different weights. During this preliminary design process, a continuous feedback loop was implemented. Concepts that initially scored the highest are thus also explored more in-depth.

Detailed design In the fourth phase, the final concepts were combined into a single complete concept, after which it was detailed and evaluated (Chapter 6).

Prototyping and iterating In the fifth and sixth phases, the design is translated into a prototype, tested, analyzed, and iterated upon. However, these phases are beyond this thesis, and only the first four phases will be described in this report.

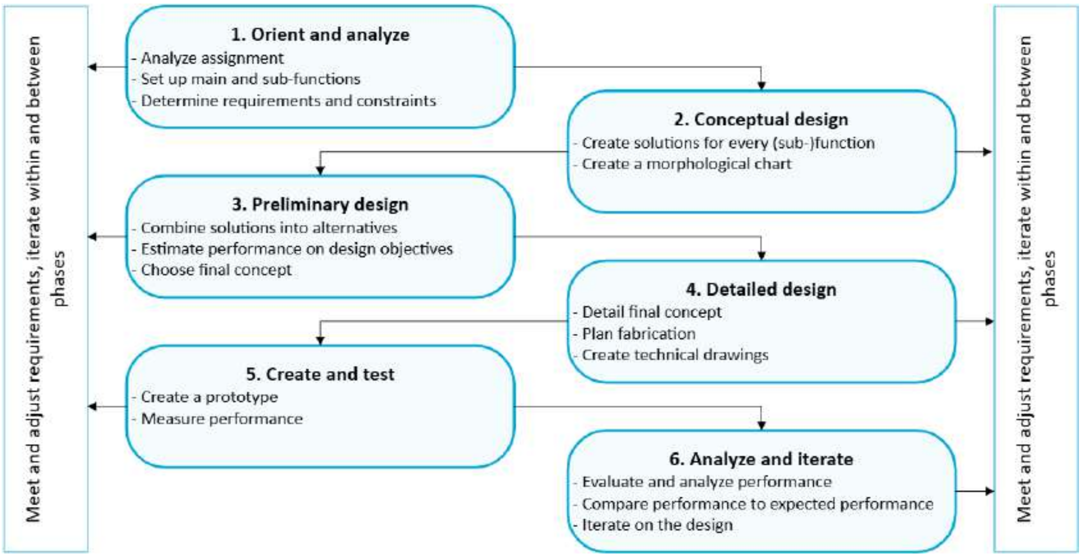


Figure 4.1: The design methodology, as prescribed by Roozenburg and Eekels [49]

4.2 Requirements and constraints

To start the design process, a general orientation and analysis of the assignment have to be done. Part of this is already described in Chapters 1 to 3. To effectively use this information in designing, the results are translated into a list of requirements and constraints, as shown in Table 4.1. The requirements are categorized and classified as either Must-Haves (MH) or Nice-to-Haves (NH). The source of either the requirement itself or the information in the requirement is also mentioned, for further reference.

Table 4.1: Requirements of the design. NB.: MH = Must-Have, NH = Nice-to-Have

Requirement		Category	Significance	Source
1	Only specified eggs should be transferred, which is between 5 - 95 % eggs in a tray	Reliability	MH	Section 1.1.1, Section 1.1.2, Section 2.2.2
2	Eggs should not be damaged (below 20 [N] compression and 1G acceleration) or contaminated by the transfer (no contact with bacteria)	Reliability	MH	Section 1.1.1, Section 1.1.2
3	It must conform to hygiene standards	Hygiene	MH	Sections 1.1.2 and 2.1.2
4	The most common egg sizes / weights must be supported, with D = 40 - 48 mm, H = 50 - 68 mm and M = 25 - 75 g	Functional	MH	Section 2.2.2
5	It must be possible to deliver both living and dead eggs separately	Functional	MH	Section 1.1.1, Section 2.2.2
6	The most common tray/basket types must be supported without major modifications	Functional	MH	Section 2.1.3
7	The capacity must be higher than the current bottleneck of 22 [$eggs/s$] in the full transfer process, when the input and output belts are 1500 [mm] apart	Performance	MH	Sections 1.1 and 2.1.4
8	The capacity should be 15 % higher than the bottleneck in the transfer process for future-proofing	Performance	NH	Section 2.1.4
9	It must fit within the design space height of 2680 mm	Constraint	MH	Section 2.1.1
10	It should fit through the doors of a hatchery without disassembly, which are at least 2500 x 2500 mm^2	Constraint	NH	Section 2.1.1
11	The footprint should be lower than the current footprint	Constraint	NH	Section 2.1.1
12	Production cost should be lower than the total current production cost of €66k	Economic	NH	Section 2.2.1

4.3 Main and subfunctions

The current process cycle of the ST, as schematically shown in Figure 2.5, was used to derive the main and subfunctions for the redesign. A list of them is shown below. Note that function 1b is not present in the current device, but from the problem analysis (Section 2.3) it was derived that this functionality should be added in the redesign.

1. **Selective grabbing:** grabbing tool
   - (a) Taking eggs out of tray
   - (b) Minimize contamination by dead embryo eggs
   - (c) Keeping eggs in tray selectively
   - (d) Delivering eggs selectively
   - (e) Accounting for egg size and orientation differences
2. **Transferring:** frame
   - (a) Moving Y-axis: between input and output lane
   - (b) Moving Z-axis: avoid basket / tray
   - (c) Moving X-axis: Account for spacing differences

These functions were used as input to the morphological chart, as described in the next paragraph.

4.4 Concepts

A morphological chart was made, based on the functions defined in Section 4.3. The current solution for moving the X-axis will be reused in the redesign, as it shows no problems and has no influence on the other concepts, requirements, or problems identified in Section 2.2; this function is thus left out of the morphological chart, unless a change is required due to a chosen solution.

The chart is shown in Appendix B. As there are many concepts, several concepts were filtered out based on their complexity, either due to parts that are not readily available and should thus be produced ourselves, or due to the required relative complexity of the system. The result of the applied filter is shown in Appendix B.1. A capacity filter is also applied, shown in Appendix B.2, which filters out concepts that are predicted to be unable to reach the required capacity.

Preliminary designs can be made by combining concepts of several subfunctions from the morphological chart. These combinations can be seen in the final resulting morphological chart, Figure 4.2, as indicated by the numbers. They are explored in more depth in the next chapter, Chapter 5.

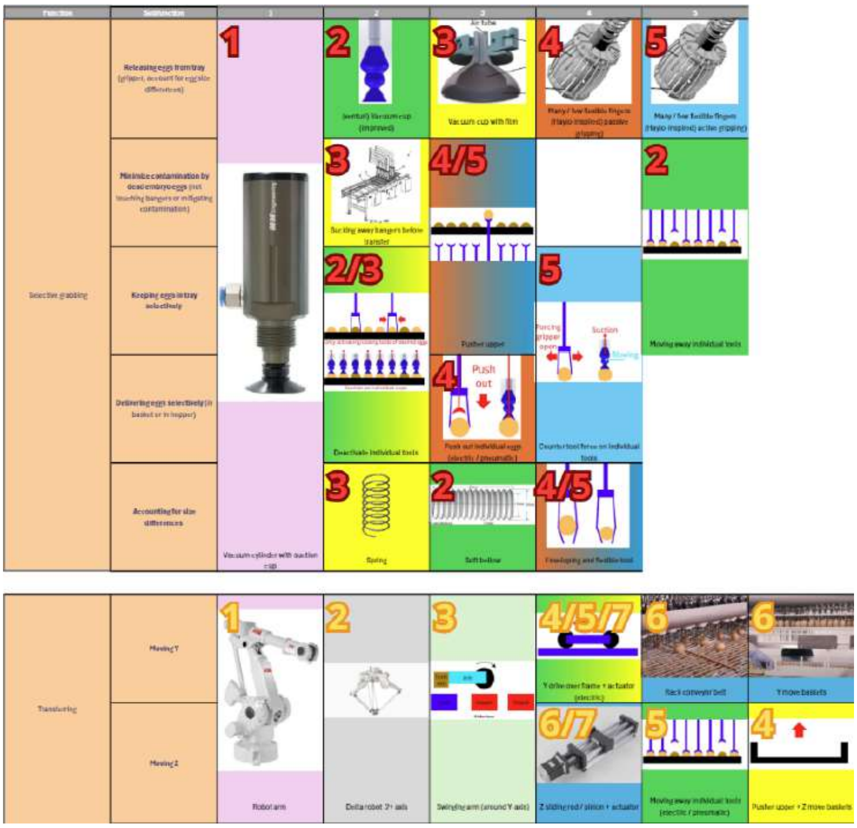


Figure 4.2: The final morphological chart, the preliminary designs are indicated by the numbers

5 Preliminary design

Having completed the conceptual design phase, the concepts from Chapter 4 can be combined into preliminary designs. In this chapter, these preliminary designs will be made and evaluated, answering the second part of the third research question:

"What solutions are possible, which is the most suitable, and what does the solution look like in detail?"

Before deciding on the most suitable final design from the morphological chart (Section 4.4), several combinations of concepts, called preliminary designs, are looked into in more detail and compared using the weighted criteria method with the design objectives delineated in Section 5.1. This method will guarantee the optimal design that can then be detailed (Chapter 6).

Several preliminary designs were proposed by combining the individual concepts in the morphological charts, as depicted by the colored combinations in Appendix B.3. It was chosen to combine concepts into preliminary designs for the functions Selective Grabbing (Section 5.2) and Moving Y/Z (Section 5.3) separately, as they can be considered separate problems and hardly influence each other. Most problems mentioned in Chapter 2 have to do with Selective Grabbing, hence why the preliminary designs for this function are prioritized above the Moving Y/Z preliminary designs.

5.1 Design objectives

The preliminary designs in this chapter will be weighed against each other, based on the weighted criteria method. This method allows for comparing concepts on various criteria with different levels of importance: weights. Design objectives must be determined for this method, with which the designs will be compared. The reliability, capacity, OPEX, and space efficiency were chosen as the design objectives, as well as the CAPEX (initial costs) and complexity of the system, as these are important to Viscon and the designer. The complexity of the system might even be an indication of the accessibility and cleanability of the system. An overview of the Design objectives, their definition, and the estimated performance of the current device is given in Table 5.1.

Table 5.1: Design objectives of the system

Design objective		Description	Value
1	Reliability	Percentage of successfully transferred trays (without breakage and microbial contamination)	99 %
2	Capacity	Amount of eggs that can be processed per unit of time	22 [$eggs/s$]
3	OPEX	Operational costs (Cleaning / maintenance costs, cost because of errors)	up to 0.5 FTE for error correction, 0.25 FTE of daily cleaning / maintenance.
4	CAPEX	The cost of the device including assembly and setup	€66k
5	Complexity	The complexity of the device, dictated by the part count, part density, and required process steps	7.3k parts, all in transfer head
6	Space efficiency	Ratio of the useful area, which is the area of trays/space between trays, to the total footprint of the machine	0.68

Not all design objectives are of equal importance. The importance ranking of the different objectives is determined by weighing them against each other, as depicted in Table 5.2.

Table 5.2: Comparison of individual design objectives. A "+" is assigned to the design objective with the highest importance.

	Reliability	Capacity	OPEX	CAPEX	Complexity	Space efficiency
Reliability	**X**	+	+	+	+	+
Capacity	-	**X**	+	+	+	+
OPEX	-	-	**X**	+	+	+
CAPEX	-	-	-	**X**	+	+
Complexity	-	-	-	-	**X**	+
Space efficiency	-	-	-	-	-	**X**
Total "+"	5	4	3	0	2	1

Using only the importance ranking, the CAPEX would weigh twice as much as the complexity. In practice, however, their weights were deemed to be almost equally important. To account for this, percentage weights were assigned to the design objectives, as shown in Table 5.4. The method of determining the score of an alternative is also mentioned in this table.

Table 5.3: Weights and method of estimation of the design objectives

Design objective	Weight	Definition and method of estimation
Reliability	30 %	Percentage of successfully transferred trays (without breakage and microbial contamination). Based on the amount of solved problems and the amount of forces the eggs experience
Capacity	25 %	Amount of eggs that can be processed per unit of time. Based on the estimated cycle time and ease of scaling the system
OPEX	20 %	Operational costs (Cleaning / maintenance costs, cost because of errors). Based on the estimated parts life, cleanability, and required labor
CAPEX	10 %	The cost of the device including assembly and setup. Based on rough estimations of the required parts and their costs
Complexity	10 %	The complexity of the device, dictated by the part count, part density, and required process steps. Based on the estimated part count, part density, required process steps, and design complexity
Space efficiency	5 %	Ratio of the useful area, which is the area of trays/space between trays, to the total footprint of the machine. Based on the estimated required area

Table 5.4: Weights and method of estimation of the design objectives

Design objective	Weight	Method of estimation
Reliability	30 %	Based on the amount of solved problems from Section 2.3 and the amount of forces the eggs experience
Capacity	25 %	Based on the estimated cycle time and ease of scaling the system
OPEX	20 %	Based on the estimated parts life, cleanability, and required labor
CAPEX	10 %	Based on rough estimations of the required parts and their costs
Complexity	10 %	Based on the estimated part count, part density, required process steps, and design complexity
Space efficiency	5 %	Based on the estimated required area

The preliminary designs will be tested against these objectives with the help of estimations and opinions from experts.

5.2 Selective grabbing

The primary focus of this research was on the Selective Grabbing solution, as most problems encountered with the current ST are caused by the Selective Grabbing system. The transferring function was considered after this, and has less of a priority.

Selective Grabbing includes taking the egg out of the tray selectively, delivering it, and minimizing contamination by banger eggs. In the next sections, each alternative is explored, after which a choice is made using the weighted criteria method shown in Section 5.2.7.

During initial concept comparisons, the preliminary designs SG1 and SG4 (Sections 5.2.2 and 5.2.5) showed the highest potential. These were thus investigated more in-depth to eliminate any potential oversights.

5.2.1 SG0: Vacuum cylinders

Design SG0 consists of the concepts listed in Table 5.5.

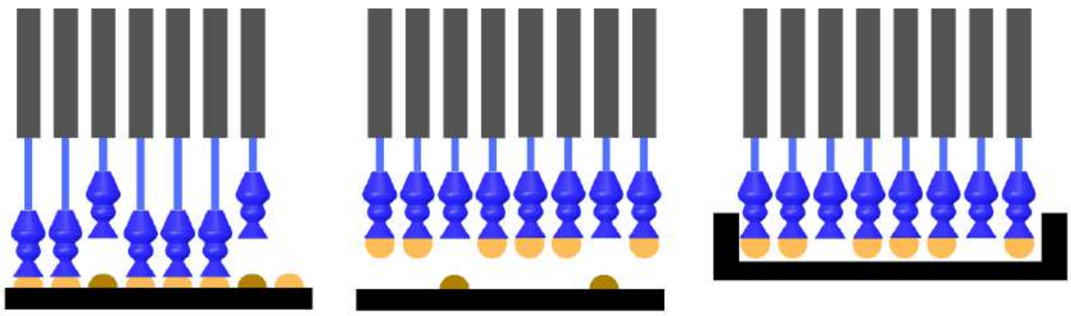
Table 5.5: Chosen concepts for design SG0

Subfunction	Chosen solution
Taking eggs out of tray	Vacuum cylinder
Minimize contamination by dead embryo eggs:	Vacuum cylinder
Keeping eggs in tray selectively	Vacuum cylinder
Delivering eggs selectively	Vacuum cylinder
Accounting for egg size and orientation differences	Vacuum cylinder / soft bellow

This concept uses vacuum cylinders with suction cups attached to them. The vacuum cylinders work as follows: Suction is applied to the cylinder, through which the cylinder is moved down. Suction flow is concurrently enabled in the suction cup by the cylinder. When an object is touched, it attaches to the suction cup due to the suction. When this happens, the cylinder automatically moves back up with the object attached, due to the vacuum created in the suction cup. Removing the suction flow releases the object almost instantly. The impact with the eggs can be minimal, as the cylinder will move up as fast as the cylinder seals with the egg (Solution 4 in Table 2.4). The touching of the bangers is also prevented, and no blow-off is required (Solutions 3 and 8 in Table 2.4).

A venturi valve can be added to create the suction. However, this might be more expensive and more complex compared to using a vacuum pump, and possibly introduces new challenges which have to be investigated as well. As dirty eggs pose a problem for suction based systems (Section 2.3), cleaning the eggs before the process should be considered when this design is selected.

The vacuum cylinders have the advantage of being very fast, and only require a single connection. However, the cylinders will be hard to clean on the inside, consume a lot of air, and they cost upwards of €120 per cylinder.



(a) 1. Enable suction to move down rods

(b) 2. The rods move up after an egg is attached with suction still on

(c) 3. Release by selectively disabling suction

Figure 5.1: Working principle of SG0

Design challenges

A few design challenges arise for this concept:

1. Air supply for the cylinders: As the specifications of these cylinders state they need around 35L/min at 0.4 bar absolute each, a very large vacuum pump will be required. Assuming this is only needed around 1/10th of the cycle, around 3.5L/min of suction flow is required per vacuum cylinder. Vacuum pumps that can supply this can be quite expensive and large. Using a venturi generator requires a constant flow of air, for at least half of the cycle. The flow required for a venturi generator is unknown, but it can be assumed to be around 4 times the required suction flow [51], meaning an average flow of 70L/min at 6 bar is needed per suction cup, which would require unreasonable large compressors. Using a vacuum pump is thus preferred over the second option.

Performance on design objectives

- **Reliability:** Both solution 3 and 8 are implemented, solving problems 1a - e, 3, (4), (5). If cleaning of the eggs is done (solution 7), problem 2 can be eliminated as well. Problem 4, however, could become worse, as cleaning might nog be easy. This increases the chances of contamination and clogging.
- **Capacity:** A very low cycle time of around 0.5 $[s]$ can be achieved, according to the specifications. The system can also be scaled up easily, as most parts are required for each individual suction cup.
- **OPEX:** The parts are off-the-shelf, and require no special maintenance as far as known. The 25 million cycles should also be plenty for the life of the device. Cleanability will increase the operational costs, and the tray reject system might also still be required, as the expected reliability low. The high flow of air required will also negatively impact the operational costs.
- **CAPEX:** It is estimated that for every egg, a vacuum cylinder and a suction cup are required. This costs around €120 + €2 respectively. The currently used valvebox costs around €50 per egg, which will be taken as an assumed price, even though vacuum valves were noticed to be more expensive. It is estimated that a vacuum pump would cost around €2000 for 100 suction cups, costing €20 per suction cup. This results in a total of €193 per vacuum cylinder to grab an egg.
- **Complexity:** The design complexity is not very high, as a single part is used for all subfunctions. At least a vacuum cylinder, suction cup, vacuum pump and valve are required for every egg.
- **Space efficiency:** Large vacuum pumps will be required, which decrease the space efficiency compared to the current solution.

5.2.2 SG1: Movable suction cups

Design SG1 consists of the concepts listed in Table 5.6.

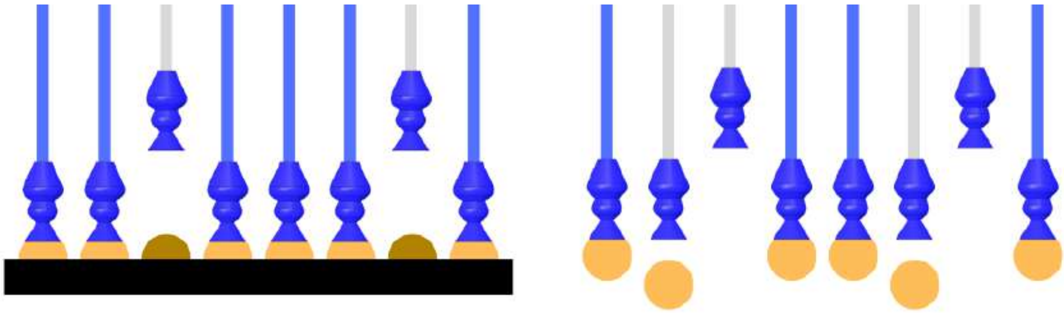
Table 5.6: Chosen concepts for design SG1

Subfunction	Chosen solution
Taking eggs out of tray	(Venturi) Suction cup
Minimize contamination by dead embryo eggs:	Moving away individual tools
Keeping eggs in tray selectively	Moving away individual tools / Deactivate individual tools
Delivering eggs selectively	Deactivate individual tools
Accounting for egg size and orientation differences	Soft bellow

This concept uses a suction cup to grab an egg, which can be moved away to prevent touching bangers (Solution 3 in Table 2.4). Either electric or pneumatic cylinders can be used for this movement. The individual tools are deactivated to prevent a loss of vacuum (Solution 8 in Table 2.4), which can be done in several ways, explored under the design challenges in the following paragraph. The suction cup will have a soft bellow to account for egg size differences.

To create the necessary suction flow, a low-pressure vacuum pump will be used, as is done in the current solution. The use of a Venturi system for this is also discussed in the following paragraph. As dirty eggs pose a problem for suction cups (Section 2.3), cleaning the eggs before the process will be considered as well, by reversing the suction flow of the pump and blowing away any loose dirt on the eggs. The hygiene of such a suction-based system is a big concern, which should be accounted for throughout the design and will be one of the main design challenges.

This solution has the advantage of only requiring a single, cheap actuator per egg, and other components that are known to work with the current ST. This decreases the complexity of the system.



(a) 1. Pick up eggs by moving rods and enabling suction

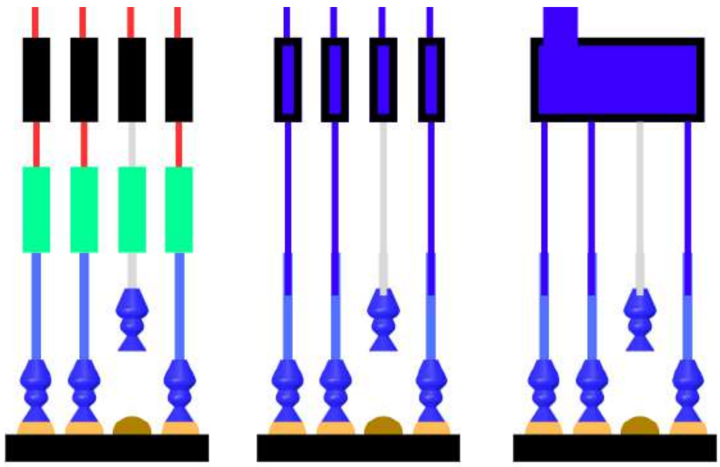
(b) 2. Release by selectively disabling suction

Figure 5.2: The working principle of SG1

Design challenges

A few design challenges arose for this concept:

1. Moving the rods: As every rod needs to be moved individually, a pneumatic or electric actuator is needed (hydraulic cylinders are only used in high-force applications). The pneumatic cylinder is mainly used for low-force and fast actuation in dirty and wash-down environments. An electric cylinder is way more expensive (from €150) than a pneumatic cylinder (from €15), and usually has lower IP ratings, which makes it harder to use in an environment that has to be cleaned regularly. For these reasons, a pneumatic actuator will be used.
2. Creating and distributing the suction flow: Several methods are possible for this. E.g., using Venturi valves and a regular valve for every suction cup (Figure 5.3a). The Venturi valves ensure no bacteria are sucked into the system, reducing the risk of contamination. However, Venturi valves continuously consume a lot of compressed air, which can pose a problem when using many suction cups simultaneously. Venturi valves also cost more than regular valves. Another option would be to use a vacuum pump similar to the current one, combined with a vacuum valve for every suction cup (Figure 5.3b). However, vacuum valves cost ±€30 more than regular valves. The simplest and cheapest option would be to use a vacuum box (Figure 5.3c), which enables the suction in a cup by the position of the rod; when the hollow rod is moved down, a hole in it enters the vacuum box, enabling suction flow in the rod.



