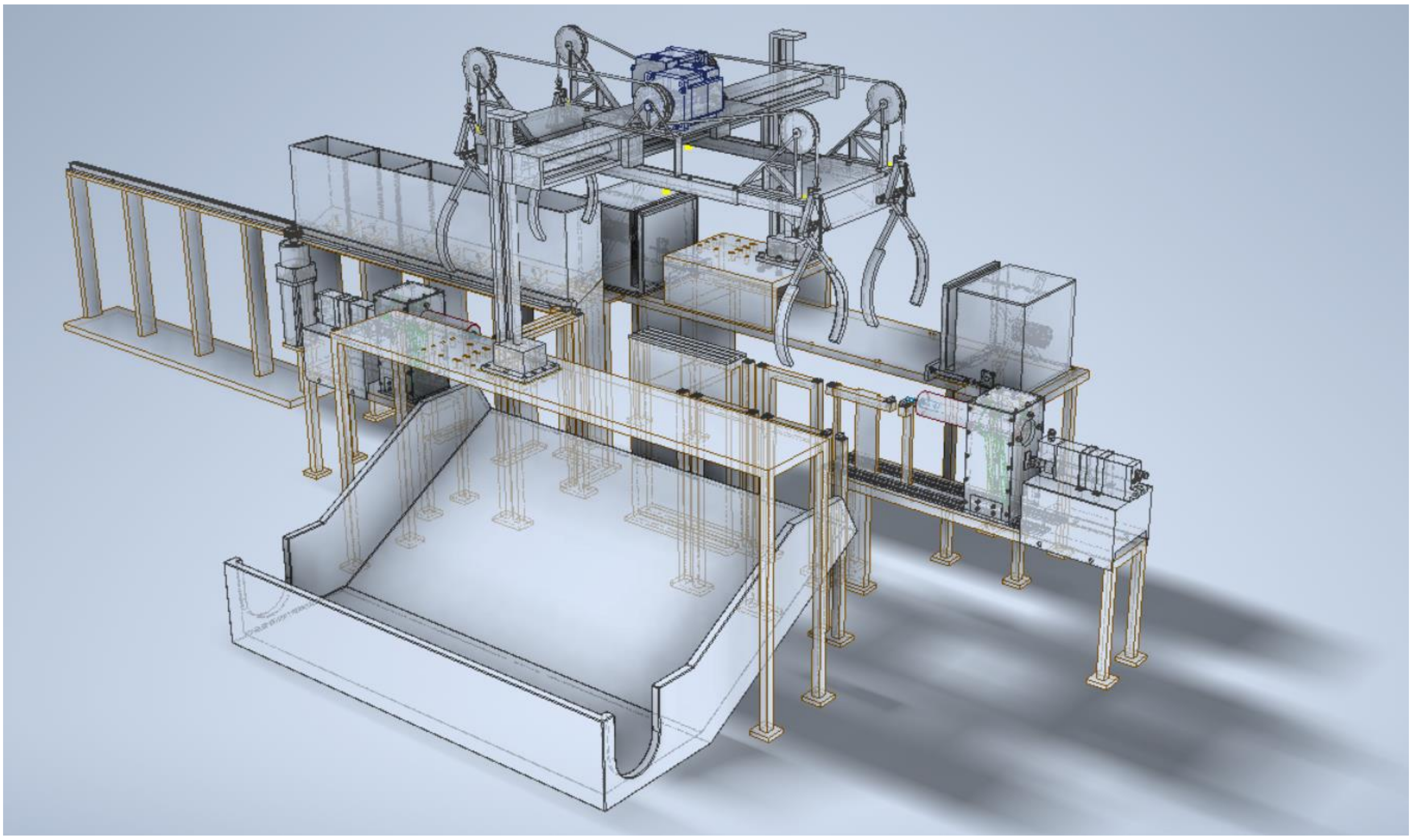
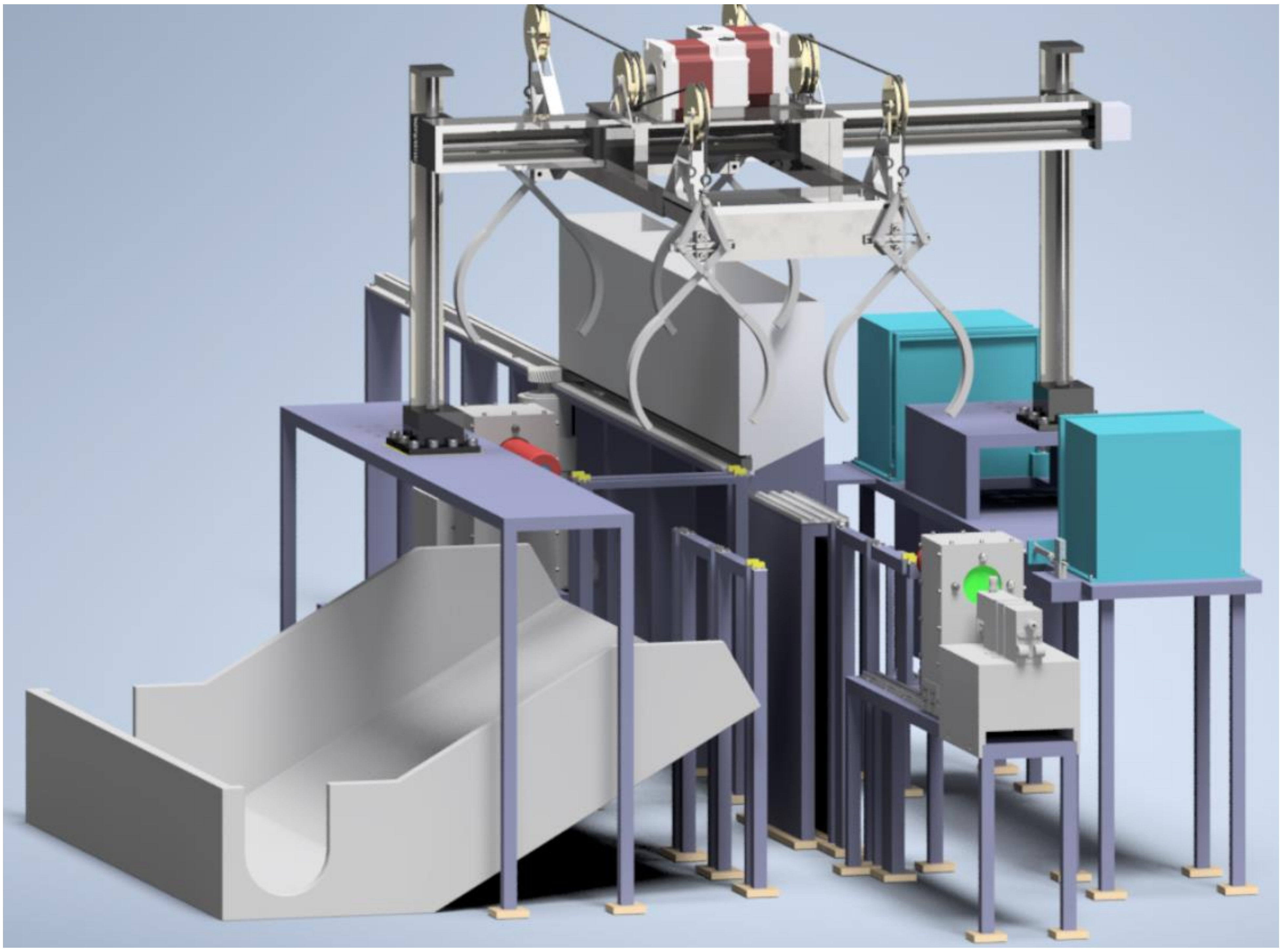


Group 39 Machine Design: Project Documentation

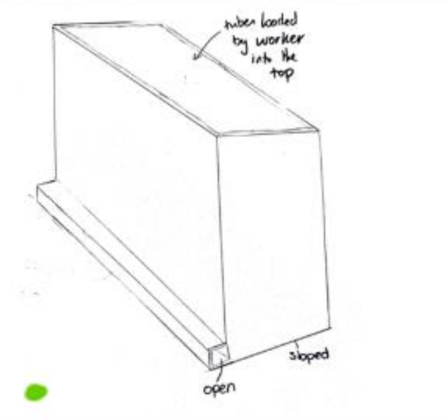
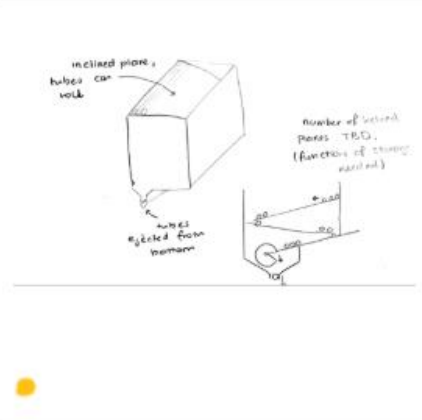
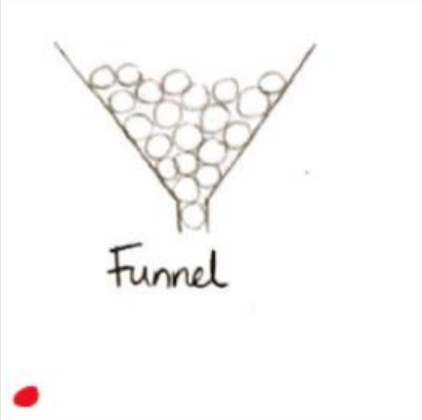
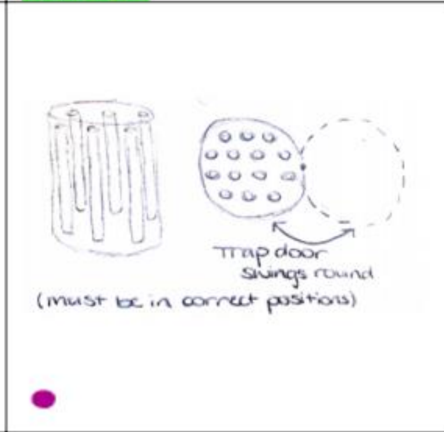
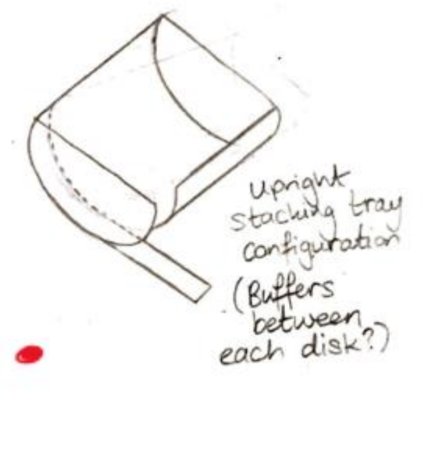
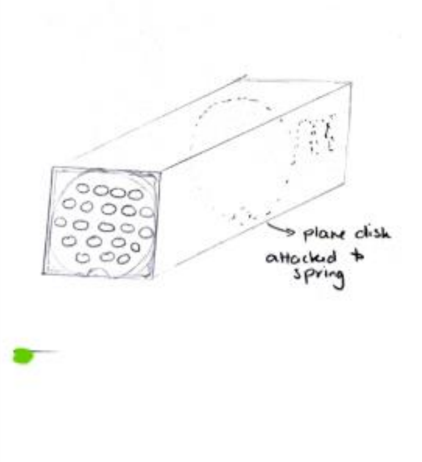
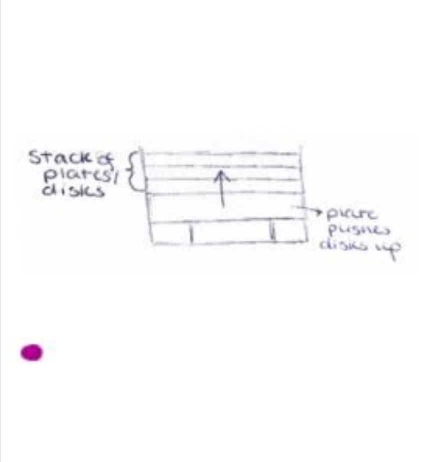
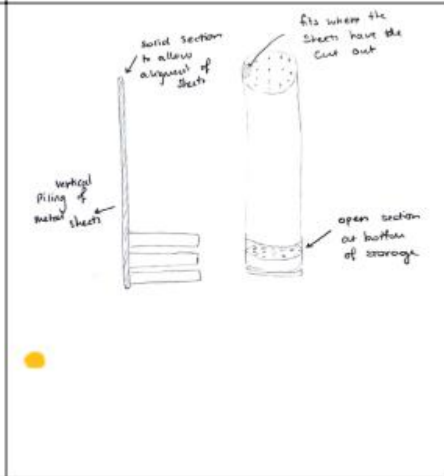
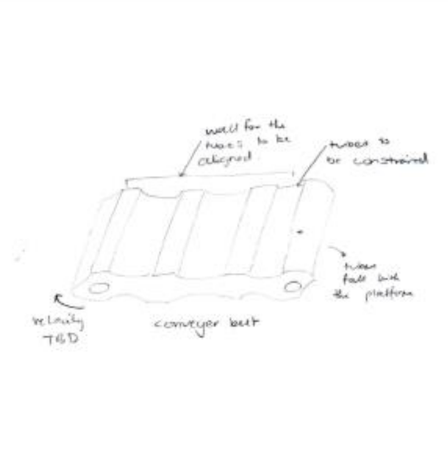
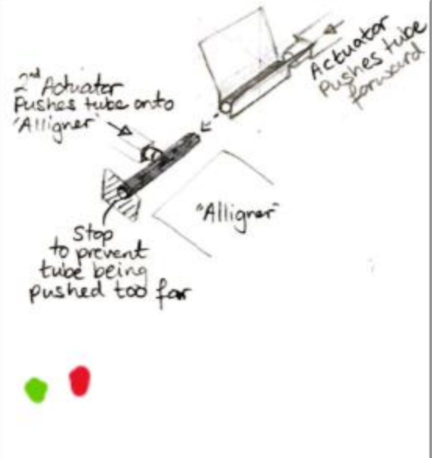
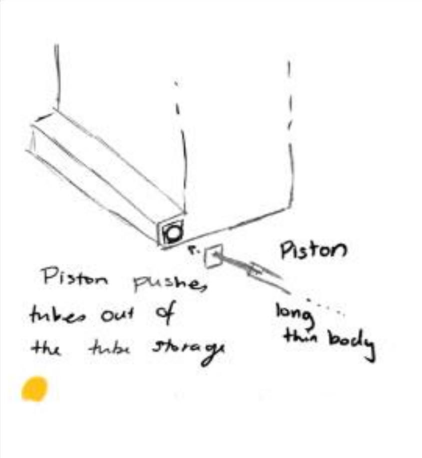
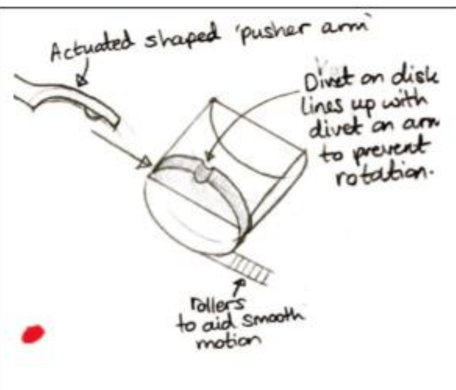
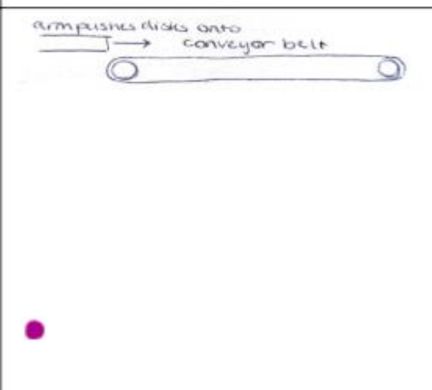
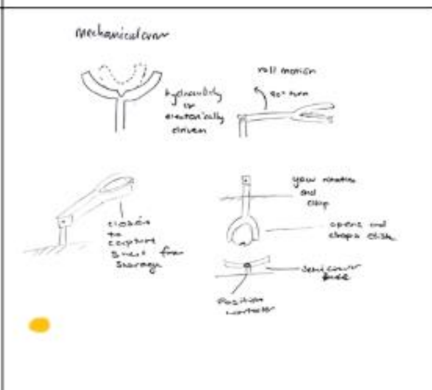
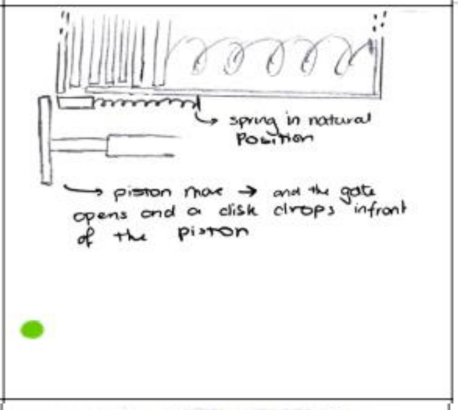
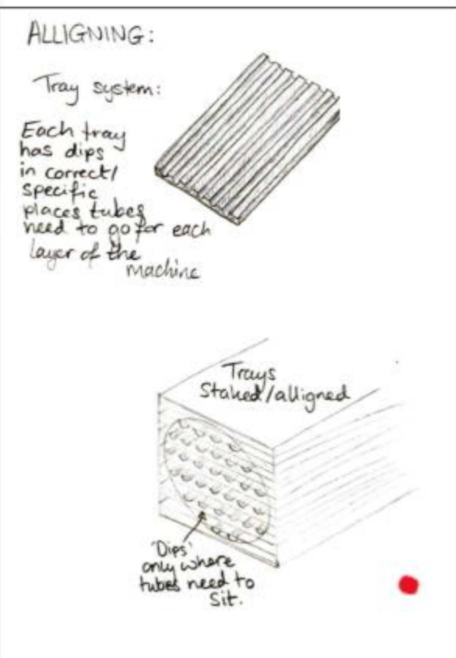
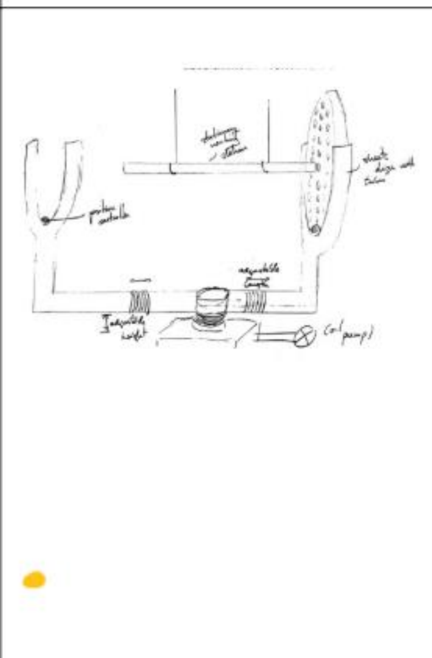
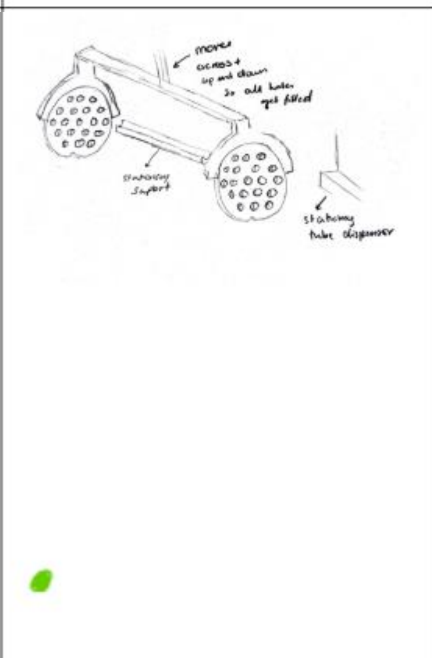