(a) Using venturi valve (green), regular valves (black) and compressed air (red)

(b) Using vacuum valves (black with blue) and suction (blue)

(c) Using a vacuum box and suction (blue)

Figure 5.3: Methods of creating and distributing suction flow in SG1

3. Clogging of the suction system: Clogging due to egg contents will mostly be reduced by the

movable rods, but initial dirt on eggs still has the potential of clogging the suction cups. Two methods are thought of to counter this problem. First, the suction cup pillars will have a larger diameter hole to not only decrease the time required to reach a vacuum, but also decrease the chances of a clog. Secondly, while the ST resets to its initial position after releasing the viable eggs, it should reverse the suction flow to a blowing flow to expel any sucked-up egg contents during the travel. A German customer of Viscon has already implemented this fix in the current ST, and it shows promising results.

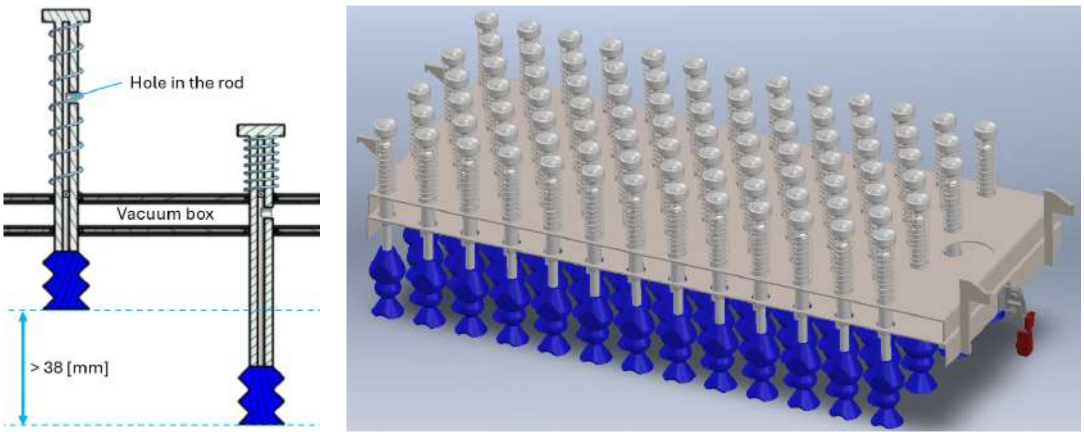
4. Cleanability: It is essential to avoid the cleanability problems encountered in the current suction-based system, which could mostly be prevented if proper cleaning were possible. The current design uses PAL profiles and fixed suction cups that are inaccessible for high-pressure washers. A vacuum box design, as proposed above, introduces the possibility of making it removable or highly accessible. Either of these options should be implemented to reach the required cleanability.

Details on the working principle

Because this concept initially scored well, some detailed drawings were made of the suction cups on movable rods (Figure 5.4a) to better estimate the feasibility and performance of the concept, considering the solutions to the above design challenges. A stainless steel vacuum box (Figure 5.4b) is used to distribute the vacuum, which also acts as a switch for enabling or disabling the suction in a suction cup, based on its Z-position. To create an airtight seal between the rods and the vacuum box, some O-ring or X-ring is used, which Viscon experts assume to be airtight enough to keep the vacuum in the vacuum box.

An actuator can push the rods down. A spring is then used to return the rod to its initial position, to avoid the actuators having to be fixed to the vacuum box assembly and enabling easy removal for cleaning of the vacuum box and the suction cups.

At least 38 [mm] of stroke is required to account for egg height differences, but eggs can also protrude from the bottom of trays, which is why around 50 [mm] of stroke would be safer to use.



(a) The left movable rod is in its resting state. The right rod is pushed down after which the suction is enabled through the vacuum box

(b) SolidWorks model of an initial removable vacuum box design. The hooks on all sides are used to connect it to the main frame of the ST

Figure 5.4: Initial conceptual drawings of SG1

Performance on design objectives

- **Reliability:** Both solutions 3 and 8 are implemented, solving problems 1a - e, 3, (4), (5). Solution 11 can also be implemented through design, reducing problem 4 and 5 even further. If cleaning the eggs is done by blowing on them, problem 2 can be eliminated as well. Soluction 5 can be implemented e.g. by blowing into the system and decreasing critical clogging points.

- **Capacity:** The cycle time will be very similar to the current cycle time of around 1 [s], as the rod movement can be done during movement. The system can also be scaled up easily, as most parts are required for each suction cup.
- **OPEX:** No special maintenance or cleaning costs are expected. The cylinders are off-the-shelf and will not require extra maintenance when positioned above the vacuum box. Cleanability can be optimized through design and should not be hard. The OPEX due to the tray reject system might decrease, as the expected reliability is high.
- **CAPEX:** It is estimated that a pneumatic cylinder and a suction cup are required for every egg. This costs around €20 + €2 respectively. A cup pillar will be used to move through the vacuum box, costing around €2 each. The vacuum box should not cost more than €5 per egg; the currently used valve box costs around €43 per egg, and the presently used vacuum pump costs around €11 per egg. This results in a total of €83 per movable rod.
- **Complexity:** The design complexity is not very high, as standard components are used. The part density is higher than for SG0, and more process steps are required, increasing the complexity.
- **Space efficiency:** No effect.

5.2.3 SG2: Removing bangers and suction cup with film

Design SG2 consists of the concepts listed in Table 5.7.

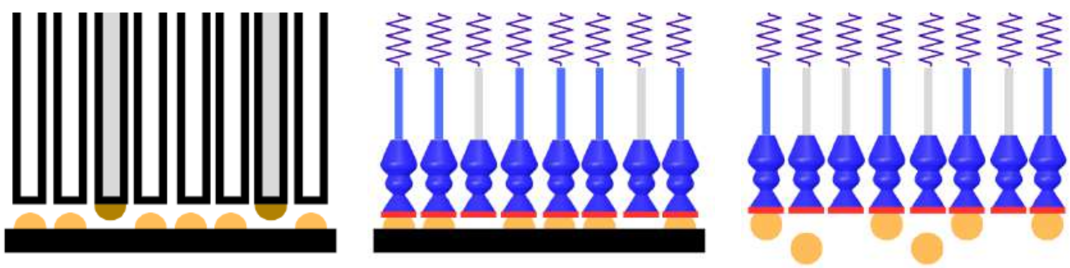
Table 5.7: Chosen concepts for design SG2

Subfunction	Chosen solution
Taking eggs out of tray	Suction cup with film
Minimize contamination by dead embryo eggs:	Sucking away bangers before transfer
Keeping eggs in tray selectively	Deactivate individual tools
Delivering eggs selectively	Deactivate individual tools
Accounting for egg size and orientation differences	Spring

This concept combines an unexplored type of suction cup with a film on it. The workings and details of this system can be found in Figure 3.2a. The design effectively removes the possibility of clogs and contamination of the vacuum system (Solution 5 in Table 2.4), as the vacuum system is closed. The eggs are gripped and released by activating the vacuum in the cups individually.

However, as contact is not avoided with banger eggs, they are removed before the transfer operation, using large suction tubes. This should be done without the possibility of contamination of other eggs, to eliminate problems 1a, 1c and 1e. Dirty eggs pose a problem for suction based systems (Section 2.3), cleaning the eggs before the process should be considered as well. The impact of contact should be limited where possible, as proposed in solution 4.

As this solution uses suction cups without potential for clogging and internal contamination, some problems can be prevented. However, the reliability and practicality of the gripper should be investigated, as no applications in the market have been made yet.



(a) 1. Suck bangers away

(b) 2. Pick up eggs by enabling suction

(c) 3. Release by selectively disabling suction

Figure 5.5: Working principle of SG1

Design challenges

A few design challenges arise for this concept:

1. How to suck away the bangers? This can be done by selectively creating a low pressure in some sort of suction tube. Banger eggs can be stuck in trays, however, which is why quite a low pressure is required. An initial calculation, assuming the 'leak' is an orifice, the leak rate to achieve 10 $[N]$ of lifting force on a 30 $[mm]$ egg is found to require a flow rate 4.39 $[m^3/h]$ at 93 $[kPa]$, which results in a large debit when multiple eggs are to be removed simultaneously.
2. How to prevent contamination and clogging? The suction system should have some sort of filtering system, e.g., a cyclone or swappable filters. Contamination should be limited by ensuring the vacuum is maintained, and no spread can occur on exploding of the bangers.
3. How to limit the pressure on the film? The film on the suction cups should not be exposed to very low pressures, to prevent damage. This can be achieved by using something like a syringe pump, or by a pressure relief valve and regular valve switching. The latter is preferred, as the former is sensitive to malfunctioning of the suction cups due to vacuum leakage.
4. How well does the suction effect work? Should the gripper body be flexible? How well should the seal with the eggs be? How to produce the suction cups? These questions will be answered through a prototype of the suction cup, presented in in the next paragraph.

Prototype of the suction cup

Because this concept initially scored well, an attempt at a prototype was made to investigate the reliability, feasibility and performance of the suction cups with a film. The prototype was inspired in form and function by the original design [34]. As no similar 3D-printers were available, an FDM printer was used to print a rigid body made of PLA, as shown in Figure 5.6a. A latex film was then fixed to the body using the clamping ring, and a syringe was used to create a vacuum (Figure 5.6b).

(a) CAD design (b) 3D-printed version, with the air sucked out (c) Lifting an egg

Figure 5.6: SG2 prototype

The device could successfully lift an egg, however, only around 50 % of the time due to a bad seal on the egg. The bad seal could possibly be solved by changing to a soft body design, as done by Koivikko et al. [34]. Multiple attempts at this were made by printing the body from TPU, a somewhat soft FDM material. However, this material was found to cause air leakage due to a bad layer adhesion.

If a closed vacuum system is used, e.g., with a syringe pump, any volume of leaked air from the closed vacuum system will change the amount of air in the system, reducing the maximum lifting pressure the closed system can reach by moving the piston.

The seal was found to be more critical than with conventional suction cups. Because this concept does not use a continuous suction air flow, even the slightest leak will compromise the gripping. Sealing problems could easily occur due to dirt on the eggs or due to dirt on the suction cups.

To reach this perfect seal, the gripper body should be very flexible and applied with a large force, which might damage the eggs. Even then, dirt might cause sealing issues. To produce such a flexible body, regular FDM printing will not suffice for creating the suction cup, and other methods, such as casting, should be considered.

Performance on design objectives

- **Reliability:** Both solution 3 and 8 are implemented, solving problems 1a - e, 3, (4), and (5). Solution 5 is attempted to be solved by applying the film over the suction cups, which potentially solves problems 1b, 1d, (4), and (5). The risk of contaminating desired eggs by purposefully touching bangers is expected to increase. No penalty is given for the airtightness problem shown in the design challenges, as this might be solved by a proper production method. However, a point is deducted since dirt is expected to cause an air leak that will make the egg detach.
- **Capacity:** In the suction cup, only a small volume of air must be evacuated, making it slightly, but not significantly, faster than regular suction cups. Scaling the system can be done easily by increasing the amount of grippers and suckers, but two systems need to be scaled up to increase the capacity, compared to the single system in the other solutions.
- **OPEX:** The sucking system will have to be cleaned well to prevent infection, but the cleaning costs of the suction cups decrease compared to regular suction cups. The tray reject system might also still be required, as the expected reliability low.
- **CAPEX:** For every egg a special suction cup is required. Assuming the suction cup is made in accordance with Koivikko et al. [34], this requires manual labour, expensive materials, and curing of the resin. This is estimated to be around €20 per suction cup. Other components, such as the rod and spring, will cost around €5 per suction cup. The currently used valvebox costs around €50 per egg, and the vacuum pump costs around €11 per egg. A spring and cup pillar are also required, costing around €5 per suction cup. Depending on the number of eggs to be removed simultaneously, more vacuum pumps will be necessary to remove the bangers. Assuming the current pump is used, this will cost €50 per sucking tube, and the removal system will also cost upwards of €10 per sucking tube. This results in a total of €60 per sucking tube to remove a banger egg + €91 per suction cup to grab an egg.
- **Complexity:** The design complexity is quite high, as the suction cups and the suction system have to be designed and tested from the ground up. The amount of parts is quite limited.
- **Space efficiency:** As another stage is required, the required space is expected to increase.

5.2.4 SG3: Passive gripper with egg-pushers

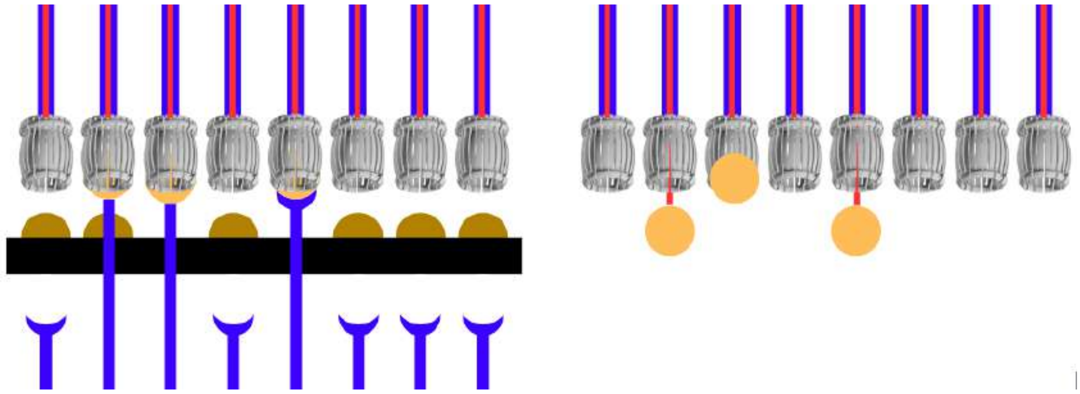
Design SG3 consists of the concepts listed in Table 5.8.

Table 5.8: Chosen concepts for design SG3

Subfunction	Chosen solution
Taking eggs out of tray	Flexible fingers, passive gripping
Minimize contamination by dead embryo eggs:	Push-up mechanism
Keeping eggs in tray selectively	Push-up mechanism
Delivering eggs selectively	Push out individual eggs
Accounting for egg size and orientation differences	Enveloping and flexible tool

This concept is aimed at avoiding the use of a vacuum system, as proposed as the first solution in Table 2.4. Most current problems can potentially be eliminated with this approach. Enveloping grippers and the like, however, cannot envelop small eggs in a tray, so pushing up the eggs is required. In this passive gripper design, the egg will be pushed into an enveloping gripper made of flexible prongs, and pushed out individually when needed, as shown in Figure 5.7. To account for egg height and size differences, the push-up device should have a large enough stroke, and the gripper should be flexible enough to grip all egg sizes. Eggs should not be allowed to be pushed outside of the gripper.

The available workspace and the limited allowed contact forces will pose challenges for this concept. The device might also be more expensive, as two actuators per egg are required, whereas SG1 and SG2 potentially only need a single actuator per egg.



(a) 1. Pick up eggs by pushing up eggs selectively into gripper

(b) 2. Release eggs by pushing out eggs selectively

Figure 5.7: Working principle of SG3

Design challenges

A few design challenges arise for this concept:

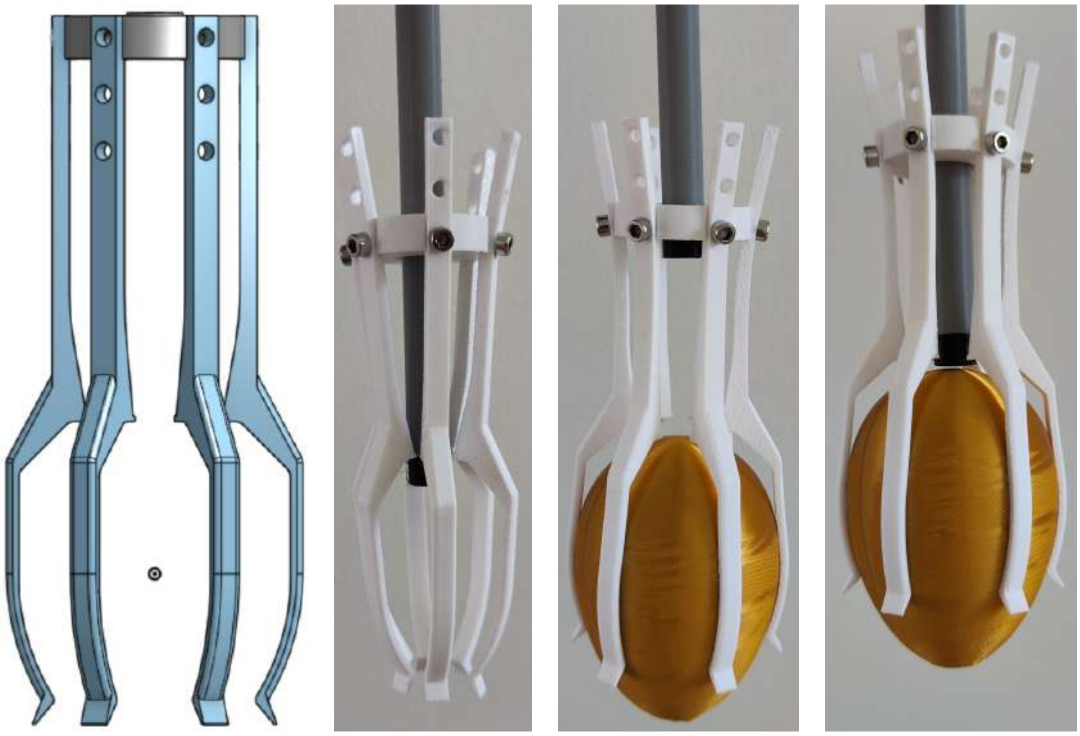
1. The choice of material, accounting for material fatigue: As this design relies on the stiffness of the material and requires considerable bending of the gripper fingers, high stresses may cause material fatigue in the future. Due to the ease of prototyping and production, an FDM printable material will be used. Materials were compared in Granta Edupack, based on the Young's modulus vs Fatigue strength. PET-G was found as a 3D-printable, food-safe, and flexible material, with a high fatigue limit. 3D-printed materials are slightly stiffer and have a lower fatigue strength [52, 53]. E.g., 3D-printed ABS only survives about 10% of the cycles compared to injection molded ABS [54]. A prototype will be made to finetune the parameters of the gripper, after which FEA will be used to analyze the stresses in the material, described in the next paragraph.
2. How well do all egg sizes go in, stay in place, and get out without breaking? This question will be answered through a prototype of the passive gripper, presented in the following paragraph.
3. The feasibility of the push-up mechanism: Initially, it was assumed that it would be feasible. After investigating the above design challenges, the feasibility of this mechanism was investigated. As shown in Section 3.2.3, Viscon has already patented a push-up mechanism design. The design is not currently used anymore, as it introduced many lifespan problems due to dirt and cleaning detergents ending up in the upward-facing cylinders below the conveyor belts. It will be assumed that this issue will also occur in this design, significantly impacting the OPEX.

Prototype of the passive gripper

Because this concept initially scored well, a prototype was created to tune the required finger thickness, length, and angle, and to better estimate the feasibility and performance of the concept. Six fingers were used, as most trays have a six-sided honeycomb pattern with six corners, with space for a finger. The parameters were varied individually and concurrently to arrive at the prototype shown in Figure 5.8, optimized for as little strain as possible. This prototype can grip and hold all eggs securely, and push them out when required, without breaking them. The fingers need to be quite stiff and pointed inward to achieve this. Pushing the eggs in and out requires the fingers to bend, and this bending results in high stresses in the material which could lead to material fatigue. FEA was used to verify this, which indeed showed stresses of 40 MPa, close to the ultimate tensile strength of PET-G [53].

Materials such as spring steel could be used to avoid this, as these show way better fatigue performance, but prototyping is currently not possible with these materials.

The push-out mechanism has a spring to account for the differences in egg height. When releasing an egg, the gripper is placed just above the basket, after which the pusher-outer pushes the egg out. This system works reliably, even when several grippers are mounted in the tray pattern.



(a) CAD design (b) Actual prototype (c) With largest egg (d) Pusher-outer engaged

Figure 5.8: SG3 prototype

Performance on design objectives

- **Reliability:** The design theoretically solves all problems. Pusher-outer makes sure all eggs are released correctly. A point is deducted, compared to SG4, due to the higher forces resulting from the stiffer fingers, especially on the largest eggs.
- **Capacity:** The cycle time is estimated to be similar to suction-based solutions such as SG1, based on the prototype. The design is easy to scale up and comparable to SG1, as most parts are required for each gripper.
- **OPEX:** Fatigue life might cause problems. It is estimated that around 15k cycles can be achieved when cycling near the UTS [53] [54]. This means that, assuming a cycle time of 8 seconds and 6 operational hours daily, it must be replaced every five days, increasing the operational costs significantly. Other materials, such as spring steel, could solve this problem. Operational costs will also increase because of the extra push-up system, which is expected to have a very short lifespan, due to detergents and egg contents penetrating the pneumatic cylinders. Compared to the original system, the OPEX will decrease due to shorter cleaning times and the removal of the tray reject system (assuming this is not needed anymore).
- **CAPEX:** For every egg, a gripper with a pusher-outer and a pusher-upper, two cylinders, and two valves are required. This is estimated to cost around €15, €40, €85 respectively. It is assumed, however, that the tray reject system can be removed, saving around €30 per egg. This results in a total of €110 per gripper to grab an egg.
- **Complexity:** The device will have more parts and be more complex than SG1, but the design and production will be less complex than SG2.
- **Space efficiency:** The required space is not expected to increase, as most new components only affect the height of the machine.

5.2.5 SG4: Active gripper with push-up

Design SG4 consists of the concepts listed in Table 5.9.

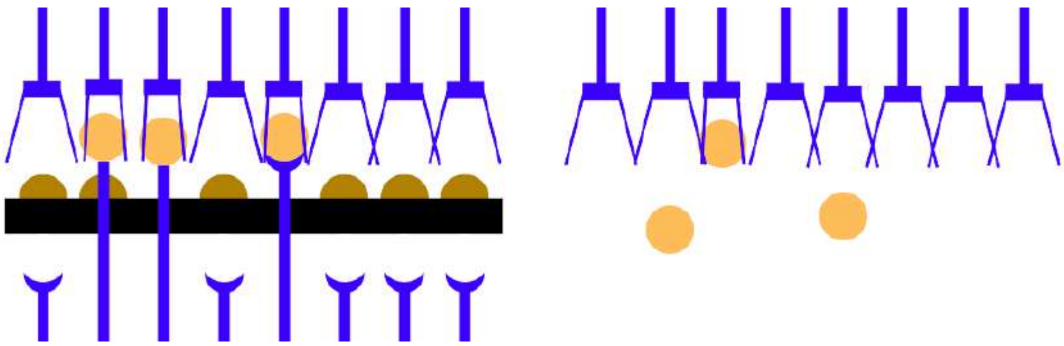
Table 5.9: Chosen concepts for design SG4

Subfunction	Chosen solution
Taking eggs out of tray	Flexible fingers, active gripping
Minimize contamination by dead embryo eggs:	Push-up mechanism
Keeping eggs in tray selectively	Push-up mechanism
Delivering eggs selectively	Push out individual eggs
Accounting for egg size and orientation differences	Enveloping and flexible tool

This concept is also aimed at avoiding the use of a vacuum system, as proposed in the first solution in Table 2.4. Here, a pushing-up mechanism is also required because of the limited space in the tray.

In this active gripper design, the egg will be pushed up, after which the gripper closes and envelops the egg. Contrary to SG3, this gripper does not rely on the passive material stiffness alone to grip the eggs, but enhances the gripping force by closing the gripper. Releasing the egg can be achieved by reopening the gripper, as shown in Figure 5.9. To account for egg height and size differences, the push-up device should have a large enough stroke, and the gripper should be flexible enough to grip all egg sizes. Eggs should not be allowed to be pushed outside of the gripper.

The available workspace and the limited allowed contact forces will pose challenges for this concept. The device might also be more expensive, as two actuators per egg are required, whereas SG1 and SG2 potentially only need a single actuator per egg.



(a) 1. Pick up eggs by pushing up eggs selectively into gripper and closing it

(b) 2. Release eggs by opening the grippers selectively

Figure 5.9: Working principle of SG4

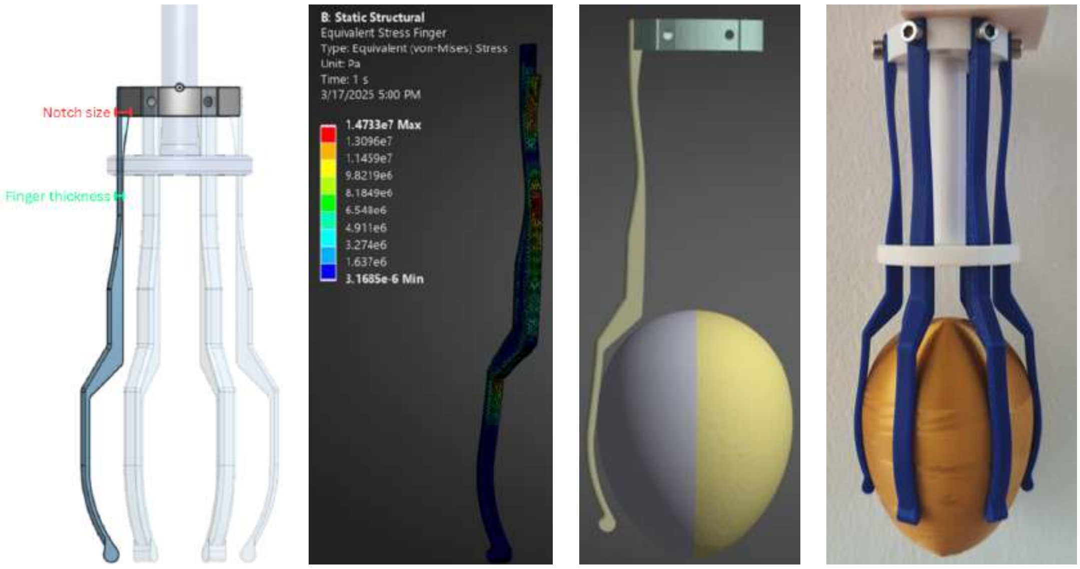
Design challenges

A few design challenges arise for this concept:

1. The choice of material, accounting for material fatigue: As this design relies on the stiffness of the material and requires considerable bending of the gripper fingers, high stresses may cause material fatigue in the future. PET-G was chosen for the same reasons as in SG3, but this again introduces fatigue strength challenges. A prototype will be made to finetune the parameters of the gripper, after which FEA will be used to analyze the stresses in the material.
2. How well do all egg sizes go in, stay in place, and get out without breaking? This question will be answered through a prototype of the passive gripper, presented in the following paragraph.
3. The feasibility of the push-up mechanism: Initially, it was assumed that it would be feasible. After investigating the above design challenges, the feasibility of this mechanism was investigated. As shown in Section 3.2.3, Viscon has already patented a push-up mechanism design. The design is not currently used anymore, as it introduced many lifespan problems due to dirt and cleaning detergents ending up in the upward-facing cylinders below the conveyor belts. It will be assumed that this issue will also occur in this design, significantly impacting the OPEX.

Prototype of the active gripper

Because this concept initially scored well, a prototype was made based on active gripping to better estimate the feasibility and performance of the concept. A plunger closes the gripper, as shown in Figure 5.10a. Several iterations were made, and optimizations on a few dimensions, using FEA. It was optimized for low stress in the finger and higher stress in the egg, by optimizing the finger thickness and notch size as shown in Figure 5.10a. The notch was found to reduce the stress in the finger, while increasing the gripping force.



(a) Design of SG4 (b) Maximum stresses in the finger (c) Deflection of SG4 in FEA (d) Actual deflection of SG4

Figure 5.10: Different images of the SG4 prototype

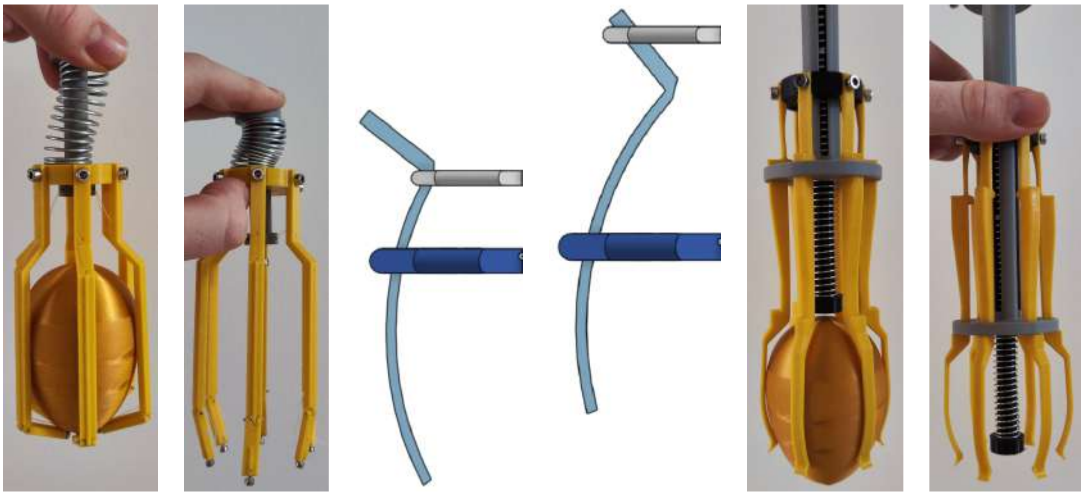
Multiple sizes of eggs were tested, and shaking the gripper was used to see whether the gripping strength would be sufficient. The initial results show that the design should work quite well, gripping and picking up all sizes of eggs consistently.

Several problem were encountered during the testing of the prototype. When the largest eggs are gripped by multiple neighboring grippers, the gripper fingers block each other, and flexing of the fingers is required to release the eggs. The gravitational force on the eggs, however, is not enough to achieve this. The fingers can not be made more flexible, as the flexibility is required to grip the eggs and account for the egg size differences. Several alternative solutions were tried, shown in Section 5.2.5.

First, a rigid tendon-driven PSEM (Section 3.2.2) was created, depicted in Figures 5.11a and 5.11b. This design has tendons to move the fingertips of the gripper, creating the required stiffness to lift the egg. The tendons are made from nylon, and the fingertip can move freely around the metal hinge which is connected to the upper part of the finger. The stiffness is released when the tendons are released, and the eggs weigh enough to open the fingertips. However, the friction in the tendons and hinge does not open the fingertips enough to pick up eggs reliably. This could be solved by increasing the weight of the fingertips, or by adding a torsional spring to each finger. The assembly time, and thus costs, are also very high due to the tendons and required adjustments.

An attempt at a rotating gripper was also made. The design has curved fingers, which are pushed through a fixed frame. This fixed frame then steers the fingers such that it envelops the egg. The working principle is shown in Figures 5.11c and 5.11d, showing the closed and opened finger respectively. The finger is actuated through the blue fixed frame by the white part. However, the fingers have to envelop at least 5 [mm], to account for egg size differences. The fingers' length also needs to be at least 40 [mm], and have a radius of at least 48 [mm] to be able to grip the largest eggs. The movement and frame require a lot of space to achieve this, and only a few millimeters are available in the trays. Because of this, the design was deemed unfeasible

Another option would be to add a push-out mechanism to SG4, like the one used in SG3 (Section 5.2.4). This forces the eggs out on release. For this to work, the plunger mechanism for opening and closing the gripper was reversed. A spring was added to account for the differences in egg height, as depicted in Figures 5.11e and 5.11f. The design is more complex and expensive than the original SG4, but initial testing shows it reliably grabs and releases eggs. The push-out mechanism was chosen as the solution and will be added to the concept.



(a) Tendon-driven PSEM, closed (b) Tendon-driven PSEM, opened (c) Rotator design, closed (d) Rotator design, opened (e) Pusher-out design, closed (f) Pusher-out design, opened

Figure 5.11: Different SG4 prototype alternatives

Another potential problem was also investigated, because it was encountered in SG3 as well: the fatigue life of the gripper. Stresses of around 14 $[MPa]$ were found using FEA, which should result in around 40k cycles before failure [53]. A simple test setup was created to confirm this problem. The largest size egg was gripped and released, as shown in Section 5.2.5, with a frequency of 3 $[Hz]$ until failure. In the test setup, the gripper indeed breaks at around 30 to 40k cycles. The results indicate that further stress reduction or different materials on high-stress points, such as spring steel, should be investigated before final implementation.

(a) Closed state of the gripper (b) Open state of the gripper

Figure 5.12: Test setup for fatigue-testing SG4

Performance on design objectives

- **Reliability:** The alternative theoretically solves all problems. Pusher-outer makes sure all eggs are released correctly.
- **Capacity:** The cycle time is estimated around 1 $[s]$ for picking up and releasing, based on the prototype. The design is easy to scale up, comparable to SG1, as most parts are required for each individual gripper.

- **OPEX:** Operational costs are expected to decrease, especially in cleaning time every day. The device also does not require a vacuum pump anymore, which decreases operational costs. Operational costs will increase because of the extra push-up system, as this system is below the trays, and very prone to damage because of dirt and egg contents. The operational costs decrease due to shorter cleaning times and due to the . due to the decreased OPEX of the tray reject system, as the expected reliability is high.
- **CAPEX:** For every egg, a gripper with a pusher-upper, two cylinders and two valves are required. This is estimated to cost around €20, €40, €85 respectively. It is assumed, however, that the tray reject system can be removed, saving around €30 per egg. This results in a total of €115 per gripper to grab an egg.
- **Complexity:** The device will have more parts and be more complex than SG1, but the design and production will be less complex than SG2. The pushing-up system, however, requires more parts and complex sealing, to prevent dirt from entering the system.
- **Space efficiency:** The required space is not expected to increase, as most new components only affect the height of the machine.

5.2.6 Current solution

The current solution consists of the concepts listed in Table 5.10.

Table 5.10: Concepts used in the current Selective Grabbing design

Subfunction	Used solution
Taking eggs out of tray	Suction cup
Minimize contamination by dead embryo eggs:	N/A
Keeping eggs in tray selectively	Counter tool force on individual tools (blow-off)
Delivering eggs selectively	Counter tool force on individual tools (blow-off)
Accounting for egg size and orientation differences	Soft bellow

The current solution is explained in more detail in Section 2.2.2, and uses suction cups and a blow-off system to achieve selective grabbing. However, all eggs are touched, drastically decreasing the reliability and operational costs, due to clogging and bacterial infection by banger eggs.

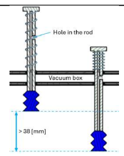
Performance on design objectives

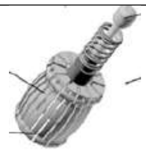
- **Reliability:** Without any improvements, all of the problems in Section 2.3 will persist, resulting in a low reliability. It is assumed that solution 7 can be easily implemented by blowing through the suction cups before picking up the eggs.
- **Capacity:** The current system needs around 0.2 $[s]$ for grabbing and 0.5 $[s]$ for releasing the eggs. The system can also be scaled up easily, as most parts are required for each individual suction cup.
- **OPEX:** Due to the low reliability and the problems, a lot of cleaning and error correction is required. It is expected the solution still performs worse than SG0 in this aspect. Other operational costs are lower than any other solution.
- **CAPEX:** For every egg, a suction cup is required, costing around €2. The currently used valve box costs around €43 per egg, and the currently used vacuum pump costs around €11 per egg. This results in a total of €56 per movable rod which can grab an egg.
- **Complexity:** The complexity is similar to SG1, they have around the same amount of parts and connections. It performs better than SG3 and SG4 on this aspect.
- **Space efficiency:** Currently, the selective grabbing solution is quite space efficient, similar to most other solutions.

5.2.7 Conclusion of Selective Grabbing solution

To find the best solution, the weighted criteria method is applied to the design objectives, which are described in Section 5.1. The values in Table 5.11 are based on the investigations described in the previous sections.

Table 5.11: Weighted Criteria Method for the Selective Grabbing solutions

							
		SG0: Vacuum cylinder		**SG1: Movable cups**		**SG2: Banger sucking**	
	Weight	Score	Weighted	Score	Weighted	Score	Weighted
Reliability	30 %	3	0.9	4	1.2	3	0.9
Capacity	325 %	5	1.25	4	1	4	1
OPEX	20 %	3	0.6	4	0.8	2	0.4
CAPEX	10 %	1	0.1	4	0.4	2	0.2
Complexity	10 %	4	0.4	3	0.3	2	0.2
Space efficiency	5 %	3	0.15	4	0.2	1	0.05
			3.4		**3.9**		**2.75**

							
		SG3: Passive gripper		**SG4: Active gripper**		**Initial solution**	
	Weight	Score	Weighted	Score	Weighted	Score	Weighted
Reliability	30 %	4	1.2	5	1.5	2	0.6
Capacity	25 %	4	1	4	1	4	1
OPEX	20 %	2	0.4	3	0.6	1	0.2
CAPEX	10 %	3	0.3	3	0.3	5	0.5
Complexity	10 %	2	0.2	2	0.2	4	0.4
Space efficiency	5 %	3	0.15	3	0.15	4	0.2
			3.25		**3.75**		**2.9**

The best-scoring concepts are SG1, the movable suction cup, and SG4, the active gripper. Even though SG4 is expected to outperform SG1 on reliability, it scores worse on most other design objectives. The concepts score very similarly, but SG1 is chosen as the final concept as it is expected to have the most manageable design challenges and the highest score.

5.3 Transferring

After having chosen the final concept for the Selective Grabbing function, preliminary designs are made for the transferring function. This function aims to get the eggs out of the tray into the basket. A movement in both the Y and Z directions is required for this, as the baskets can be up to 150 $[mm]$ deep, and the trays and baskets arrive on separate conveyor belts.

Some assumptions are made to estimate the performance of the solutions. First of all, the reliability is affected by the count and magnitude of forces on the eggs (Section 3.1). For the transferring solutions, this means that the reliability decreases with the amount of required accelerations and decelerations, as this increases the risk of damaging the eggs. Also, a travel distance of around 1000 to 1500 $[mm]$ and a maximum acceleration of 0.5G is assumed for all movements, well below the 1G limit to ensure no embryonal damage is caused (Section 3.1.3). It is also assumed that the Selective Grabbing solution weighs at least 100 $[kg]$ for a 150 egg picker. For cost estimations, Viscon suppliers and similar previously used parts will be used as much as possible to get a rough estimation. Construction costs are ignored in the CAPEX estimation, as they are hard to estimate and are indirectly penalized by the complexity design objective.

In the coming sections, all the concepts from the morphological chart (Section 4.4) are explored more in-depth. The focus was put especially on M3 and M6, as they scored best during initial evaluations.

5.3.1 M0: Robot arm

Design M0 consists of the concepts listed in Table 5.12.

Table 5.12: Chosen concepts for design M0

Subfunction	Chosen solution
Moving Y	Robot arm
Moving Z	Robot arm

This concept uses a robot arm to achieve both the moving Y and moving Z functions. Robot arms are used for various tasks, including automation and pick-and-place operations. Robot arms can have five or six degrees of freedom, which are not all needed for our application.

The biggest advantage of such a robot arm is its flexibility. However, the design of a robot arm can be very complex, and the development of such a robot arm for this specific application would not be feasible. On the market, ready-to-install options are available, several of which are capable of lifting over 100 [kg]. The robot would be placed between the input and output line, and rotate about its main axis (Figure 5.13a). The turning speed around the main axis ranges from 75 to 130 [deg/s] for such high-payload robots.

Design challenges

No particular design challenges arise as the robot arm can be bought as a single part. The robot arm would have to be mounted to the floor of the hatchery or a solid frame, and fencing would have to be designed for safety reasons.

Performance on design objectives

- **Reliability:** The reliability of this design is expected to be quite high, as robot arms are capable of smooth motion from A to B. The design is also taken care of by companies specialized in these robot arms, which should guarantee reliable operation. The precise movement control decreases the chance of damaging eggs due to pressing the tools on the eggs, especially if the egg size range is known by the operator.
- **Capacity:** Assuming an average 100 [deg/s] turning rate and the position of the robot being between the input and output lines, 4 [s] is estimated to be required for a full cycle from an input tray to an output basket, based on the specifications of several robot arms. Assuming the tool head can pick up around 150 eggs simultaneously, and the grabbing / releasing cycle takes around 1 [s] (as is currently), the capacity would be 30 [$eggs/s$].
  To scale up the system, however, higher payload robot arms or multiple robot arms are required.
- **OPEX:** Robot arms require regular maintenance, costing around 10 - 20 % of the initial costs each year [55]. Daily cleaning should not be a problem, as they are often designed with cleanability in mind. Such robots are already often deployed in similar environments.
- **CAPEX:** Prices of industrial robots with high payloads can cost upwards of €100k [56], excluding deployment.
- **Complexity:** The device is ready to buy and install. The part density is very high, but does not have to be assembled by Viscon.
- **Space efficiency:** As most robot arms have a minimum reach of above 500 [mm], the space efficiency will be limited somewhat. The hopper for eggs must also be placed between the conveyor belts, limiting the space efficiency. Other than that, the robot arm is quite space-efficient.

5.3.2 M1: Delta robot

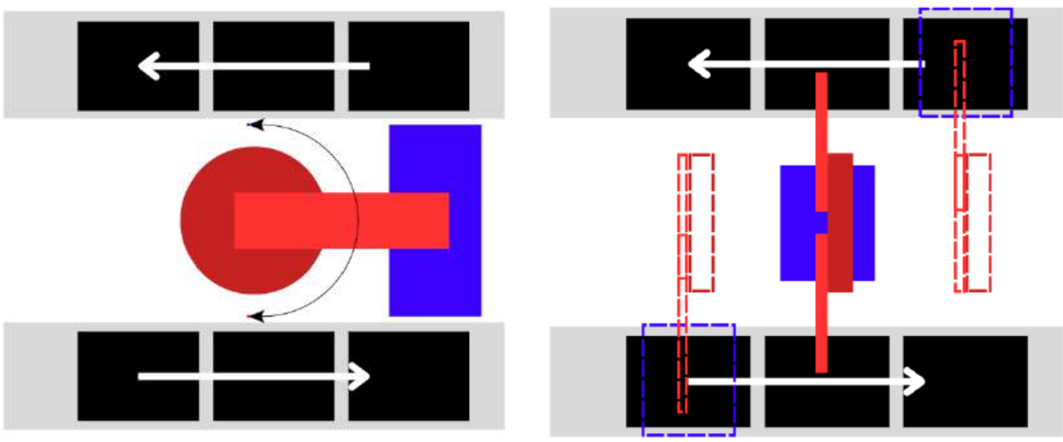
Design M1 consists of the concepts listed in Table 5.13.

Table 5.13: Chosen concepts for design M1

Subfunction	Chosen solution
Moving Y	Delta robot
Moving Z	Delta robot

This concept uses a delta robot to achieve both the moving Y and moving Z functions. The setup would be very similar to the robot arm, as shown in Figure 5.13b. The delta robot would be mounted to a frame, above the input and output lines. Delta robots can have varying degrees of freedom, and a two-degree-of-freedom variant would already suffice for this application.

Delta robots are known for their fast operation, but often only support payloads up to 15 $[kg]$. This may require multiple delta robots to achieve the desired capacity, or a very fast cycle time. The design of a delta robot can be very complex, which is why one has to be bought.



(a) M0 - robot arm

(b) M1 - delta robot

Figure 5.13: Top views of concepts M0 and M1. The robots are depicted in red, carrying a blue tool head

Design challenges

As this concept can be bought as a part, no big design challenges are expected. A frame has to be designed for the suspension of the delta robot, and the high accelerations would have to be supported by the Selective Grabbing concept. The eggs should also not break due to these accelerations.

Performance on design objectives

- **Reliability:** The reliability of this design is expected to be quite high, as delta robots are capable of smooth motion from A to B. The design is also taken care of by companies specialized in these delta robots, which should guarantee reliable operation. High accelerations, however, might cause problems for the embryos.
- **Capacity:** For the delta robot to work, large trays cannot be processed simultaneously, and a downsized tool head has to be made. The cycle speed is estimated to be around 2.5 $[s]$ for a cycle, based on the specifications of several delta robots. Assuming the sized-down tool head can pick up around 30 eggs simultaneously, and the grabbing / releasing cycle takes around 0.5 $[s]$ (half of what is currently, due to the downsizing), the capacity would be around 10 $[eggs/s]$. To reach the minimum required capacity of 22 $[eggs/s]$, at least three delta robots are required.
  Scaling up the system could be achieved by increasing the number of delta robots.
- **OPEX:** The same percentage of maintenance costs for robot arms is estimated for delta robots, with 10 - 20 % of initial costs every year. Daily cleaning should not be a problem, as they are often designed with cleanability in mind. Such robots are already often deployed in similar environments.

- **CAPEX:** Initial costs are estimated to be upward of €50k for the three delta robots, excluding deployment. A frame has to be built as well, which is estimated to cost around €2000, excluding building costs and PLC programming.
- **Complexity:** The device is ready to buy and install. The part density is very high, but does not have to be assembled by Viscon.
- **Space efficiency:** This is expected to be similar to solution M0, the robot arm.

5.3.3 M2: Swinging arm

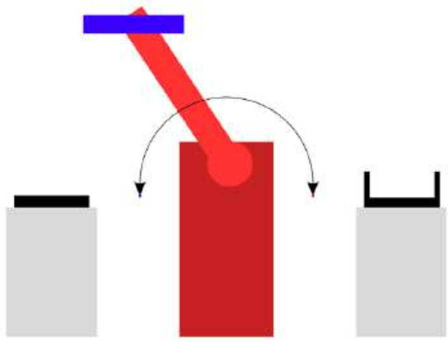
Design M2 consists of the concepts listed in Table 5.14.