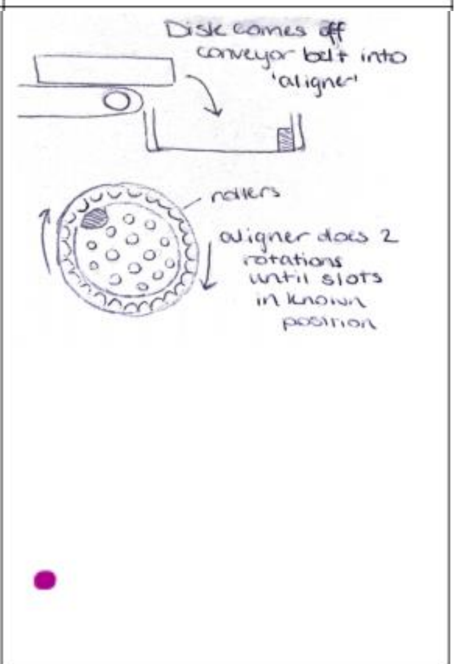
By Lani Widdeson, Sophie Hadden-Becker, Iona Mitchell and Pedro Esperanco

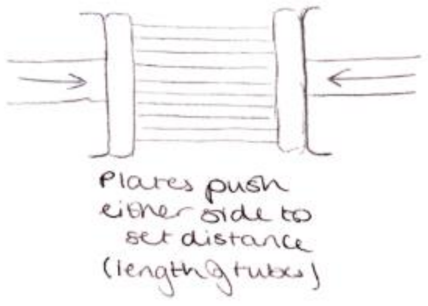
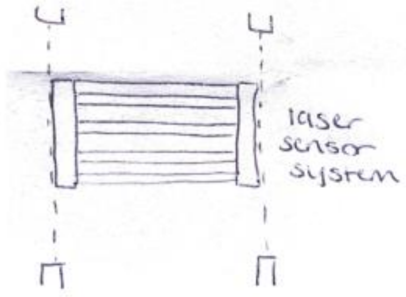
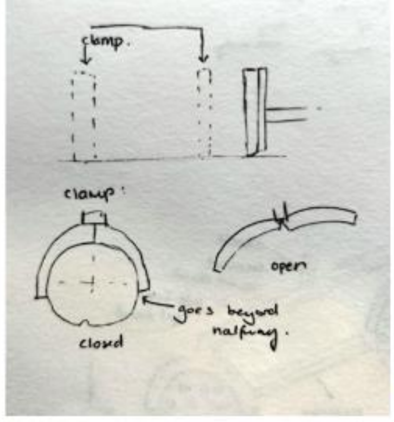
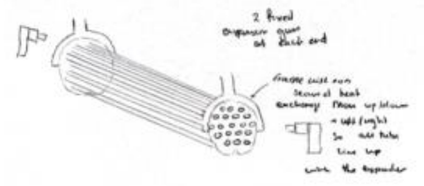
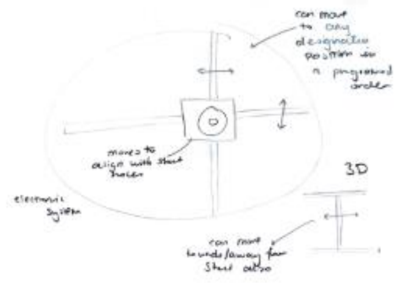
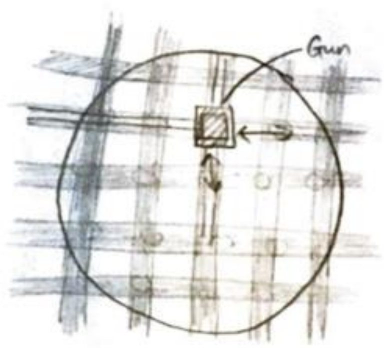
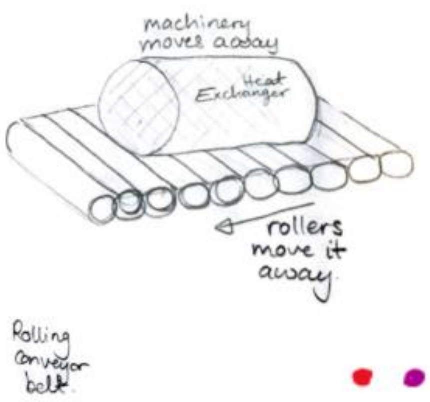
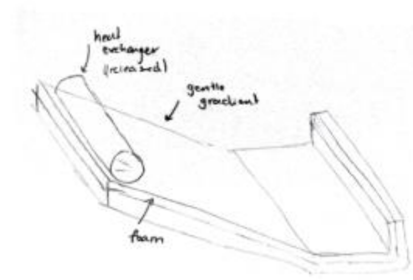
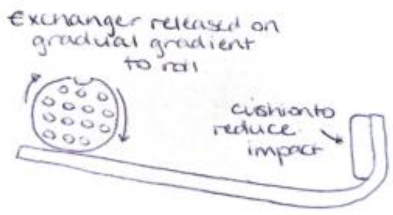
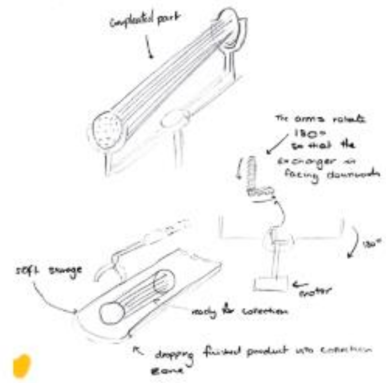
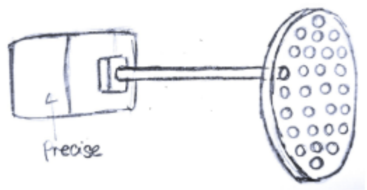
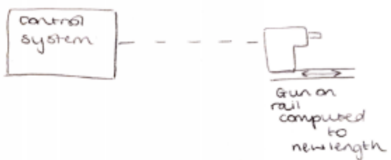


PDS

Group #39		**PRODUCT DESIGN SPECIFICATION**	Issued on 11/03/22 Revision 3	
D / W	Weighting	**Requirements**	Responsible	Changes
		1. Operation		
D		• The machine shall operate for 2000 hours per year for a minimum of 10 years		