Table 5.14: Chosen concepts for design M2

Subfunction	Chosen solution
Moving Y	Swinging arm
Moving Z	Swinging arm

This concept uses a swinging arm to achieve both the moving Y and moving Z subfunctions. This is done using an arm that swings around the central point between the input and output conveyor belts, as shown in Figure 5.14a. The design is based on previous and competitors approaches, such as the egg transfer device made by Mach-C [57], shown in Figure 5.14b.

A big advantage of this design is its combination of moving Y and moving Z in a single motion, which ensures as few parts and accelerations/decelerations as possible. However, the design details will be very dependent on the pitch between the conveyor belts, which can vary from hatchery to hatchery, and the driving and frame components will have to withstand the high forces associated with the suspended tool head.



(a) M2 - Swinging arm

(b) Mach-C swinging arm

Figure 5.14: Side view of concept M2. The concept is depicted in red, carrying a blue tool head

Design challenges

A few design challenges arise for this concept:

1. Avoid contact with baskets: As the swinging arm moves simultaneously in both the Z- and Y-direction (circular motion), the Y-movement could cause problems when moving towards the basket. Quick calculations show that in the worst-case scenario, a basket with a depth of 150 $[mm]$ and a swinging arm length of 750 $[mm]$, the Y-movement while the tool head is within the basket can be limited to under 4 $[mm]$. As the trays are around 15 $[mm]$ smaller than the baskets, it should be possible to make the tool head at least 4 $[mm]$ smaller than the baskets. Avoiding the baskets should thus be possible with proper alignment of the basket and swinging arm.
2. Minimizing the weight of the tool head: As the tool head is suspended on an arm, its weight plays a crucial role in the dimensioning of the required motor and other components. The moving weight should thus be minimized as much as possible.
3. Ensuring the tool head stays horizontal: This can be done by active compensation, or mechanically by a stationary gear and chain-chain connection between the swinging arm center

of rotation and the central axis of the tool head (as usually done in swinging arm applications). The latter is the least complex and cheapest, as it only requires two sprockets and a chain, compared to sensors and another actuator.

4. Dropping empty eggs in the hopper: Since a central driving axis will most likely be used, this would be right above the hopper, if positioned between the conveyor belts. The eggs should not be dropped on this axis to avoid contamination, requiring a solution to avoid this. Viscon has used cantilevered flaps made of rubber for redirecting eggs in the past, which could also be implemented to solve this problem.

Performance on design objectives

- **Reliability:** The device has a single moving component, and only a single acceleration and deceleration are required for the transfer. The device will be self-made and includes high-torque movements, so it might be less reliable than M0.
- **Capacity:** It is estimated that a single cycle can be completed in around 2.75 [s]. This is calculated assuming 0.5G acceleration and deceleration, for a swinging arm of 0.75 [m]. A motor with more than 1100 [Nm] would be required for this, but as only a low [rpm] is needed, this can be achieved with a relatively common motor combined with a gearbox.
  A slow approach to the final positions is accounted for as well by applying a factor of 2. Assuming the tool head can pick up around 150 eggs simultaneously, and the grabbing / releasing cycle takes around 1 [s] (as is currently), the capacity would be 40 [$eggs/s$].
  Scalability is achieved easily by increasing the motor size linearly with the tool head weight.
- **OPEX:** The operational costs should be way lower than for the M0 and M1 concepts, as no complex components and electronics are required. Daily cleaning should not be a problem. Similar swinging arms are already deployed in similar environments, and this kind of system can be designed with great accessibility due to the low part count.
- **CAPEX:** The estimated required components are a high-torque motor (estimated around €2700 from Viscon purchase history), a rigid frame (estimated to cost around €3000), bearings, chain, sprockets (estimated around €1000). This adds up to €6700, excluding building costs and PLC programming.
- **Complexity:** The system has few parts and few required process steps, but has to be built by Viscon. The design complexity is expected to be average, however, small changes in the setup required by the customer, e.g., a change in the pitch between the input and output conveyor belt, require a redesign of most parts.
- **Space efficiency:** The space efficiency will be similar to M0 and M1, as the device is placed between the conveyor belts, and space between the conveyor belts is required for the hopper for eggs without an embryo.

5.3.4 M3: Z-move basket

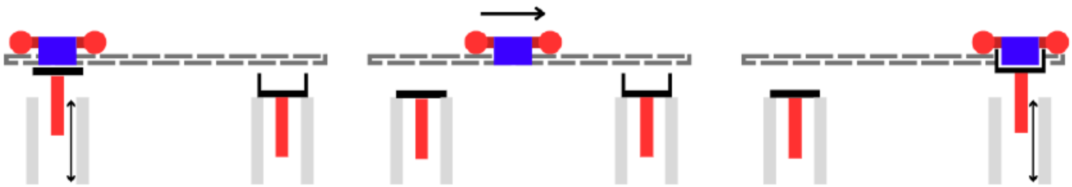
Design M3 consists of the concepts listed in Table 5.15.

Table 5.15: Chosen concepts for design M3

Subfunction	Chosen solution
Moving Y	Drive over frame
Moving Z	Pusher-upper/Z-move tray and Z-move basket

This concept uses wheels and a belt and pulley system to achieve the Y-movement (as currently done), and the Z-movement is achieved by moving up the basket and trays. The system operates as follows: First, the tray is pushed up as depicted in Figure 5.15a. After gripping the desired eggs with the tool head, the tool head is then pulled over the frame to the baskets, after which the baskets are pushed up for the release of the eggs (Figures 5.15b and 5.15c).

The advantage of moving the trays and baskets instead of moving the tool head in the Z-direction is in the weight difference and part density. The tool head weighs at least 100 [kg], while the trays and baskets only weigh a few kilograms. The required parts are also shared between multiple systems, instead of being concentrated in only the tool head, increasing the accessibility and cleanability of most components.



(a) Move up the tray (b) Drive the tool head over the frame (c) Move up the basket

Figure 5.15: Side view of concept M3. The parts of the concept are depicted in red, carrying a blue tool head

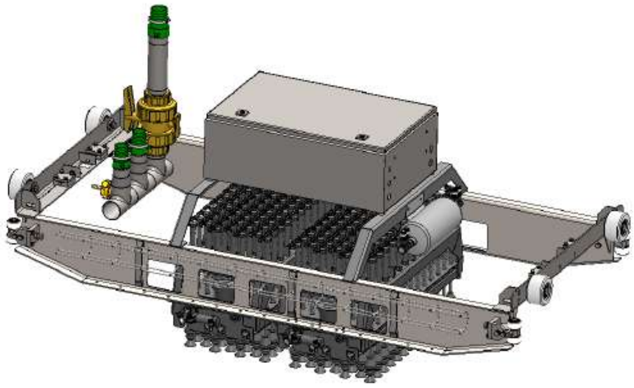
Design challenges

A few design challenges arise for this concept:

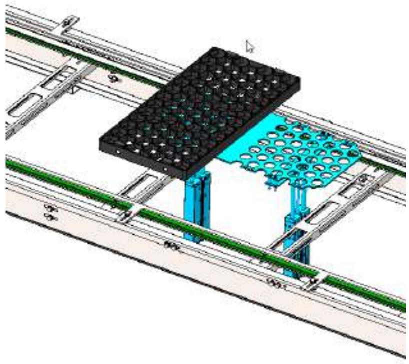
1. Ensuring the correct alignment: Especially the basket should be moved up to a very specific height, as the eggs should not be dropped from more than a few millimeters. If pneumatic drives are used for the Z-movement, it should be height-adjustable. Electric drives could be used instead of pneumatic drives to achieve this, but these are very expensive as they need to be watertight and chemically resistant. Driving over the frame also requires a tight alignment to avoid derailing of the system.
2. Preventing banger eggs from exploding: After the trays are pushed up, they need to be placed back on the conveyor belt again. The impact of this placement should not cause the remaining banger eggs to explode. This can be done by limiting the speed of the movement, either through using a controllable electric actuator or through limiting the return speed of the pneumatic actuator.
3. Preventing trays from attaching to the suction cups. If eggs are stuck in the trays, they might keep the tray from moving back down. Currently, a mechanism is deployed that blocks trays from moving in the Z-direction. However, this mechanism would not work with the M3 solution. A downward force must be applied to the tray when the push-up mechanism is moved down, which can be achieved in several ways.
4. Preventing collisions with trays and baskets: Trays and baskets might move on the push-up system, possibly causing collisions with trays and baskets on the conveyor belts. To avoid this, the trays and baskets on the conveyor belts should be held away from the pushed-up trays and baskets. This can be achieved using pneumatic cylinders, which physically block trays or baskets from moving when extended.

Details on the working principle

Because this concept initially scored well, detailed drawings were made to try and solve the design challenges and better estimate the feasibility and performance of the concept. It was decided that the mainframe could stay the same, as no problems were identified with it, while the moving frame was redesigned (Figure 5.16a), together with a push-up system (Figure 5.16a). During this process, all design challenges were investigated in more detail, and possible solutions to them were put together.



(a) Frame for the Y-movement, the Selective Grabbing solution is colored dark gray



(b) Push-up system for the Z-movement, highlighted in blue

Figure 5.16: Detailed preliminary drawings of the M3 concept

In Figure 5.16a, the frame for Y-movement can be seen. A belt and pulley system, together with a driving motor, are connected to the mainframe and the driving frame. Using the wheels, it can be driven over the mainframe from the input to the output belt.

A vacuum distributor, valvebox, and air reservoir are also designed and mounted for the Selective Grabbing solution. For the push-up system, two guided cylinders are used, which are placed under the snare conveyor belt. These guided cylinders can be adjusted in Z-position, allowing for adjustments to the system. When extended, the cylinders push up the trays above them.

Performance on design objectives

- **Reliability:** The device has multiple moving components, and will be self-made, which is why it might be less reliable than M0 and M1. The eggs will experience multiple accelerations in a cycle, but the movements are all simple and linear. The reliability will therefor be similar to M2.
- **Capacity:** Assuming 0.5G acceleration and deceleration and no limit on the actuation speed, cycle speeds of around 2.9 $[s]$ should be achieved, including the Z-movements of the basket and tray. Assuming the tool head can pick up around 150 eggs simultaneously, and the grabbing- and releasing cycle takes around 1 $[s]$ (as is currently), the capacity would be around 38.5 $[eggs/s]$.
  Scalability is achieved easily by increasing the actuator sizes linearly with the tool head size.
- **OPEX:** The operational costs should be way lower than for the M0 and M1 concepts, as no complex components and electronics are required. Daily cleaning should not be a problem, as the systems can be designed with great accessibility.
- **CAPEX:** The estimated required components are a motor and controller for the frame drive (More powerful than the current one to reach higher accelerations, but the price stays similar: €2000), belts, pulleys, bearings, and couplings (€535). The frame and other components are estimated to cost around €2000, the push-up mechanisms are estimated to cost around €500 each, consisting of a frame, sliding guides, and pneumatic cylinders with position sensors. This adds up to €5535, excluding building costs and PLC programming.
- **Complexity:** The system has quite some parts, and requires multiple process steps. The three systems are not complex, however, and are separated from each other. The score will be higher compared to M6 and the current solution.
- **Space efficiency:** The space efficiency will be similar to the previous concepts, as the device is placed between the conveyor belts, and space between the conveyor belts is required for the hopper for eggs without an embryo.

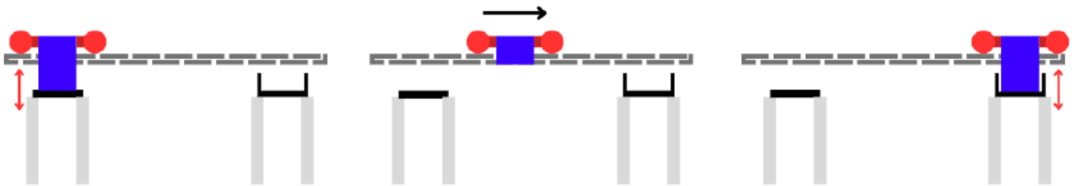
5.3.5 M4: Moving tools

Design M4 consists of the concepts listed in Table 5.16.

Table 5.16: Chosen concepts for design M4

Subfunction	Chosen solution
Moving Y	Drive over frame
Moving Z	Moving tools

This concept works best with the Selective Grabbing concept: SG3/SG4, if the cylinder for activating the gripper or pushing out the egg can also be used for moving the tool. It would, however, also be theoretically possible with SG1. As some Z-movement is already integrated into the tools of the Selective Grabbing concept, it could be exploited to avoid contact with the trays and baskets as well if long-stroke actuators can be used. The concept uses wheels and the frame to achieve the Y-movement, and the movable tools achieve the Z-movement. First, the tools are moved down as depicted in Figure 5.17a. After gripping the eggs with the tool head, the tools are moved up again and driven over the frame to baskets, after which the tools are again lowered for the release of the eggs (Figures 5.17b and 5.17c).



(a) Move the tools down (b) Drive the tool head over the frame (c) Move the tools down

Figure 5.17: Side view of concept M4. The parts of the concept are depicted in red, carrying a blue tool head

Design challenges

A few design challenges arise for this concept if combined with the chosen Selective Grabbing solution:

1. Ensuring the correct alignment: As with concept M3, proper alignment is required to avoid derailing of the driving mechanism.
2. Controlling tool movement: As the tools in concept SG1 rely on their lowered position for activation of the suction in the suction cups, a change has to be made to allow for lifting of the tools without deactivating the vacuum. This can be achieved with several methods, listed below. Options that control the vacuum using regular solenoid valves instead of a vacuum box are left out, as this would be very sensitive to contamination and impossible to clean, besides being the most expensive solution.

    - Block air from leaving the rods in the up-position. Using this method, the vacuum stay in the rod, and the egg should stay attached to the suction cup. When the rod is pushed down, air should be able to move freely to achieve the vacuum or release the eggs. Such a system could be created by a spring-loaded door, which blocks the air hole in the rod when outside of the vacuum box. Several springs and extra sealing are required for every rod in this solution, increasing the costs and decreasing the cleanability.
    - Change to electric cylinders and use three positions for the rods: up and open, up and closed, down and open. Hygienic and watertight electric cylinders, however, are over ten times as expensive as pneumatic cylinders, and many of them are required. This would increase the costs by an unreasonable amount.
    - Ignore the pressure loss when an egg is to be left in the tray, and connect every rod to the vacuum pump always, only controlling their position to avoid picking up undesired eggs. However, combined with the intended larger air holes in the rods, to increase cleanability and reliability, a vacuum pump with a very large air flow would have to be used to compensate for the air leakage. This would negatively impact the reliability, capacity, and cleaning costs.

    Out of these options, the first seems the most plausible.

Performance on design objectives

- **Reliability:** The device has multiple moving components, and will be self-made, which is why it might be less reliable than M0 and M1. The eggs will experience multiple accelerations in a cycle, but the movements are all simple and linear. The reliability would similar to M2. As the Selective Grabbing reliability is affected by this solution as well, and increases the chances of failure due to the mechanism of keeping a vacuum while the rods are up, a point is subtracted.
- **Capacity:** Assuming 0.5G acceleration and deceleration and no limit on the actuation speed, cycle speeds of around 2.9 $[s]$ should be achieved. Assuming the tool head can pick up around 150 eggs simultaneously, and the grabbing and releasing cycle takes around 1 $[s]$ (as is currently), the capacity would be around 38.5 $[eggs/s]$.
Scalability is not affected by this solution, as every tool has its own actuator which will stay sufficient after scaling up.
- **OPEX:** The operational costs of the framedrive only have to be accounted for, as the moving rods are already a part of the selective grabbing solution. They should be a bit lower than for the M2 and M3 concepts, as few components that need maintainance and electronics are required. Daily cleaning should not be a problem, as the systems can be designed with great accessibility.
- **CAPEX:** The estimated required components are a motor and controller for the frame drive (More powerful than the current one to reach higher accelerations, but the price stays similar: €2000), belts, pulleys, bearings, and couplings (€535). The frame and other components are estimated to cost around €2000. The extra costs per cylinder are around €15 for the long stroke cylinder, and another €10 is required for a vacuum control mechanism, which adds up to around €5000 if 200 suction cups are used. This adds up to €9535, excluding building costs and excluding PLC programming.
- **Complexity:** The system to control the tool movement and vacuum will be quite complex, and causes a very high part count and density. The system is considered the most complex out of all the concepts.
- **Space efficiency:** The space efficiency will be similar to the previous concepts, as the device is placed between the conveyor belts, and space between the conveyor belts is required for the hopper for eggs without an embryo.

5.3.6 M5: Y-move basket

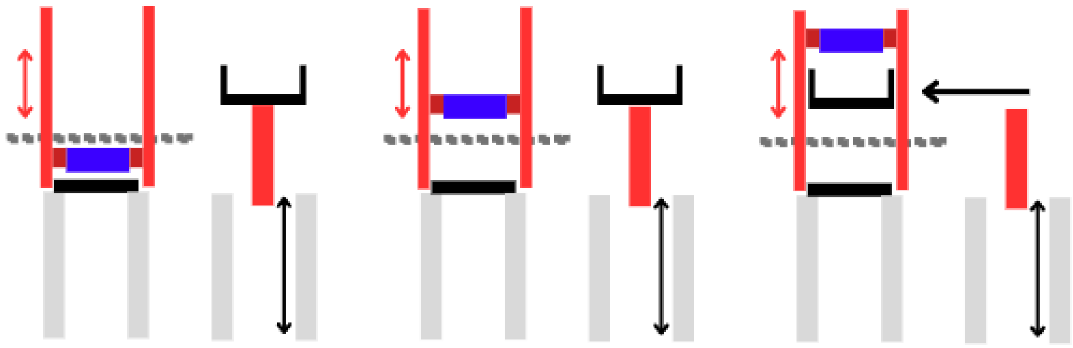
Design M5 consists of the concepts listed in Table 5.17.

Table 5.17: Chosen concepts for design M5

Subfunction	Chosen solution
Moving Y	Y-move basket + rack-conveyor
Moving Z	Z-sliding rods

This concept uses sliding rods for the Z-movement (as currently done), a rack-conveyor to drop the unfertilized eggs on, and Y-movement of the basket for the eggs with living embryos. First, the desired eggs are picked up by the transfer head, as shown in Figure 5.18a. The transfer head then moves up, and the rack conveyor is moved underneath it, after which it releases the unfertilized eggs on the rack conveyor (Figure 5.18b). The rack conveyor puts these eggs into the hopper, while a mechanism transfers the basket from the output belt to the input belt, allowing the transfer head to release the eggs still remaning on the transfer head into the baskets (Figure 5.18c).

The advantage of such a system would be the decreased complexity of the transfer head, as it only has to move up and down. The baskets also weigh much less compared to the transfer head, making it lighter work to move them compared to the full transfer head.



(a) Move the tool head down to grab eggs

(b) Move the tool head up and drop eggs on rack conveyor

(c) Move the tool head up and move basket in

Figure 5.18: Side view of concept M5. The parts of the concept are depicted in red, carrying a blue tool head

Design challenges

A few design challenges arise for this concept:

1. Moving and guiding the basket: The baskets should be lifted up from the conveyor belt, after which they have to be moved in the Y-direction, and moved back afterwards. Several methods can be used to achieve this, such as pneumatic actuators. To avoid interference with the transfer head, extendable guides would have to be used for the baskets.
2. As the basket is pushed up from below and away from the conveyor belt, it might move on the mechanism, risking misalignment with the tool head or the conveyor belt. As this is unwanted, proper guidance should be provided.

Performance on design objectives

- **Reliability:** The device has multiple moving components, and will be self-made, which is why it might be less reliable than M0 and M1. The eggs will experience multiple accelerations in a cycle, more than for concepts M2 to M4. The reliability will lower due to this.
- **Capacity:** The estimated required cycle time is similar to the current device. Assuming 0.5G acceleration and deceleration and no limit on the actuation speed, cycle speeds of around 4.9 $[s]$ should be achieved. The cycle speed is assumed to be limited by the basket movement, which is slower than the other methods because it needs to wait for the baskets to swap out before it can continue. Assuming the tool head can pick up around 150 eggs simultaneously, and the grabbing and releasing cycle takes around 1 $[s]$ (as is currently), the capacity would be around 25.4 $[eggs/s]$.
  Scalability is achieved easily by increasing the actuator sizes and frame sizes linearly with the tool head size.
- **OPEX:** The operational costs should be way lower than for the M0 and M1 concepts, and similar to M3, as these work fairly similarly. Daily cleaning should not be a problem, and the device should be quite accessible as it is smaller.
- **CAPEX:** The estimated required components are pneumatic cylinders for moving the basket in the y-direction (€300) and z-direction (€100). The frame and other components are estimated to cost around €2000. The rack conveyor and its frame are estimated to cost around €750. Moving the tool head up and down will require a G-motor (€2000), multiple sliding blocks (€350), a belt and pulley system (€400). This adds up to €5900, excluding building costs and PLC programming.
- **Complexity:** The system has more parts than M3, and more process steps are required. The part density is also higher, due to the smaller footprint.
- **Space efficiency:** The space efficiency will be better than for the previous concepts. The hopper can be put underneath a conveyor belt, decreasing the required space.

5.3.7 M6: Improved current solution

Design M6 consists of the concepts listed in Table 5.18.

Table 5.18: Chosen concepts for design M6

Subfunction	Chosen solution
Moving Y	Drive over frame
Moving Z	Z-sliding rods

This concept works the same as the current concept as described in Section 2.2, using a sliding rod for the Z-movement and driving over the frame for the Y-movement. However, as the current system does not reach the required capacity, the motor for the Y-movement is recalculated to achieve a higher acceleration and reach the required cycle time.

The current device was designed to reach a 7 $[s]$ cycle time with a pitch of 1000 $[mm]$ between the input and output lines, with a maximum acceleration of 2.2 $[m/s^2]$ (0.2G). With this acceleration and a pitch of 1500 $[mm]$, which is more common, the required capacity is not reached. Using the assumption of 0.5G accelerations, the required capacity is reached easily.

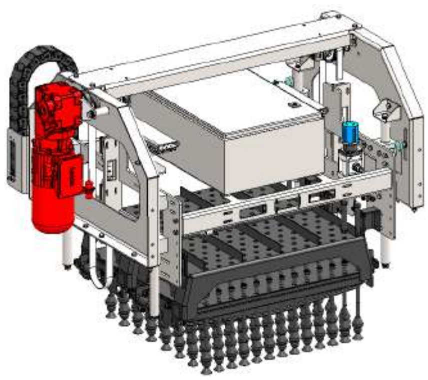
Design challenges

A few design challenges arise for this concept:

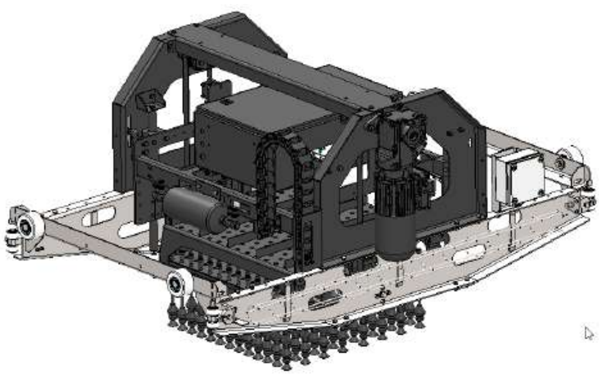
1. Ensuring the correct alignment: As with concept M3, proper alignment is required to avoid derailing of the driving mechanism.
2. Keeping the complexity low: As all functions have to be fulfilled by only the transfer head, the part density might become very high, decreasing accessibility and cleanability.

Details on the working principle

Because this concept initially scored well, detailed drawings were made to better estimate the feasibility and performance of the concept. The current moving frame was adapted to fit the new Selective Grabbing solution, as shown in Figures 5.19a and 5.19b.



(a) Frame for the Z-movement, the Selective Grabbing solution is colored dark gray



(b) Driving frame for the Y-movement

Figure 5.19: Detailed preliminary drawings of the M6 concept

In Figure 5.19a, the frame for the Z-movement is depicted. Sliding rods and bearings are used to achieve this motion, combined with a belt and pulley system driven by a geared motor. The frame for the Z-movement is placed on a frame for moving in the Y-direction, as shown in Figure 5.19b, which is again driven by a belt and pulley system mounted to the mainframe. A vacuum distributor, valvebox, and air reservoir are also designed and mounted on this frame for the Selective Grabbing solution.

Performance on design objectives

- **Reliability:** The device has multiple moving components, and will be self-made, which is why it might be less reliable than M0 and M1. The eggs will experience multiple accelerations in a cycle, but the movements are all simple and linear. The reliability will be similar to M2 and M3.
- **Capacity:** Assuming 0.5G acceleration and deceleration and no limit on the actuation speed, cycle speeds of around 2.9 $[s]$ should be achieved, including the Z-movements of the basket and tray. Assuming the tool head can pick up around 150 eggs simultaneously, and the grabbing and releasing cycle takes around 1 $[s]$ (as is currently), the capacity would be around 38.5 $[eggs/s]$.
Scalability is achieved easily by increasing the actuator sizes linearly with the tool head size.
- **OPEX:** The operational costs should be way lower than for the M0 and M1 concepts, as no complex components and electronics are required. Daily cleaning should not be a problem, and should be similar to M3 and M4.
- **CAPEX:** The estimated required components are a motor and controller for the frame drive (More powerful than the current one to reach higher accelerations, but the price stays similar: €2000), belts, pulleys, bearings, and couplings (€535). The frame and other components are estimated to cost around €2000. Moving the tool head up and down will require a G-motor and a controller (€2000), multiple sliding blocks (€350), a belt and pulley system (€400). This adds up to €7285, excluding building costs and PLC programming.
- **Complexity:** The system has a similar number of parts as M3, but the part density is higher, due to all systems being on the transfer head. This increases the complexity compared to M3.
- **Space efficiency:** The space efficiency will be similar to previous concepts such as M3 and M4.

5.3.8 Current solution

1. Moving Y: Drive over frame
2. Moving Z: Sliding rod

The current solution consists of the concepts listed in Table 5.19.

Table 5.19: Concepts used in the current Transferring design

Subfunction	Used solution
Moving Y	Drive over frame
Moving Z	Sliding rod

This concept is the current ST as described in Section 2.2, using a sliding rod for the Z-movement and driving over the frame for the Y-movement.

Performance on design objectives

- **Reliability:** The device has multiple moving components, and will be self-made, which is why it might be less reliable than M0 and M1. The eggs will experience multiple accelerations in a cycle, but the movements are all simple and linear. The reliability will be similar to M2 and M3.
- **Capacity:** The current cycle time including grabbing and releasing is at least 8 $[s]$. Assuming the tool head can pick up around 150 eggs simultaneously, and the grabbing and releasing cycle takes around 1 $[s]$ (as is currently), the capacity would be around 18.8 $[eggs/s]$.
Scalability is achieved easily by increasing the actuator sizes linearly with the tool head size.
- **OPEX:** The operational costs should be way lower than for the M0 and M1 concepts, as no complex components and electronics are required. This value should be similar to M3 and M6, as they are very similar.
- **CAPEX:** The estimated required components are a motor for the frame drive (€1581), belts, pulleys, bearings, and couplings (€535). The frame and other components are estimated to cost around €2000. Moving the tool head up and down will require a G-motor (€2000),

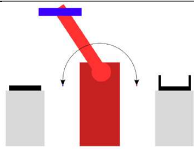
multiple sliding blocks (€350), a belt and pulley system (€400). This adds up to €6866, excluding building costs and PLC programming.

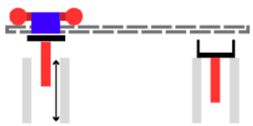
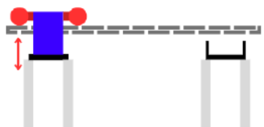
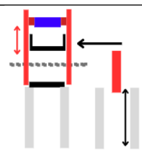
- **Complexity:** The system has a similar number of parts and part density as M6.
- **Space efficiency:** The space efficiency will be similar to previous concepts such as M3 and M4.

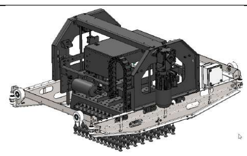
5.3.9 Conclusion of Transferring solution

To find the best solution, the weighted criteria method is applied to the design objectives, which are described in Section 5.1. The values in Table 5.20 are based on the investigations described in the previous sections.

Table 5.20: Weighted Criteria Method for the Transferring solutions

							
		M0: Robot arm		**M1: Delta robot**		**M2: Swinging arm**	
	Weight	Score	Weighted	Score	Weighted	Score	Weighted
Reliability	30 %	5	1.5	4	1.2	4	1.2
Capacity	25 %	3	0.75	3	0.75	5	1.25
OPEX	20 %	1	0.2	2	0.4	3	0.6
CAPEX	10 %	1	0.1	2	0.2	4	0.4
Complexity	10 %	5	0.5	5	0.5	2	0.2
Space efficiency	5 %	3	0.15	3	0.15	3	0.15
			3.2		**3.2**		**3.8**

							
		M3: Z-move basket		**M4: Moving tools**		**M5: Y-move basket**	
	Weight	Score	Weighted	Score	Weighted	Score	Weighted
Reliability	30 %	4	1.2	3	0.9	3	0.9
Capacity	25 %	4	1	4	1	2	0.5
OPEX	20 %	4	0.8	4	0.8	3	0.6
CAPEX	10 %	5	0.5	3	0.3	5	0.5
Complexity	10 %	4	0.4	1	0.1	2	0.2
Space efficiency	5 %	3	0.15	4	0.2	5	0.25
			4.05		**3.3**		**2.95**

					
		M6: Improved current		**Current solution**	
	Weight	Score	Weighted	Score	Weighted
Reliability	30 %	4	1.2	4	1.2
Capacity	25 %	4	1	1	0.25
OPEX	20 %	4	0.8	4	0.8
CAPEX	10 %	4	0.4	4	0.4
Complexity	10 %	3	0.3	3	0.3
Space efficiency	5 %	3	0.15	3	0.15
			3.85		**3.1**

The best-scoring concepts are M3, the Z-moving baskets, and M6, the improved current solution. M3 scores similarly on reliability and capacity, but is expected cost less and have a lower complexity. The concepts score very similarly, but M3 is chosen as the final concept as it is expected to have the most manageable design challenges and the highest score.

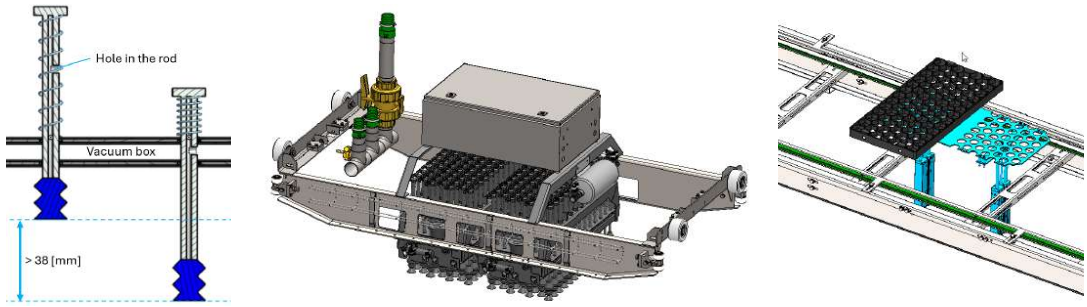
5.4 Conclusion

In the previous sections, several concepts were presented, combined into preliminary designs, and compared to each other using the weighted criteria method. This was done to answer the second part of the third research question, "What solutions are possible, what do these look like, and which is the most suitable?".

The weighted criteria method was applied using the design objectives of reliability, capacity, OPEX, space efficiency, CAPEX, and complexity. Separate analyses were done for the Selective Grabbing of eggs, and required Y/Z movements, as they can be considered separate designs that hardly influence each other.

Using this method, the vacuum box design as described in Section 5.2.2 was found to be the best performing and most feasible Selective Grabbing solution. The design uses movable rods with suction cups on them to avoid contact with banger eggs (Figure 5.20a), the main cause of contamination. The system should be designed with cleanability and accessibility in mind, as suction systems can be contaminated easily.

For the Y/Z movements, a system that pushes up trays and baskets, and a belt and pulley system to move from the input to the output conveyor belt is chosen as the best alternative (Section 5.3.4). This alternative combines a high capacity with a low complexity and CAPEX, and is shown in Figures 5.20b and 5.20c.



(a) The left movable rod is in its resting state. The right rod is pushed down after which the suction is enabled through the vacuum box

(b) Frame for the Y-movement, the Selective Grabbing solution is colored dark gray

(c) Push-up system for the Z-movement, highlighted in blue

Figure 5.20: Preliminary drawings of designs SG1 and M3

The required movement in the X-direction will be left as it currently is (described in step 7 of Section 2.2.2), as no problems were found with it, and no improvements were required. The chosen concepts will be combined into a single device, which will be detailed in Chapter 6.

6
Detailed design

Previously, preliminary designs were made and their performance estimated (Chapter 5), leaving only the best preliminary designs to be combined and detailed. In this chapter, the last part of the third research question will be answered:

"What solutions are possible, which is the most suitable, and what does the solution look like in detail?"

The final detailed design will be presented in this chapter, detailed for the most common configuration, as per the scope. The main frame was left unchanged as much as possible, as no particular problems were found with the frame.

The details will be shared in the same order they were designed, starting with the Selective Grabbing solution (Section 6.1), shown in lightblue in Figure 6.1. After that, the Transferring solution is presented in Section 6.2, shown in orange and green in Figure 6.1. Then, in Section 6.3, a full cycle of the device is shown to fully grasp its workings.

Also, the final research question will be answered in Section 6.4:

"How does the solution perform compared to the current system, and does it satisfy the requirements?"

To answer this last research question, the performance of the redesign will be estimated first in Section 6.4.1. This will then be compared to the performance of the current device in Section 6.4.2. Lastly, the requirements of the system will be verified in Section 6.4.3.

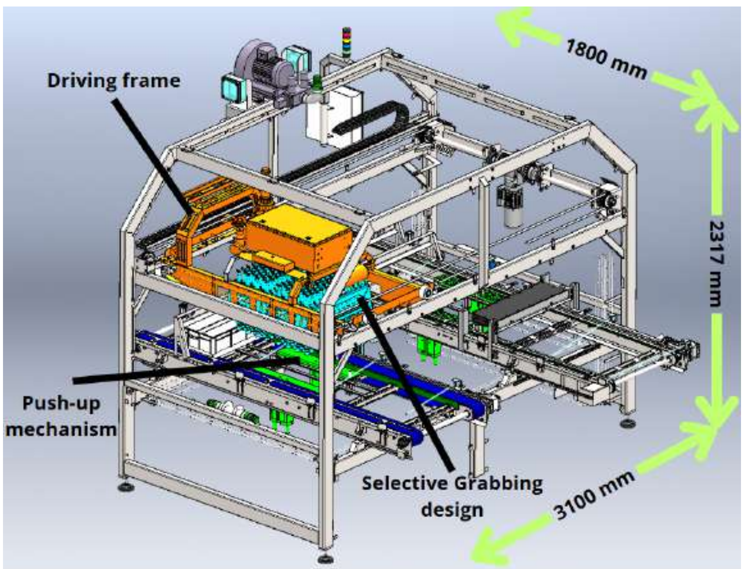
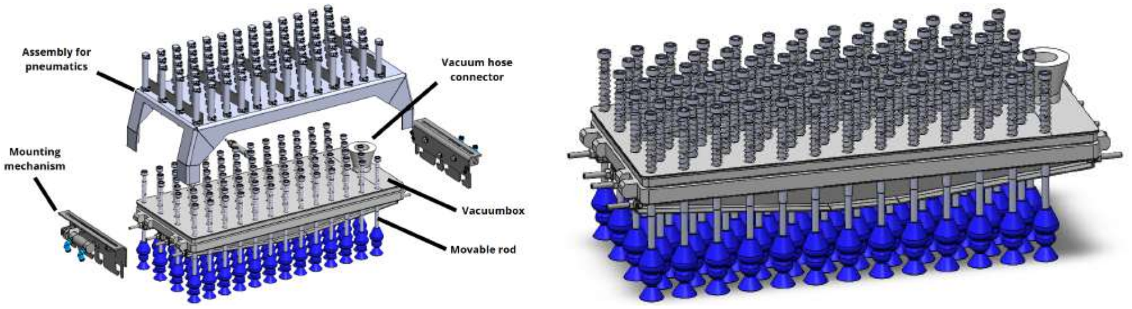


Figure 6.1: CAD model of the full detailed design

6.1 Selective Grabbing design



(a) Exploded view of the Selective Grabbing solution

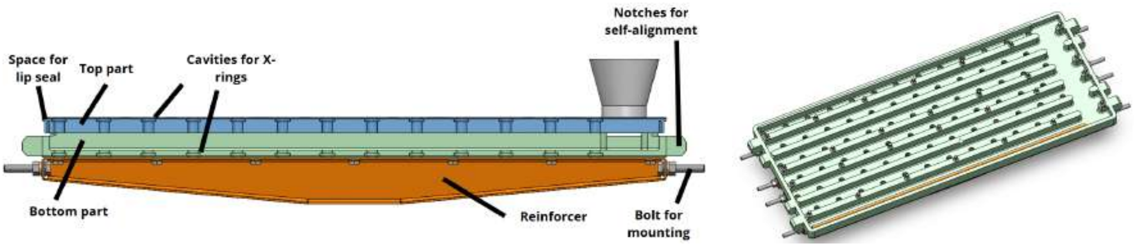
(b) Main overview of the vacuumbox

Figure 6.2: The detailed Selective Grabbing solution

The idea of the new Selective Grabbing design was to create a vacuumbox with guaranteed accessibility, to prevent known problems with suction systems in a dirty environment. This is achieved through a removable vacuumbox design, as shown in Figure 6.2b, which can be accessed and opened, and thus be thoroughly cleaned. The full Selective Grabbing assembly is shown in Figure 6.2a.

Pneumatic cylinders are used to move rods in order to prevent touching banger eggs and vacuum deficit, and a soft bellow suction cup is used to account for egg size and orientation differences. In the following sections, all components will be shown in detail.

6.1.1 Vacuumbox



(a) Cross-section of the vacuumbox, parts are colored

(b) Vacuumbox with the top removed

Figure 6.3: The detailed vacuumbox

To achieve the greatest accessibility, the vacuum box was made removable, so it can be inspected and cleaned properly. The vacuumbox consists of a top and bottom part, as depicted in Figure 6.3a, made from POM. A lip seal is used to create a vacuum-tight connection between the two parts.

The top and bottom parts have holes matching the pattern of the tray, through which the movable rods can slide. Vacuum-tight sealing of the rods is done using X-rings. X-rings are used instead of conventional O-rings, as they usually have less friction, wear, and do not experience wrinkling in dynamic sliding applications. The material of the X-rings is chosen to be FKM, which should perform better against the chemicals used for cleaning and have a lower coefficient of friction than EPDM or NBR [58].

POM was chosen as the main material for the vacuumbox, as it is strong (Tensile strength of 71.5 [MPa]), not very flexible (E-modulus of 2.6 [GPa]) and has good resistance to many chemicals, fatigue, and continuous loading [59]. Stainless steel was also considered, but this resulted in a very heavy vacuum box, especially since the X-rings have to be locked up, which requires at least 6 [mm] of thickness. POM can be machined easily, allowing for smooth radii and surfaces everywhere, increasing the cleanability. The highly accurate machining process is also used to achieve a tight fit on the moving rods to increase their stability by decreasing their play.

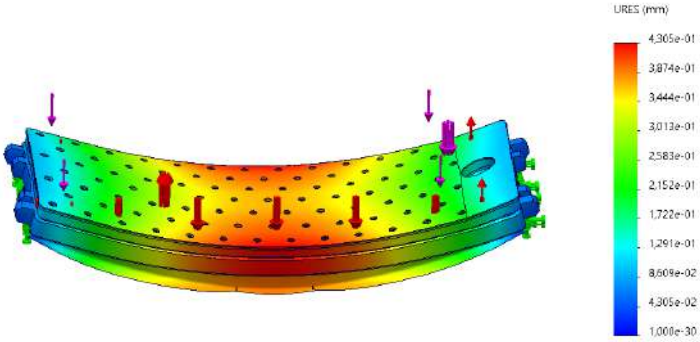
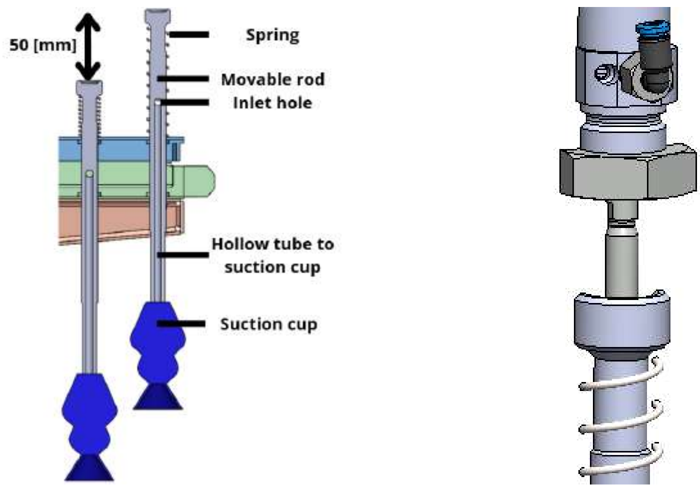


Figure 6.4: FEM analysis of the vacuumbox using reinforcers

FEM analysis showed that using only POM, the vacuumbox would bend several millimiters due to the large spring force (Section 6.1.2) on the top part, even though strengthening ribs were already added (visible in Figure 6.3b). Large displacements are undesired, as they can cause misalignment of the holes through which the rods move, causing a jam. Stainless steel reinforcers were therefore added to the bottom part, decreasing the deflection to a maximum of 0.4 $[mm]$ with the springs used, as depicted in Figure 6.4. The top and bottom parts of the vacuumbox are also connected by several metal pins to make sure no lateral movements between the top and bottom holes occur.

Different tray sizes require different vacuumbox sizes and patterns. The reinforcers are designed for the configuration with the largest span, and thus the largest load. The reinforcers should thus suffice for other tray types as well. Other tray types can be accommodated by changing the hole pattern in the vacuum box and, if needed, increasing the length and amount of reinforcers of the vacuum box.

6.1.2 Movable rods



(a) Cross-section of the movable rods in the vacuumbox

(b) Blunt connection between the pneumatic cylinder and the rod

Figure 6.5: The detailed movable rods

The movable rods are made of POM as well. They are hollow inside and allow for a suction cup to be mounted to the end. Every rod can be pushed down individually by a pneumatic cylinder. The inlet hole of the movable rod is inside the vacuumbox when pushed down, as visible at the left movable rod in Figure 6.5a. If the movable rod is not pushed down, the inlet hole is above the vacuumbox and the vacuum inside the suction cup is relieved.

The rods are pushed up by a spring to prevent the need for a fixed connection to the pneumatic cylinders used for pushing them down (Figure 6.5b and section 6.1.3). The required spring strength depends on the friction of the X-rings, which, due to time, could not be experimentally established. Literature about O-rings was used to estimate that the friction of an X-ring would be at most 3 [N], as this occurred in O-rings of a larger diameter in the same application [60]. Stainless steel springs with a compressible length of 70 [mm] and a spring constant of 0.54 were chosen, which can only extend 55 [mm] before they are limited in movement by the cylinders above them. The springs thus always exert over 8 [N] on the vacuumbox, as a pre-tension, to ensure that the rods overcome the static frictional force always, ensuring correct operation. The pre-tension also ensures the top and bottom parts are pushed together (as the bottom part is mounted to the main frame, Section 6.1.5), to ensure the lip sealing is effective.

The suction cups attached to the movable rods will be the same as those used in the current design. These 34 [mm] suction cups are special egg suction cups, and they apply around 5 [N] of force on the egg when fully compressed, which should not damage it (Section 3.3). They also allow for enough egg height difference compensation.

6.1.3 Pneumatics

As the movable rods need to be pushed down, cylinders are required. Pneumatic cylinders were chosen because of their high speed, force, and low price. They are mounted above every movable rod, as depicted in Figure 6.5b, using the frame shown in Section 6.1.3. The double-acting cylinders have a diameter of 16 [mm], a stroke of 50 [mm], and are moved down by 6 [bar] of pressurized air, individually controlled per cylinder with 3/2 valves, already included in the current design for the blow-off function. The lower side of the cylinder is continuously connected to a 1 [bar] pressure supply, acting as a return air spring once the 6 [bar] pressure is removed. The wiring scheme is shown in Figure 6.6.

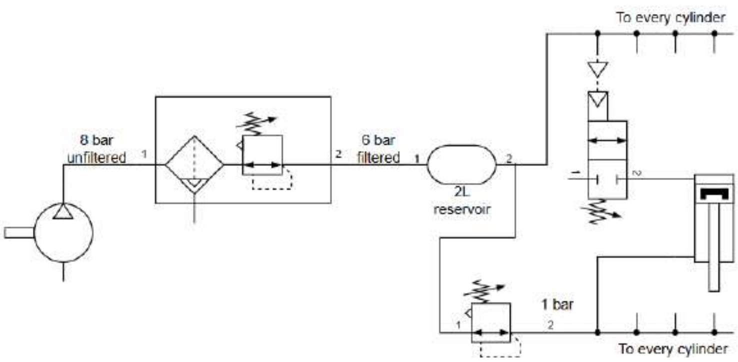


Figure 6.6: Pneumatic wiring scheme

If the movable rods are all moved down at the same time, it causes a high peak in air usage. To prevent problems, an air buffer tank of 2 [L] is used. This should contain more air than is required to move all 176 cylinders at the same time.

6.1.4 Vacuum system

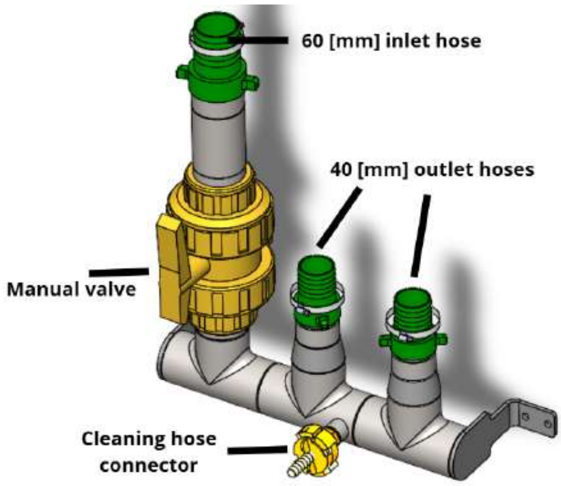


Figure 6.7: Detailed vacuum distributor assembly for the 2 HT88 configuration

The vacuumbox is connected to a vacuum system. Vacuum hoses go from the pump through a vacuum distributor, depicted in Figure 6.7, after which they connect to each vacuumbox using a Guillemin quick connector, required to remove the vacuum box. The hose diameters were chosen as large as possible to decrease pressure losses and loud noises.