D		• The machine shall operate automatically and autonomously		
D		• The machine shall automatically retrieve 85 tubes and 2 tube sheets from their respective buffers		
D		• The machine shall insert all the tubes into the tube sheets and both ends shall be flush with the outermost face of the sheets		
D		• When correctly placed, the tubes shall undergo physical expansion to meet inner diameter of metal sheets, remaining flush with the outermost face of the metal sheet		
D		• When the expansion process is finished, the machine shall gently eject the assembled heat exchanger core into a collection zone		
D		• The machine shall be able to operate at a room temperature of 20 degrees	P.S.G.E	04/03/22
		2. Performance		
D		• When the operator wishes to change the size of the heat exchanger core, the machine shall allow manual intervention.	S.H.B	11/03/22
W	M	• The adjustment process should take the shortest possible period		
D		• The machine shall account for one or more bespoke hole expansion machines, capable of performing each expansion process in 7 seconds		
W	H	• One operation should take the machine no more than 1 hour to complete		
D		• The alignment gun control system shall be contained within machine, and when activated, it shall deliver a 24V power supply to the tool, and receive a confirmatory signal once the process is finished	I.M.M	11/03/22
		3. Geometry		
D		• The machine shall fit within a maximum volume of 4x4x4 m^3		
D		• The machine shall be capable of assembling cores of 600 mm, 800 mm, 1000 mm in length		
D		• The machine shall account for hydraulic hoses and electric wires from the expansion tool power having 6 m lengths		
		4. Kinematics		