At the vacuum pump, an electronically controlled valve is installed, which allows for controlling the direction and volume of flow.

Required vacuum pressure

The system currently uses a vacuum pump, which operates at 23 [kPa] of vacuum pressure, and suction cups that have a maximum and minimum diameter of 34 [mm] and 9 [mm], respectively. This means between 1.5 [N] and 20.9 [N] of force is exerted on the egg, depending on the actual contact diameter of the egg with the suction cup, which is hard to estimate. However, at least 5 [N] of force is exerted on the eggs, as shown in Section 2.2.2 step 3. Less than 1 [N] should already be enough to lift the eggs, and as this higher force could affect the hatchability of the eggs due to haircracks (Section 3.3), a lower vacuum pressure pump will be used. This smaller pump has the same airflow of 210 [m^3/h], but operates at 15 [kPa] of vacuum pressure, decreasing the forces on the eggs by 35 %, while also decreasing in cost.

Air evacuation time

With the current vacuum pump, about 0.2 [s] is used to evacuate air from the system, once the eggs are touched. The total internal volume of the vacuumbox and the movable rods is about twice the volume of air that had to be evacuated in the previous situation. However, the air leakage in the current situation is estimated to be way lower; no blow-off is used (which acts as large air leak), and air leakage past seals is typically orders of magnitude lower than the extraction rate of the vacuum pump [61, 62]. Using this information, and considering that a smaller vacuum will be used, it is estimated that less than 0.2 [s] will be required in the redesign.

$$t = \frac{V}{\dot{Q}} \cdot ln(\frac{p_0}{p_1}) \tag{6.1}$$

Using a common simple air evacuation time estimation, Equation (6.1), it is estimated that only 0.02 [s] is required to evacuate all air from the system. For safety, however, the 0.2 [s] currently used can be used again, as this only comprises a small part of the cycle time but highly affects the reliability.

Leakage due to bad sealing

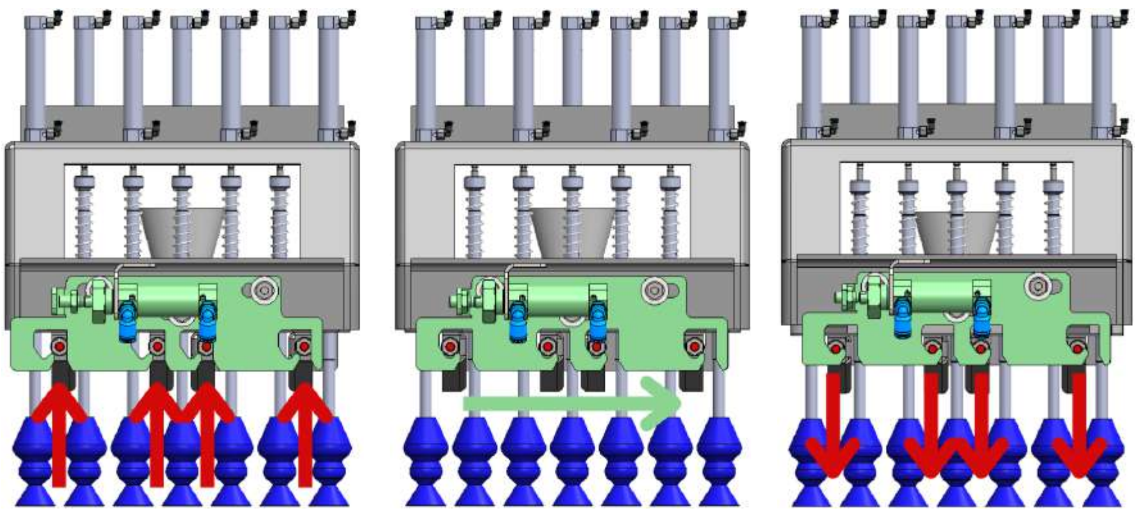
It is also important to consider leakage in case of a bad seal between a suction cup and an egg, which leaves an egg in the tray and consequently results in the movable rod leaking air. Saint-Venant's leak equation is commonly used to calculate the leakage rate through an orifice [63] [64]:

$$\dot{m} = C_d A \rho_0 * \sqrt{2(\frac{\kappa}{\kappa-1})\frac{p_0}{\rho_0}P^{2/\kappa}(1-P^{(\kappa-1)/\kappa})},\ \kappa = C_{v,air}/C_{p,air} = 1.4,\ P = p_0/p_1 \tag{6.2}$$

Calculating with $p_0 = 100000$ $[Pa]$, $p_1 = 80000$ $[Pa]$, and $A = 19.6E-6$ $[m^2]$ (a 3mm hole), this results ~ 5 $[m^3/h]$ of leakage if an egg is left behind because of a bad seal. A 210 $[m^3/h]$ blower fan should thus be able to handle at least 42 bad seals, which is 24 % of the 176 suction cups. This never happens in practice, according to Viscon experts. Increasing the hole size to 5 $[mm]$ increases the leakage rate to 14 $[m^3/h]$, allowing for 14 bad seals, which is still more than expected to occur.

6.1.5 Mounting mechanism

The full vacuumbox turned out to weigh around 17 $[kg]$, which is too much to comfortably lift out of the ST manually for cleaning. To solve this, an automatic mounting system with an input box was designed, as shown in the following pictures.



(a) The vacuumbox is pushed up to the correct height

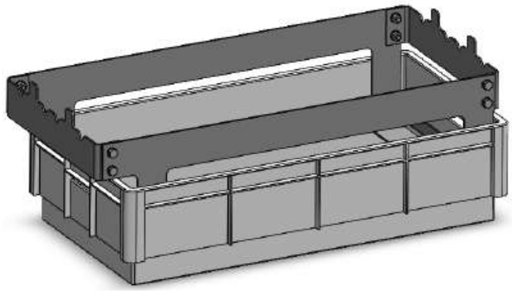
(b) The mounting mechanism closes

(c) The vacuumbox is released and seated through the spring-force

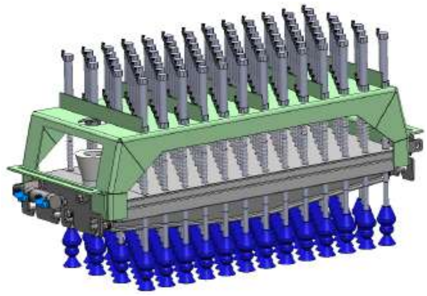
Figure 6.8: The detailed mounting system. The mounting bolts of the vacuumbox are shown in red, the mounting system is colored green.

To mount the vacuumbox, it has to be placed on the input basket, depicted in Figure 6.9a, which is placed on the basket conveyor belt. The input basket is then loaded onto the push-up system (Section 6.2.1), after which it is pushed up to the correct height (Figure 6.8a).

Carefully placed notches and chamfers take care of the alignment of the vacuumbox, after which the automatic mounting system closes using a pneumatic cylinder (Figure 6.8b). The push-up system then drops down again, and the springs make sure the vacuumbox is seated into the mounting system correctly, as shown in Figure 6.8c. The operator then has to manually connect the vacuum hose using the Guillemin connector. Demounting the vacuumbox requires the reverse operation.



(a) Input basket for the vacuumbox



(b) The full Selective Grabbing assembly is connected through a frame

Figure 6.9: Detailed components of the mounting mechanism. The main connecting frame is colored green.

All components are connected through a simple frame, shown green in Figure 6.9b, which can be adjusted in width easily, and should work for all sizes of vacuumbox. The frame is bolted onto the driving frame, where its position can be adjusted as required.

6.1.6 Cleaning of the full system

Cleaning of the system is very important to maintain correct operation. To do this, several steps can be taken.

Firstly, the whole assembly can be cleaned on the outside using high-pressure water and detergents.

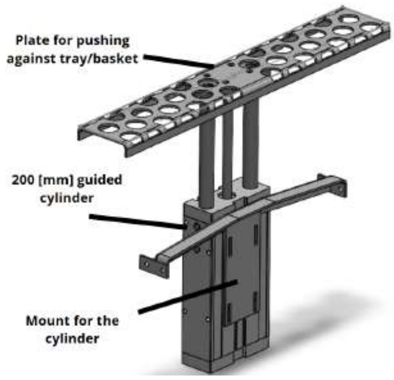
Secondly, the vacuum distributor contains a connector to which a hose can be attached. It is advised to flush the full vacuum system with cleaning detergents while the movable rods are in their lowered position. The system should then be flushed with water.

Lastly, the vacuumbox can be taken out and opened to inspect and clean the inside of it. The rods can be cleaned on the inside using a 5 [mm] pipe cleaning brush. To make sure no bacteria accumulate, the full vacuumbox should then be immersed in cleaning detergents, after which it has to be rinsed using water.

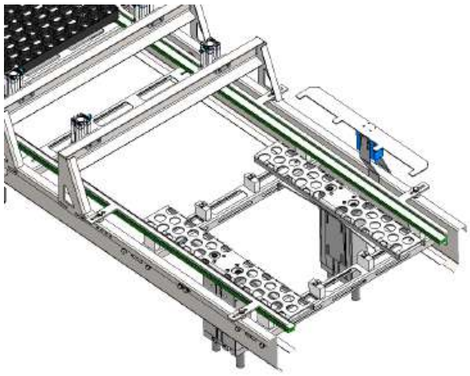
6.2 Transferring design

The redesign of the Transferring frame included a separate mechanism for the Z-movement and the Y-movement, to decrease complexity, costs, and increase cleanability. The push-up mechanism for the Z-movement is mounted between the conveyor belts (Section 6.2.1), and a driving frame is made to achieve the Y-movement (Section 6.2.2).

6.2.1 Push-up mechanism



(a) Overview of the push-up mechanism



(b) Two push-up units mounted in a conbeyor belt

Figure 6.10: The detailed push-up system.

For the push-up mechanism, a simple system was made (Figure 6.10a) that fits between the existing conveyor belts, with minor modifications. Two of these systems are used on each conveyor belt, one for each side of the trays/baskets, as shown in Figure 6.10b.

The system consists of a 200 [mm] stroke guided cylinder, a bent plate that pushes against the tray/basket, and a mount for the guided cylinder. Around 30 [mm] of adjustment in the Z-direction is available, so the final height of the trays and baskets can be fine-tuned. The system can experience a large load of over 1 [kN] when the vacuum box is mounted (due to the springs being compressed), so it has been designed for this load.

6.2.2 Driving frame

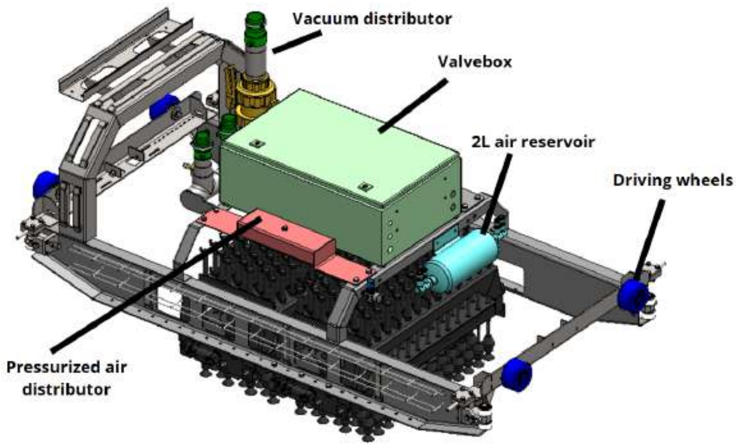


Figure 6.11: Detailed transferring frame with colored parts

The vacuumbox and its frame are mounted to the main driving frame, as depicted in Figure 6.11. This frame also hosts the air reservoir, valvebox, and pressure distributor box for the cylinders, and a vacuum distributor for the movable rods and vacuumbox.

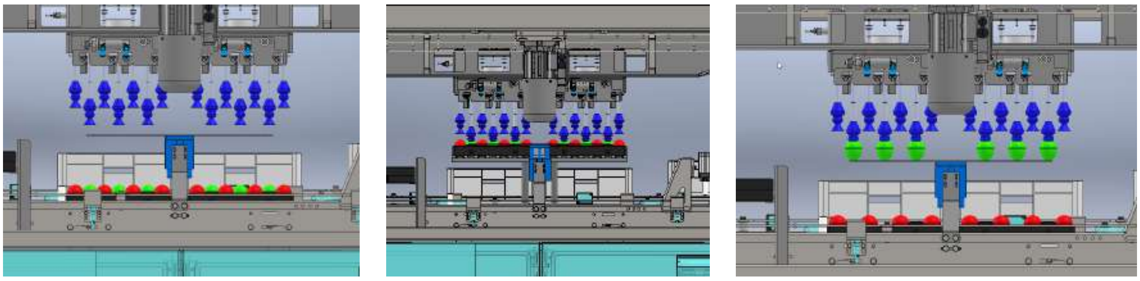
The frame drives over the current frame using wheels and is pulled by a belt, driven by a geared motor. This motor is chosen using Lenze software [65], and should be able to travel 1500 [mm] within 1.5 [s]. As the weight of the driving frame has decreased by 25 % to 134 [kg] compared to the prior art, the motor size does not have to be increased by much, and costs stay the same.

X-movement

If spacing between sets of suction cups, in the X-direction, is required, a sliding rod and bearing blocks can be placed between the vacuumbox frame and the driving frame. A pneumatic cylinder can be placed between the vacuumboxes to achieve the motion for the X-movement. This system is used in the current ST as well, and works without problems.

6.3 Working principle of the device

The software of the device is as important as the hardware, and without proper setup, the device will not function properly or reach its capacity. A single cycle of the device is therefore included as an example to clearly show its workings and ensure proper setup.



(a) Step 1: Move up all rods for eggs which should stay in the tray

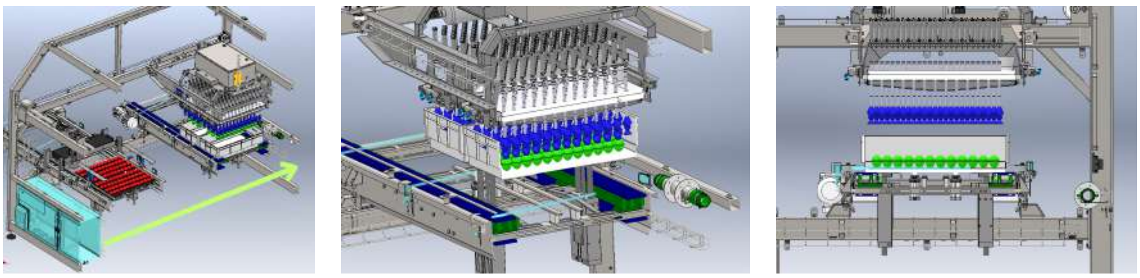
(b) Step 3: Push up the trays

(c) Step 6: Move down the trays, the eggs should stay on the suction cups

Figure 6.12: The first six steps of the cycle. The red eggs depict the undesired eggs, and the green eggs depict the desired eggs.

The cycle looks quite similar to the cycle of the original design, but there are some important changes. In the following list, every step in the cycle is explained.

1. 0.0 [s]: Wait for the trays to arrive. Move up all rods for eggs which are to be left in the tray (Figure 6.12a). This prevents contact with undesired eggs, such as banger eggs.
2. 0.0 [s]: Switch vacuum pump to blowing mode to remove loose dirt on the eggs
3. 0.0 - 0.8 [s]: Move up trays. This is the same speed as used currently, and the cylinders of the push-up system should be configured to match this speed. (Figure 6.12b)
4. $\sim$ 0.5 [s]: Switch vacuum pump to sucking mode.
5. 0.8 - 1.0 [s]: Wait for vacuum in the suction cups. This is the same period as is currently used, and without an airflow increase, the same period is required.
6. 1.0 - 1.8 [s]: Move down trays. This is the same speed as used currently, and the cylinders of the push-up system should be configured to match this speed. A spring-loaded mechanism mounted to the conveyor belt makes sure the tray is detached from the eggs. (Figure 6.12c)



(a) Step 7: Move the Y-axis towards the baskets

(b) Step 9: Push up the baskets

(c) Step 13: Move down the baskets, the eggs should stay in the baskets

Figure 6.13: The other steps of the cycle. The red eggs depict the undesired eggs, and the green eggs depict the desired eggs.

7. 1.8 - 3.3 [s]: Move Y-axis. The recalculated motor should be able to achieve a 1.5 [s] travel time. At the same time, the new trays can be swapped in. (Figure 6.13a)
8. $\sim$ 2.1 [s]: Move up the rods of the eggs which should be dropped between the conveyor belts, to release them.
9. 3.3 - 4.1 [s]: Move up baskets. This is the same speed as used currently, and the cylinders of the push-up system should be configured to match this speed. (Figure 6.13b)
10. $\sim$ 4.0 [s] Switch vacuum pump to blowing mode. The pump can be left on to release as many bacteria in the system as possible to the environment, which is preferred to blowing them on the eggs in the next cycle.
11. 4.1 - 4.6 [s]: Wait for the suction cups to release the eggs. This is the same period as is currently used, and without an airflow increase, the same period is required.
12. 4.6 [s]: Move down all rods.
13. 4.6 - 5.4 [s]: Move down baskets. This is the same speed as used currently, and the cylinders of the push-up system should be configured to match this speed. (Figure 6.13c)
14. 5.4 - 6.9 [s]: Move Y-axis back. At the same time, the new baskets can be swapped in.

6.4 Results of the redesign

In this section, the results based on the estimated performance of the redesign will be delineated.

6.4.1 Estimated performance

The performance must be known to be able to compare the redesign to the original design. This can be done using the design objectives defined in Section 5.1, as these points summarize the performance of the device.

However, the redesign has only been made digitally, as construction would take many months. Therefore, estimations were made for all design objectives, which are elaborated in the following sections.

The reliability

Reliability is the most important design objective. Without a prototype and actual testing, the reliability cannot be verified. The problems affecting the reliability of the current machine, however, are known (Section 2.3), and most of them have been solved: problems 1, 3, and 4 are addressed by the redesign. Problem 2 is accounted for by blowing on the eggs; however, testing is required to verify the effectiveness of this solution. The fifth problem should be automatically addressed by addressing all the other problems. Also, the maximum force on the eggs has been decreased from 15 [N] to around 11 [N], which decreases the chance of breaking or damaging an egg due to the suction force.

As no actual prototype has been made, a very conservative estimation will be done to account for unforeseen problems after construction. Solving all problems would result in perfect reliability, but a 50 % error margin will be taken, resulting in a reliability of 99.5 %. This conservative estimation still means that the amount of failed transfers is at least halved, and possibly even more.

The capacity

Currently, the capacity of the double HT88 configuration is around 22 [$eggs/s$]. With the calculated increased travel speed of the detailed design, however, the eggs can be transferred in 6.9 [s], resulting in 25.5 [$eggs/s$] for the same tray configuration. This specific capacity was aimed for due to the set requirements, but further improvements can be achieved by increasing the motor speed, as the current maximum acceleration of 3 [m/s^2] does by far not exceed the maximum egg acceleration of 9.81 [m/s^2].

OPEX

Another important design objective is the OPEX, which is difficult to estimate. No big changes in daily cleaning costs are expected, as more manual cleaning is required, but the cleanability should have increased. Maintenance costs can increase due to the many pneumatic cylinders, but pneumatic cylinders are generally rated for millions of cycles [66] under normal conditions.

The OPEX is expected to change mostly because of the decreased error correction required, due to the increased reliability. It is assumed that it can thus at least be halved to 0.25 FTE, as the failure rate has halved.

CAPEX

The capital expense for this device can be split into the costs of the materials and the costs of construction. The device has a lower complexity (Section 6.4.1) but is harder to align, as this cannot be done through software but through hardware adjustments. The building costs will therefore be assumed to be similar.

For the materials, the costs of the main components were calculated, using the costs registered internally at Viscon in June 2025. The redesign does not require a second geared motor with controller, has several fewer sliding bearings and sliding rods, and uses a cheaper vacuum motor, saving a total of €2850. However, 176 cylinders and a vacuumbox assembly are added, as well as four guided cylinders for the push-up system. In total, this adds up to around €5080; meaning the original price of the ST would increase by 3 %. However, possibly the error-correction unit will not be required anymore if the reliability turns out to be nearly perfect, if the costs of lost eggs do not justify the OPEX and CAPEX of the tray reject unit anymore.

Complexity

The current device has 7.3k parts in SolidWorks, which are all concentrated in the transfer head. The new solution has 7.8k parts, but they are spread across multiple systems, and several components are used multiple times, resulting in decreased complexity for assembly and maintenance. The process steps of both devices are similar.

Space efficiency

The space efficiency was the least important design objective, and no attention was put towards it. Due to time constraints and the absence of problems, the current frame was reused. This means the space efficiency has not changed. However, there is enough space in the frame to make it smaller if required in the future.

6.4.2 Performance comparison

A comparison can be made using the estimated performance of the redesign and the measured performance of the old device. Table 6.1 presents this comparison.

Table 6.1: Performance comparison between the measured old design and the estimated redesign

Design objective		Weight	Current value	New value	Improvement
1	Reliability	30 %	99 %	99.5+ %	0.5 %
2	Capacity	25 %	22 $[eggs/s]$	25.5 $[eggs/s]$	3.5 $[eggs/s]$
3	OPEX	20 %	up to 0.5 FTE for error correction, 0.25 FTE of daily cleaning / maintenance.	up to 0.25 FTE for error correction, 0.25 FTE of daily cleaning / maintenance	0.25 FTE
4	Space efficiency	5 %	68 %	0.68 %	0 %
5	CAPEX	10 %	€66k	€68.2k	€2.2k
6	Complexity	10 %	$\sim$ 7.3k parts, all in transfer head	$\sim$ 7.8k parts, spread over multiple systems	500 more parts, but lower density

From the table it can be concluded that the device has improved on all design objectives, except for the CAPEX. The increase is only 3 %, however, and it might even decrease if the tray reject system turns out to be redundant.

Especially the improvements in reliability and capacity could save a lot of problems and money. As stated in Section 1.2, eggs are worth around €0.25, and millions of them are processed every week. The increased reliability thus saves hundreds of euros every week. The decreased OPEX also contributes to saving money, and all of these values are still estimated conservatively.

6.4.3 Requirement verification

A list of requirements was set up in Section 4.2, to which the design should comply. In Table 6.2, the theoretical performance of the redesign is tested against the requirements to check whether it suffices.

Table 6.2: Requirements fulfillment of the redesign. NB.: MH = Must-Have, NH = Nice-to-Have

Requirement		Category	Significance	Fulfilled?
1	Only specified eggs should be transferred, which is between 5 - 95 % eggs in a tray	Reliability	MH	Yes
2	Eggs should not be damaged or contaminated by the transfer	Reliability	MH	Yes
3	It must conform to hygiene standards	Hygiene	MH	Yes
4	The most common egg sizes / weights must be supported, with D = 40 - 48 mm, H = 50 - 68 mm and M = 25 - 75 g	Functional	MH	Yes
5	It must be possible to deliver both living and dead eggs separately	Functional	MH	Yes
6	The most common tray/basket types must be supported without major modifications	Functional	MH	Yes
7	The capacity must be higher than the current bottleneck of 22 $[eggs/s]$ in the full transfer process, when the input and output belts are 1500 $[mm]$ apart	Performance	MH	Yes
8	The capacity should be 15 % higher than the bottleneck in the transfer process for future-proofing	Performance	NH	Yes
9	It must fit within the design space height of 2680 mm	Constraint	MH	Yes
10	It should fit through the doors of a hatchery without disassembly, which are at least 2500 x 2500 mm^2	Constraint	NH	Yes
11	The footprint should be lower than the current footprint	Constraint	NH	No
12	Production cost should be lower than the total current production cost of €66k	Economic	NH	No

As shown in the table, all requirements are fulfilled, except for non-compulsory requirements 12 and 13. While requirement 12 is not fulfilled, the footprint has also not increased, and the footprint could be decreased, as quite some open space is still left in the device. The total costs have increased by 3 %, hence why requirement 13 is not fulfilled.

6.5 Conclusion

The detailed design has been described in previous sections, answering the last part of the third research question and the fourth research question.

The detailed solution consists of a vacuumbox with suction cups that can move up or down individually to avoid contact with banger eggs. When moved down, the suction cup touches an egg, and suction flow is supplied through the vacuum box to create a vacuum in the cup, lifting the egg. The entire vacuumbox, including the suction cups, has been made removable to guarantee cleanability through accessibility. The vacuum system has also been revised, reducing the applied forces on eggs by over 25 %.

The vacuumbox, the toolhead, is mounted to a moving frame that can move from the input to the output belt. Compared to the prior art, the motor size has increased, increasing the capacity to the required level. Vertical movement of the trays and baskets is achieved through pushing them up from underneath, between the snares of the conveyor belt.

The redesign is estimated to match or outperforms the current solution on all design objectives, except for the CAPEX, which increased by 3 %. Important steps are made on the most important design objectives, such as reliability and capacity, which should theoretically save a lot of time and effort in the egg transferring process. The device also became more appealing to hatcheries, as the device now complies with hygienic regulations, due to the guaranteed accessibility to the vacuum system. All mandatory requirements are satisfied as well, confirming the suitability of the redesign to fulfill its function in the transfer line.

In the final chapter, Chapter 7, several conclusions will be drawn and recommendations for future research will be given.

7 Conclusion and recommendations

7.1 Conclusion

Commercial hatcheries worldwide use a transfer process to transfer incubated eggs from special incubation trays to baskets optimized for hatching. Selectively transferring eggs with a living embryo reduces embryo and chick mortality caused by accumulated bacteria in the dead or unfertilized eggs. In recent years, this selective transfer process was automated by companies such as Viscon.

This thesis aimed to improve Viscon's Selective egg Transfer (ST) device, as many undesired transfers or missed eggs are caused by the identified reliability and cleanability problems, mostly concerning the vacuum system of the device. Especially as the current ST presses suction cups on banger eggs, eggs with bacterial accumulation within, as these eggs are prone to bursting and consequently spreading bacteria and sticky egg yolk into the suction system. Also, the capacity of the device was found to be a bottleneck in the complete transfer process, which should be addressed for future-proofing.

Important properties of eggs were first identified, such as the maximum contact forces and accelerations of an embryo. It was found that forces should be limited as much as possible: above 22.7 $[N]$ should be avoided to prevent cracking of the eggs, but even forces as small as 5 $[N]$ can already have an effect on hatchability because of haircracks [18, 3]. Accelerational forces of the ST should also be limited to 1G, to avoid damaging the embryo [22].

State-of-the-art investigation revealed several viable gripping methods for eggs, but most methods, except for SPA, vacuum, and PSEM grippers, would not suffice for the specific environmental requirements of the ST. Several ideas were then systematically compared using the Delft Design Method [49], resulting in a single best-scoring solution. This solution uses suction cups on rods that can individually move in the vertical direction to avoid contact with the banger eggs. The rods move through an openable vacuumbox, which can be removed from the ST automatically, enabling accessibility and cleanability.

Conservatively estimated, the improved design should at least halve the amount of unsuccessful transfers because of the change in working principle and the over 25 % reduction of forces on eggs. The initial investment increased by €2200 (3 %), but the higher reliability should significantly reduce operational costs and costs associated with lost eggs, saving hundreds of euros every week of operation. The device also became more appealing to hatcheries, as it now complies with hygienic regulations, due to the guaranteed accessibility to the vacuum system. The new system also has a lower part density and variation, as well as increased accessibility, which is why maintenance and cleaning costs are expected to decrease further. The design can thus be implemented in hatcheries to increase the efficiency and performance of the transfer process.

7.2 Discussion and recommendations

The redesign presented in this thesis resulted in a substantial improvement for the transfer process in hatcheries, yet several recommendations can be made for future research. First of all, there is a lack of publicly accessible research on fertilized egg handling. While much research has been done on handling eggs for consumers, this does not integrate the effects of forces and accelerations on embryos. Companies such as HatchTech [5] have done internal research on this matter, which is not publicly available. However, for further optimization of processes within hatcheries, engineers should have publicly accessible safe acceleration limits available to be able to push the boundaries of automation.

Secondly, there is currently limited research available on X-rings. These rings are particularly interesting for sliding applications, but data on, e.g., friction coefficients is still missing in scientific literature.

The final design in this thesis also leaves room for future research. Testing should be done to confirm the static and sliding friction forces encountered in the movable rods, due to the X-rings. This could have a large effect on the required spring strength, and consequently, the forces and required strength of the vacuumbox and surrounding components.

Constructing and testing a full-scale prototype can also help in revealing new and unforeseen design challenges. For example, theoretically, differences in actuator timing might cause problems with the push-up system or compromise the stability of the vacuumbox.

As per the scope, other devices in the layout of the transfer line were left as is. However, devices such as the in-ovo vaccination device might be combined with the ST, possibly improving several design objectives such as the OPEX, space efficiency, and CAPEX. A change in the transfer line layout, e.g., by joining the input and output belts, might also lead to increased performance as no travel movement would be required anymore. Future research could look into these options.

A
Scientific Research Paper

The research paper begins on the next page.

Improving Egg Transfer in Hatcheries: A Redesign of Viscon's Selective Egg Transfer

E. Schokker, W. van den Bos, D.L. Schott
Department of Maritime and Transport Technology, Delft University of Technology

***Abstract*—This paper delineates the redesign process of a very high-capacity selective egg transfer device. This device is used in hatcheries to selectively transfer eggs with live embryos from incubation trays into hatching baskets, while the other eggs are left in the trays. Reliable and hygienic selective transfer is essential to achieve high hatchability and low mortality, but this is compromised by severe shortcomings encountered in the current design.**

The research contains a comprehensive analysis of the current device and environment, which revealed several shortcomings, especially with the grabbing mechanism of the current device. Thorough literature and patent research was done to identify important design limitations and possibilities for handling eggs. Several designs were then created, which were assessed and compared using the weighted criteria method and set design objectives.

The best-scoring design was then designed in detail. It consists of a removable vacuumbox with movable rods, which can avoid contact with eggs infected with bacteria. The modular design of the system enables thorough inspection and cleaning, theoretically eliminating most of the problems encountered with the prior art while improving its capacity.

***Keywords*—poultry, design, egg handling, high-capacity, FEA**

I. Introduction

In chicken hatcheries, the answer to the famous chicken-and-egg problem is clear: it all starts with the egg, and each egg is worth a lot if it ultimately results in a successfully hatched chicken. Reliable automation has therefore been a key step forward for the processes within these hatcheries, increasing the maximum capacity to comply with the ever-increasing demand for eggs and chickens. However, automation in hatcheries comes with a few challenges. Eggs are vulnerable products, and handling should be done with the greatest care, as many factors can affect the hatchability of an egg. Cleanability and accessibility of the devices can also be challenging to achieve in practice, but are of a very high priority as dirt and bacterial accumulation promote dangerous diseases such as Salmonella, and can severely affect the hatchability and health of embryos [1].

Eggs within a hatchery are incubated in trays for around 18 days after arrival from a laying farm, after which they should be transferred to hatching baskets for the final 3 days of the hatching process. The incubation trays have a seat for each egg, required for tilting the eggs in the incubation process, whereas the hatching baskets have a flat bottom to allow for hatched chicks to walk around. The best hatching results can be achieved when only eggs with an alive embryo are transferred, as other eggs that were not fertilized or died earlier in the process have a chance of bacterial accumulation within. Leaving these eggs in the process significantly increases the chance of sickness or mortality of hatched chicks when they come into contact with these bacteria.

Fig. 1. Side view of the ST designed by Viscon

The transfer process consists of a few steps. Firstly, the incubation trays are unloaded from the trolleys in incubation cells onto a conveyor belt. The eggs are then scanned by a Live Embryo Detection (LED) system to determine whether they contain an alive embryo, and, if mandatory or desired by the customer, they are vaccinated in-ovo against diseases such as the bird flu. After that, the viable eggs are to be transferred to the hatching baskets. One device that does this, the Selective egg Transfer (ST) device shown in Figure 1, was previously developed by Viscon [2], an engineering company in 's Gravendeel, the Netherlands.

This study aims to improve the design of their ST, without changing other devices or the layout of the transfer line. The current ST design consists of a driving frame with a suction cup for every egg, which can be driven over a stationary frame from the input belt with incubation trays to the output belt with hatching baskets. Examples of an incubation tray and a hatching basket are shown in Figure 2.

The system process is shown schematically in Figure 3; it works by moving the transfer head down, pressing suction cups on all eggs in a tray, and enabling suction flow in them.

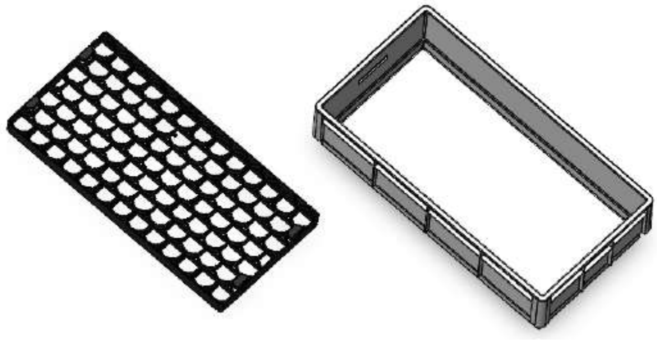


Fig. 2. Examples of an incubation tray (left) and a hatching basket (right).

The suction cups have a compressible soft bellow to account for the size differences of eggs. To leave the undesired eggs in the tray, a compressed air flow is enabled in the suction cups above these eggs, called a blow-off, preventing a vacuum from forming. The transfer head is then moved up with the desired eggs attached to the suction cups, after which it is driven towards the output belt. Finally, the suction flow is reversed to a positive pressure flow (a blower fan is used), gently releasing all eggs into the baskets.

Viscon has managed to make their design modular, making it suitable for the many types of trays and baskets used in hatcheries, which vary both in size, pattern, and egg count depending on the brand of the incubation and hatching machines. Typically, eggs are organized in a square or honeycomb pattern, and about 50 to 200 eggs sit in a single tray. The ST can also be easily customized to be able to release eggs without an embryo mid-air during the travel movement, if these are required for, e.g., making cattle feed. The device can also be customized to change the spacing between suction cups to accommodate for differences in pitch between the trays and baskets.

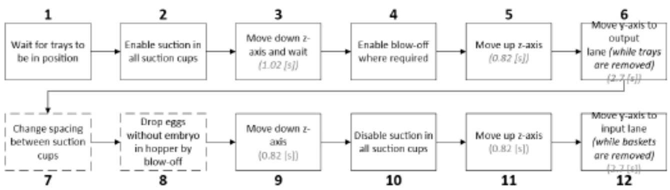


Fig. 3. Process schematic of the current ST

However, several shortcomings were identified with the Selective Grabbing mechanism. First and foremost, all eggs in the tray are touched by the suction cups. Up to 5 % of eggs, those without a living embryo, can erupt from even a slight impact due to bacterial gas accumulation inside the shell. Since the blow-off is also activated above these eggs, they have a high chance of erupting. The ejected egg yolk consequently causes clogs in the suction system and bacterial infection of embryos through the eggshell or the vaccination hole. It can also prevent a good vacuum seal from forming on the desired eggs, which causes them to be unintentionally left behind in the incubation tray. Such an improper vacuum seal can also happen due to eggs being dirty before they enter the transfer process, which comprises about 0.5 % of the eggs.

Occasionally, the opposite also happens, and undesired eggs are transferred as well due to a pressurized air deficit. This occurs primarily when eggs from old or low-quality flocks are used, and up to 95 % of eggs have to be blown off, more than the pressurized air system can handle.

At the very high capacity of the ST, which can process up to 80.000 $[eggs/hour]$, many eggs can get lost or infected due to these problems. It is estimated that about 1 % of trays are not transferred successfully, meaning without contaminating or leaving behind eggs. To counter the issue of leaving behind eggs, an error-correcting unit is regularly installed behind the ST, which uses an expensive sensor to detect eggs with a living embryo and notifies an operator to transfer the missed egg manually.

Every device in the hatchery is cleaned daily with chemicals to prevent dirt and bacteria accumulation. However, cleaning the current ST has turned out to be difficult, as the suction cups and the system behind them are inaccessible to cleaners. Bacterial culture testing has also proven that the automatic flushing and soaking of the suction system is ineffective. EU regulations for this industry require devices to be cleaned entirely before every day of use, without leaving chemicals behind, to which the suction cup system thus does not comply.

Viscon also calls for an increase in capacity, as the current system is one of the bottlenecks in the transfer process. An improvement of about 15 % is therefore needed to match other devices in the transfer line.

The research described in this paper aims to solve the abovementioned problems by redesigning the ST. A thorough literature and patent research was first done to establish design possibilities and boundaries when handling eggs, and to explore and evaluate potential solutions, as outlined in Section II. The detailed design of the best-performing concept is described in Section III.

II. CONCEPTUAL DESIGN

Firstly, two separate literature studies are described, regarding egg properties that could aid or limit the design, and to explore prior art and potential concepts for gripping eggs. Lastly, the design methodology and conceptual design phase of this paper are also delineated in this section.

A. Literature study on egg properties

Literature provides data on multiple studies describing egg properties that could affect the design, which is summarized in Table I.

First of all, cracking of the eggshell is known to affect hatchability. This can easily occur if the eggs are impacted or pinched. The so-called rupture force of an eggshell correlates positively with the thickness, shape, and eggshell weight, while the egg size, breed, and storage time are negatively correlated [3, 4, 5, 6, 7]. The recorded rupture forces range between

TABLE I
EGG PROPERTIES FROM SCIENTIFIC LITERATURE

Property	Value
Rupture force	≥ 22.7 [N]
Hairline crack force	≥ 5 [N]
Impact energy before cracking	≥ 1.90 [mJ]
Maximum acceleration	≥ 1G
Highest coefficient of friction	≤ 0.280

22.7 [N] between solid plates and 750 [N] between rubber compression plates [6, 7, 8, 9, 10]. However, forces as small as 5 [N] were shown to induce microcracks, invisible with the naked eye, which negatively affect the hatchability [11], and reverse loading also shows a reduced strength of the egg [12].

Impact on an egg can also cause cracking. The absorbed energy before rupture was quantified in several studies, and values range from 1.90 [mJ] when impacted by a stiff plate at a low speed of 0.33 [mm/s], to values above 6 [mJ] when dropped [7, 8, 13].

As reported by Besch et al. [14], accelerational forces can affect the hatchability of fertile eggs as well, as blood vessels and yoke sacs can break because of them. These effects have not been studied extensively, but some studies show a reduction in hatchability of 25 % when exposed to 1.8G accelerations for longer periods [15]. All studies on this topic, however, were done early during the incubation process, while the transfer occurs at the end of the process, which could cause different results. In the past, Viscon has cooperated with HatchTech [16], who performed internal research showing that machine accelerations of at least 1G can be used as a safe benchmark without affecting the hatchability.

Static friction coefficients were also briefly studied, revealing that both rubber and plywood show the highest coefficients of friction, with reported values largely ranging from 0.028 to 0.280 [7, 8].

B. Literature and patent study on prior art

Grippers are a vastly studied topic, and many gripper types and classes have been reported in scientific literature and patents. Useful concepts have been identified by systematically checking them against the available space in incubation trays, required capacity, egg shape, and required gripping force. Due to the specific requirements, most grippers could be eliminated for the application, except for grippers in the SPA, vacuum, and PSEM classes.

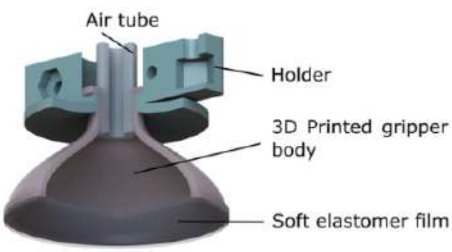


Fig. 4. Suction cup effect gripper [17]

One suitable gripper type was the suction cup effect gripper created by [17], among others. This gripper consists of a regular suction cup with a silicone film applied over the open end, as demonstrated in Figure 4. This gripper is pressed onto the object, after which air is evacuated from the suction cup. This results in the film being pulled into the air chamber, creating a low-pressure cavity between the film and the object and enabling it to lift the object. As the suction system is closed, no bacteria can enter it, removing the need to clean the inside.

Passive grippers were also found to be suitable, relying on the flexibility of the fingers to allow an object to enter, after which it is automatically enveloped or pinched. To release the object, it has to be pushed out again.

Most other grippers identified as suitable were found in the Passive Structure with External Motor (PSEM) class. This type of gripper uses friction-based or enveloping-based gripping and contains some arrangement of fingers, actuated through tendons or direct contact with the object.

C. Methodology and concepts

The design methodology depicted in Figure 5 was used to structure the unpredictable design process. This method is developed by Roozenburg and Eekels [18], but the prototype phase of their model was excluded in this effort due to time constraints.

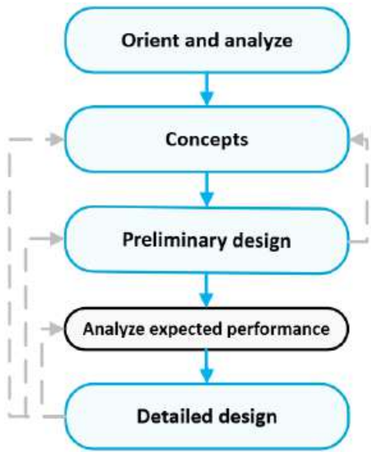


Fig. 5. Schematic of the global design methodology

Several out-of-the-box ideas, prior art, and ideas from scientific literature were gathered for each required function in a morphological chart, in the first phase of the process. Preliminary designs were then created by combining these concepts for each subfunction into complete systems. This was done individually for a Selective Grabbing (for selectively gripping the eggs) and a Travelling mechanism (for moving the gripped eggs from the input to the output), as these hardly affect each other, but simplify the design process when studied separately.

Five Selective Grabbing designs were created, which have the primary focus of the research since the foremost important problems, mostly reliability and cleanability-related, were caused by this mechanism. Seven travelling concepts were then created based on the chosen Selective Grabbing solution, to possibly improve the capacity and other design objectives. The main stationary frame of the current ST was chosen to be retrofitted to work with the final designs, as no problems with it were identified.

The performance on a set of design objectives and requirements was then estimated for every design, either through exploratory prototypes, calculations, or reasoning.

Several gripper-type solutions were investigated and prototyped, but they all require each individual egg in an incubation tray to be selectively pushed up above the tray because of the limited space in the trays, meaning hundreds of actuators are required for this push-up motion. Such a system, however, was expected and has previously been proven to cause many cleanability problems, as all dirt and chemical cleaning detergents end up on them due to their position underneath the conveyor belts.

Suction cup effect grippers were also looked at in more detail and prototyped, which revealed that a perfect seal with the eggs is always required when using such a gripper. This is because even the smallest gap would already cause the small volume of low-pressure air (Section II-B) to rapidly equalize with ambient pressure, leading to a complete loss of gripping force. A perfect seal, however, can not be guaranteed as eggs are irregularly shaped and positioned, and can be dirty.

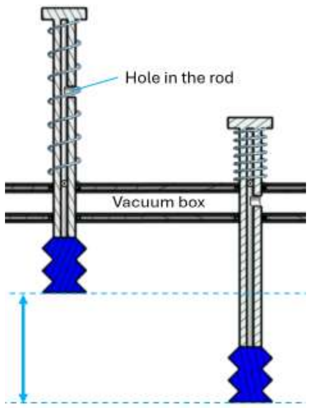


Fig. 6. Concept of the best-scoring Selective Grabbing design

The best performing concept, shown in Figure 6, consists of suction cups on hollow rods whose vertical position can be altered using a pneumatic cylinder, to avoid contact with eggs other than the desired ones and to prevent the need for a blow-off system. If an egg needs to be transferred, the suction cup is moved down onto the egg, and suction flow is enabled in it to create a vacuum. The suction flow is distributed by an openable vacuumbox through which the hollow rods, on which the suction cups are mounted, move. The vacuumbox is made to be automatically removable by the ST, allowing for regular cleaning and inspection, preventing dirt and bacterial buildup.

This concept is combined with the best-scoring Travelling design, which uses a push-up system to achieve vertical motion, and a belt and pulley system for horizontal motion between the input and output conveyor belt. Such vertical motion is required to avoid contact with the hatching baskets, which can be up to 150 [mm] high.

Section III will describe and depict the detailed design in more depth.

III. Detailed design

The final design was detailed for the most common tray and basket configuration, resulting in the ST shown in Figure 7. In this section, the design will be introduced, after which the estimated results will be shown.

A. *Final design*

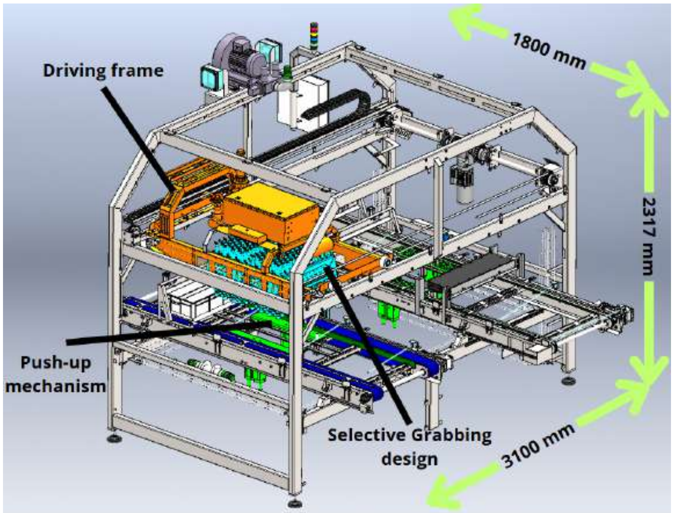


Fig. 7. CAD model of the full detailed design, the redesigned components are indicated and colored.

The main innovation is the Selective Grabbing design, as depicted in Figure 8. The movable rods move 50 [mm] through a vacuumbox when pushed down by their respective pneumatic actuator, and they return to their initial position by a spring. A hole in the rod allows air to flow through the hollow rod when in the lowered position. This approach using springs is required to be able to keep the vacuumbox assembly disconnected from the pneumatic actuators, making it removable and thus inspectable and cleanable. To ensure the movable rod always returns to its initial position, the spring must always exert at least 8 [N] on the rod to overcome gravity and frictional forces, even in the initial position.