D		• The hole expansion tool shall be controlled by a hydraulic system using oil, connected to an electric control system		
D		• For the expansion process to be successful, the machine shall place the tool's datum face against the end of the tube	P.S.G.E	04/03/22
W	M	• The machine shall avoid uncontrolled motion of items	I.M.M	04/03/22
		5. Safety		
W	H	• The machine may include some failsafe and operator safety measures to ensure the integrity of the machine itself, the core, and the operators		
W	H	• Manual intervention whilst the machine is running should be kept to a minimum to reduce the risk of injury from moving parts. This is in line with the provision and use of work equipment regulations 1998 (PUWER 98)	I.M.M	11/03/22
W	H	• The machine shall comply with the supply of machinery regulations 2008 (2006/42/EC)	I.M.M	11/03/22
W	H	• The machine will adhere to BS EN ISO 14120 and shall hence include guards where necessary	I.M.M	11/03/22
W	H	• The machine will adhere to BS EN ISO 13857 by choosing appropriate materials, safety distances and construction methods minimising the risk and exposure to hazards	I.M.M	11/03/22
		6. Maintenance		
W	L	• The machine should account for maintenance of its components and shall not be difficult to dismantle		
W	L	• The disks shall be stored with protective barriers between them to prevent scratching	S.H.B	04/03/22
		7. Price		
D		• The total machine cost shall not surpass £75,000		
W	M	• The total machine cost should consist of approximately 80% purchased and 20% manufactured parts	L.M.W	04/03/22
W	M	• The machine shall be bought as an individual unit so the production should be cost effective for the small quantity of parts required	I.M.M	04/03/22

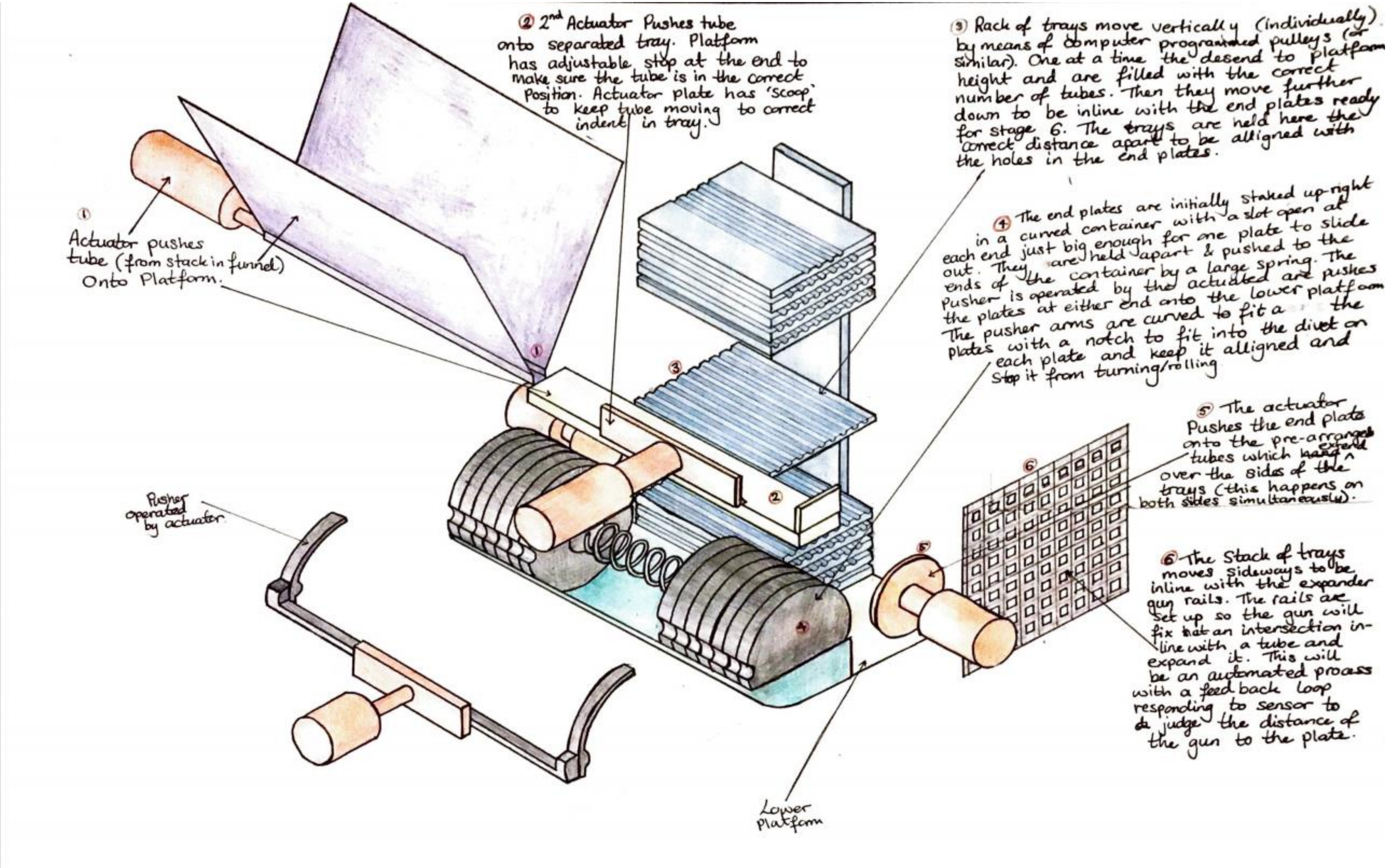
Morphological chart

Functions	Concept 1	Concept 2	Concept 3	Concept 4
Store tubes				
Store disks				
Transporting tubes to assembly station				
Transporting the sheets to the assembly station				
Align the tubes with the disks				

Ensure the disks are the appropriate distance apart			Sensors at either end of the component holding the tubes so it devise pushing the disks knows when they are close enough/the right distance to stop.	
Align the gun and the tube ends		(Assembly in known position, guns computed to set locations)	 - Gun is constrained to move in 2D on a platform that can move in a 3rd dimension. Gun moves between holes (in a pattern to be determined) using electric actuator system.	 Gun moves along rails to predetermined positions that will allign with holes in disk (need method to allign rails with notch in disks).