Rubber X-rings are used on the rods to prevent leakage from the vacuumbox. These X-rings are associated with lower frictional forces, wear, and better vacuum-tightness in linear sliding applications than regular O-rings. The frictional forces resulting from them are estimated through literature about O-rings [19], as no closer literature was available.

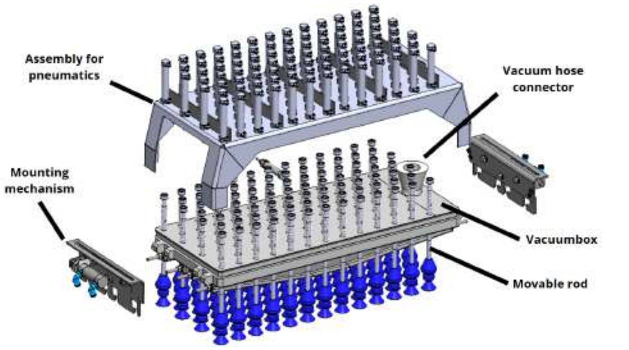


Fig. 8. Exploded view of the Selective Grabbing final design

The vacuumbox itself consists of a top and bottom part made from an engineering plastic, POM, with stainless steel reinforcements to withstand the large forces resulting from the movable rod return springs. The parts of the vacuumbox were iteratively designed using FEA analysis, and are CNCed to achieve several cleanability improvements through smoother surfaces and radii, and a lighter design weighing just over 17 $[kg]$ for the most common tray type, which contains 88 eggs. Different tray types can be accommodated by changing the size and hole pattern of the vacuumbox for the movable rods, to match it to the used tray type.

The prior art used a blower fan to achieve the suction flow. These fans achieve high air flow and low vacuum pressures, suiting the application well. The exact suction force exerted on the eggs is unknown due to the flexibility of the suction cup, but the compression of the suction cup shows it is over 5 $[N]$, possibly affecting the hatchability of the embryo. In the redesign, the vacuum pressure is therefore reduced by over 25 %, still maintaining plenty of lifting force and, as an added benefit, increasing the air evacuation speed.

An automated mounting mechanism is also included, as the design is too heavy to remove by hand at full reach. The ST can automatically release and pick up the vacuumbox after manually disconnecting the vacuum hose, using a special guidance system on the basket conveyor belt. Alignment during (de)mounting is achieved using several notches and chamfers.

Besides the Selective Grabbing solution, the Travelling design was detailed as well. One or multiple vacuumbox assemblies can be mounted to the driving frame shown in Figure 9, depending on the required capacity. Valves, reservoirs, and distributors for both the pressurized air and vacuum systems are mounted to it as well, and it is mainly made of stainless steel to prevent corrosion from cleaning detergents. The lateral motion of this frame is achieved by driving it over the main stationary frame, pulling it with a belt and pulley system. The travel time was decreased due to a reduced moving mass and different driving motor compared to the prior art, increasing the maximum capacity by 15 % to up to 90.000 $[eggs/hour]$.

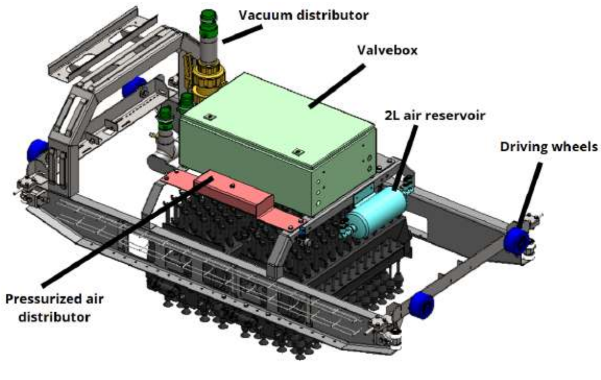


Fig. 9. Transferring frame final design

A push-up mechanism for vertical movement of the trays and baskets is fitted between the conveyor belts, resulting in decreased complexity, weight, and costs of the moving transfer head compared to the current solution, where all motion occurred within the moving frame.

B. Results

The redesign costs around €2.200 (3 %) more compared to the prior art, but it also outperforms it. Theoretically, most problems encountered with the original ST should be solved by the change in working principle. The problem of dirty eggs at the input was not explicitly accounted for in the design, but it will be addressed by blowing on the eggs using the blower fan when the trays are pushed up. The new design also decreases suction forces with the eggs by over 25 %, decreasing the chance of damaging an egg or embryo. Conservatively estimated and accounting for unforeseen problems after construction, these measures should at least halve the number of trays with an unsuccessful transfer, increasing the reliability to at least 99.5 %. Such an increase in reliability significantly reduces operational costs and costs associated with lost eggs, saving hundreds of euros weekly. The redesign should be more appealing to hatcheries, as it now complies with hygienic regulations, due to the guaranteed accessibility of the vacuum system. The new system also has a lower part density and part variation, besides the increased accessibility, which is why maintenance and cleaning costs are expected to decrease further.

IV. Discussion and Recommendations

This research resulted in a redesign that, in theory, will substantially increase the efficiency of the transfer process within hatcheries. Yet several recommendations can be made for future research.

First of all, some assumptions had to be made during the design process, which could not be backed up by scientific literature or prototypes. While much research has been done on handling eggs for consumers, the effects of accelerations and forces on embryos within industrial processes have not been studied much by the scientific community. Such studies, however, are essential to optimize the industry further. Also, little research on X-rings is yet available. These rings are particularly interesting for sliding applications, but data on friction coefficients, e.g., is still missing in scientific literature.

Secondly, the expected performance of the final design is currently based on estimations, as no prototype or full simulation of the device has been made. In future research, a prototype or simulation could be made to enable testing of the device, potentially revealing oversights in the final design. If the design turns out to be more reliable than predicted, it might even remove the requirement for the error correction system, significantly reducing operational and capital costs.

Finally, according to the scope, other devices in the layout of the transfer line were left as is. Further research could be done on combining devices within the transfer process, such as the in-ovo vaccination and the Selective Transfer devices, possibly improving the combined performance on the design objectives. Changing the transfer line layout, e.g., by joining the input and output belts, might also lead to increased performance as no lateral travel movement would be required anymore.

V. Conclusion

In conclusion, this research aimed to improve the design of a hatchery device that selectively transfers eggs with an alive embryo from incubation trays to hatching baskets. The prior art suffered several shortcomings, but by following a methodical design process, all of them could be addressed, significantly improving the expected performance.

The prior art and the transfer process were first analyzed to identify problems, requirements, and design objectives. Several issues were identified, mainly causing low reliability, poor cleanability, and subsequently resulting in bacterial accumulation and high operating costs.

Secondly, literature was consulted on the properties of eggs, which could aid or limit the concepts in the design process. Several important properties were established, which were accounted for in the design phase. Combined with patents, scientific literature was also used to systematically find viable gripping methods, which could be applied for handling eggs in the specific environment of the ST.

Next, functions and requirements were set up, and ideas were gathered in a morphological chart and combined into preliminary designs. Twelve preliminary designs were then explored more in-depth, and their performance was tested against several design objectives using the weighted criteria method. The most promising design consists of a removable and cleanable vacuumbox with suction cups that can move vertically, avoiding contact with eggs that should not be transferred. The transfer movements are achieved through tray and basket push-up systems and a driving frame, which can move between the input and output lanes.

Finally, the best-scoring design was detailed, resulting in a design that successfully meets the set requirements and solves all problems encountered with the prior art. Also, the suction forces on eggs could be reduced by over 25 %. This, conservatively estimated and accounting for unforeseen problems after construction, should at least halve the number of trays that are unsuccessfully transferred, increasing the reliability to at least 99.5 %. Subsequently, the operational costs decrease by hundreds of euros weekly, making it only a matter of weeks to return the initial extra investment of 3 %. The capacity was also increased by 15 %, the complexity reduced, and the ST now complies with hygienic regulations due to guaranteed accessibility and cleanability, ultimately resulting in a much more efficient and appealing Selective Transfer device for hatcheries.

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B
Morphological chart

The morphological charts begin on the next page.

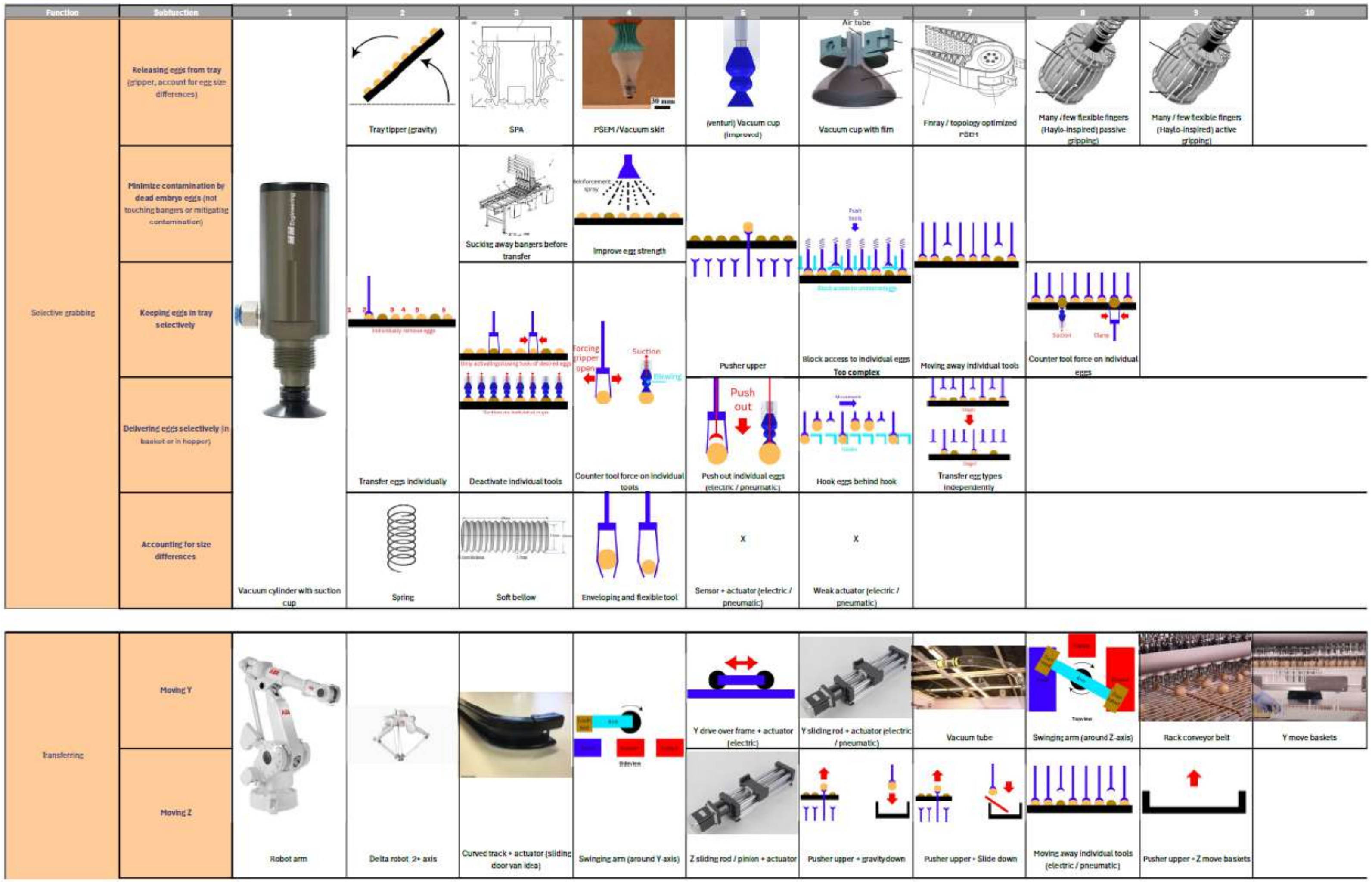

Figure B.1: The original morphological chart used for the design. Every row shows the concepts for each subfunction shown in the orange cells at the beginning of the row.

B.1 Complexity filter

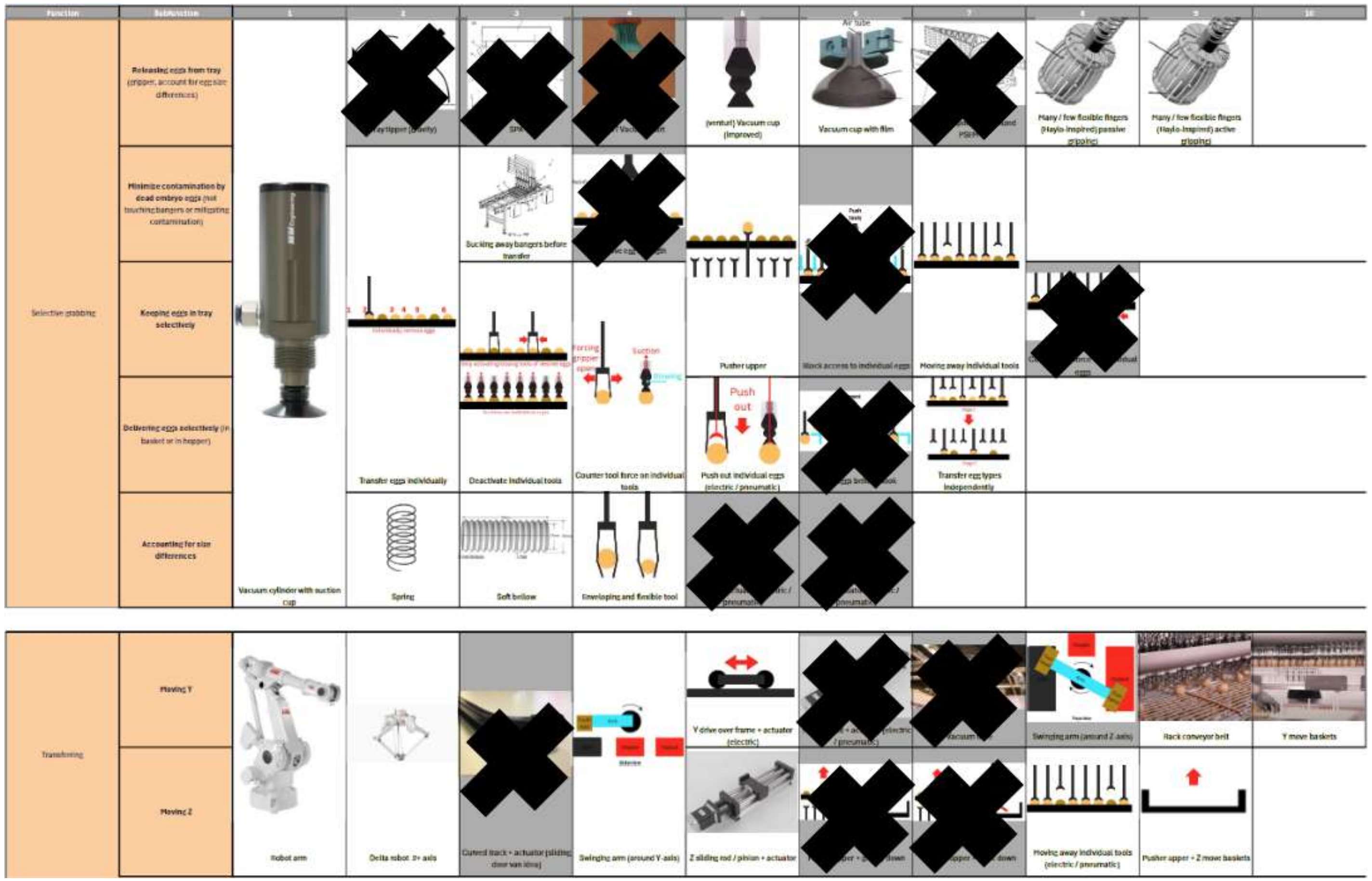

Figure B.2: The morphological chart with the abandoned concepts crossed out after the complexity filter was applied. This filter causes concepts that are predicted to be relatively complex to be filtered out. Every row shows the concepts for each subfunction shown in the orange cells at the beginning of the row.

B.2 Capacity filter

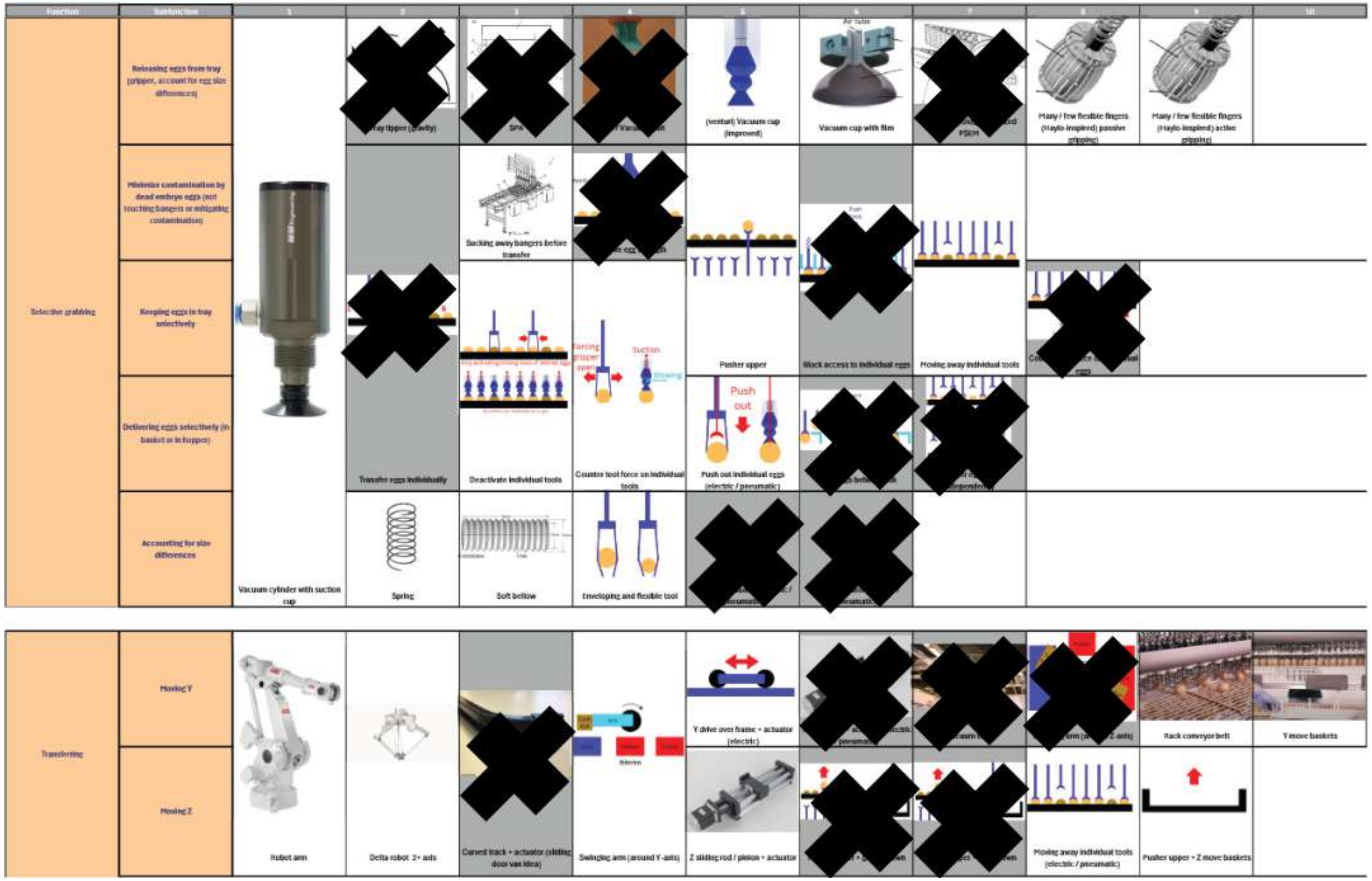

Figure B.3: The morphological chart with the abandoned concepts crossed out after the capacity filter was applied. This filter causes concepts that are predicted to support relatively low capacity to be filtered out. Every row shows the concepts for each subfunction shown in the orange cells at the beginning of the row.

B.3 Preliminary designs

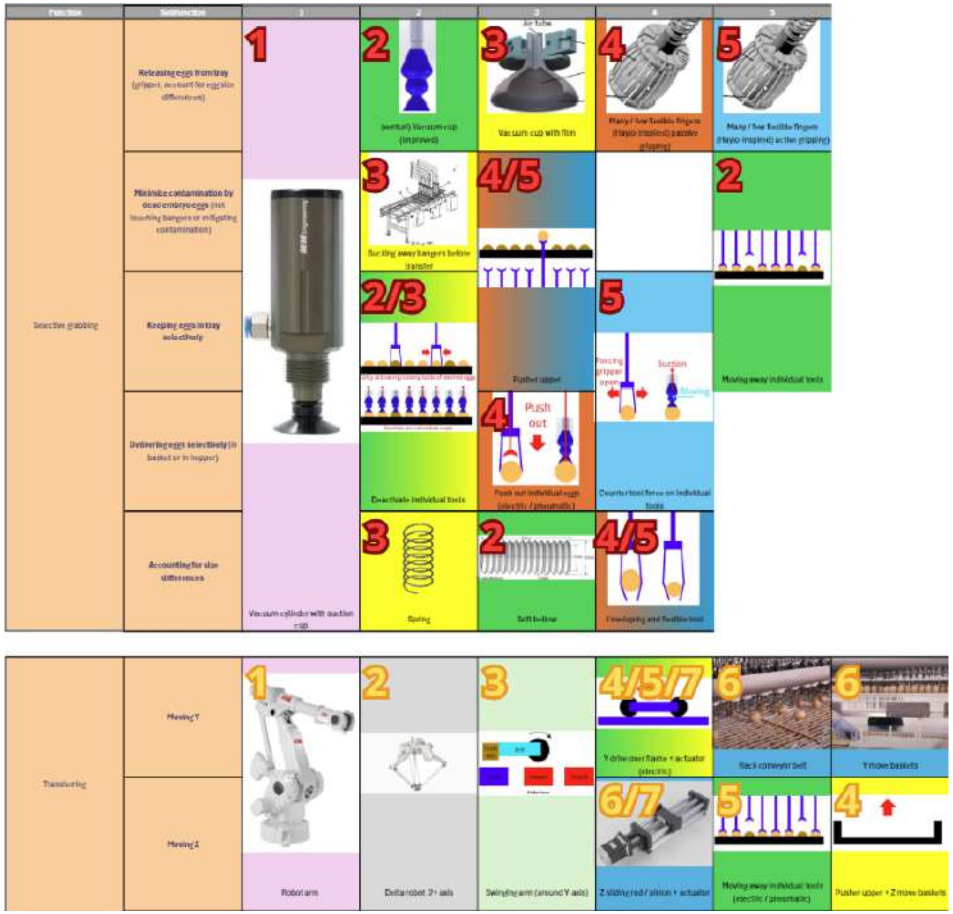

Figure B.4: The final morphological chart with the preliminary design combinations colored and numbered. Separate preliminary designs were made for the Selective Grabbing and Transferring functions. Every row shows the concepts for each subfunction shown in the orange cells at the beginning of the row.

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