Release heat exchanger gently				
Ensure the machine can be adjusted for each of the lengths of heat exchanger	Use sensors to determine distances instead of using fixed distances.  SKD-20S 20m mini Laser Distance measurement Sensor – Xi'an Zhizun International Trade Co., Ltd., n.d. [Online]. Available from: https://www.top1sensor.com/product/skd-20s-laser-distance-sensor/ [Accessed 28 March 2022].	- Hydraulic/Electrical system controlling alignment of tube with sheets in working section must account for a possible displacement of around 300 mm. - Must account for laser and sensor controlling flushed tubes with sheet to be adjustable 		- The storage of the tubes is sloped so tubes are always flush at one end - The pistons that eject the tubes and disks can be set to 3 different lengths - The frames that locate the disks can be manually altered to the desired length. (Just the one furthest from the disk storage - The support for the tube position is appropriate for the shortest heat exchanger and it also can be manually moved so that it is always centrally located between the two disks - The guns can be manually positioned at different distances apart depending on heat exchanger length.

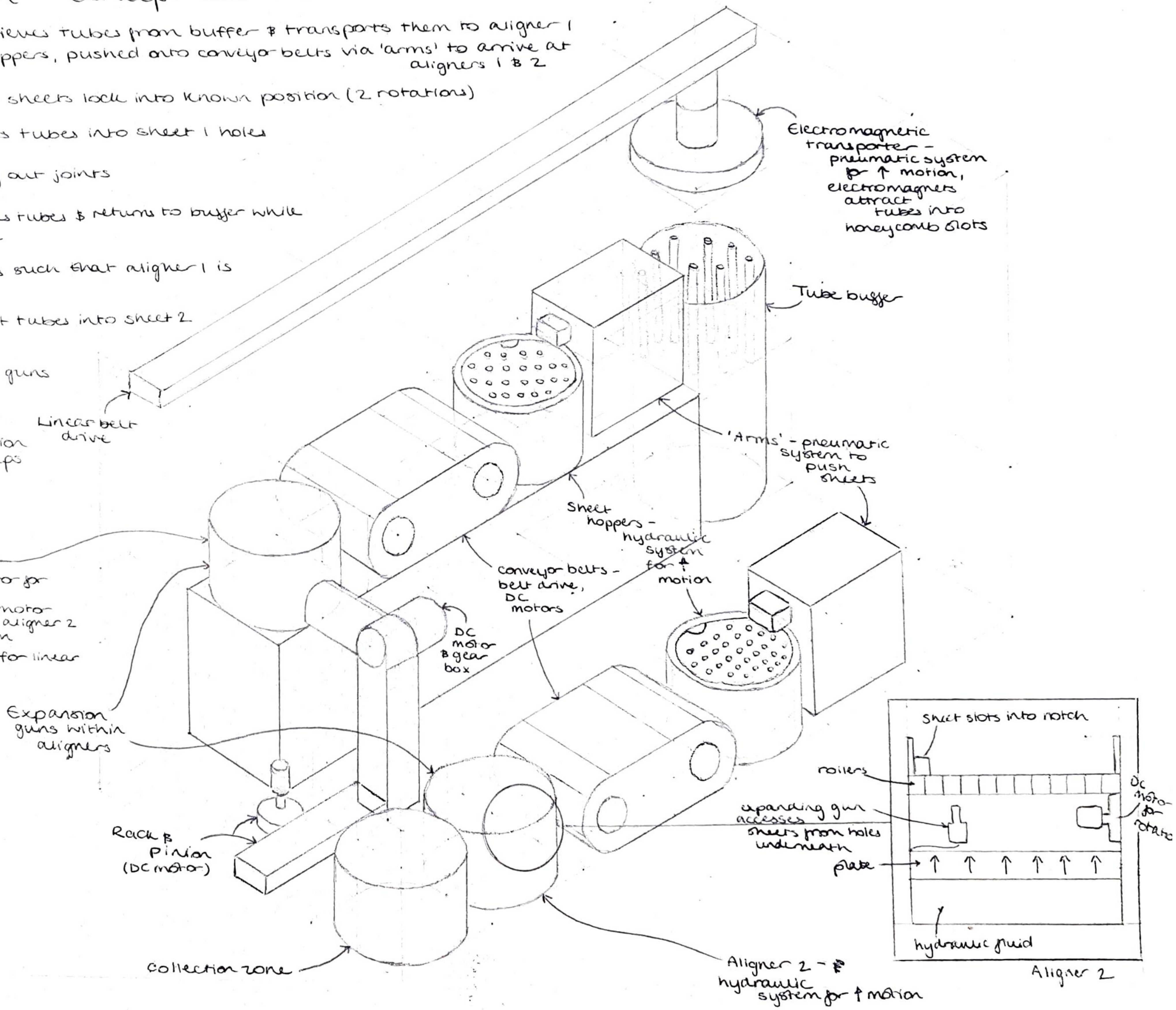
Initial Concept Sketches

Concept 1



Machine Design - Concept Sketch

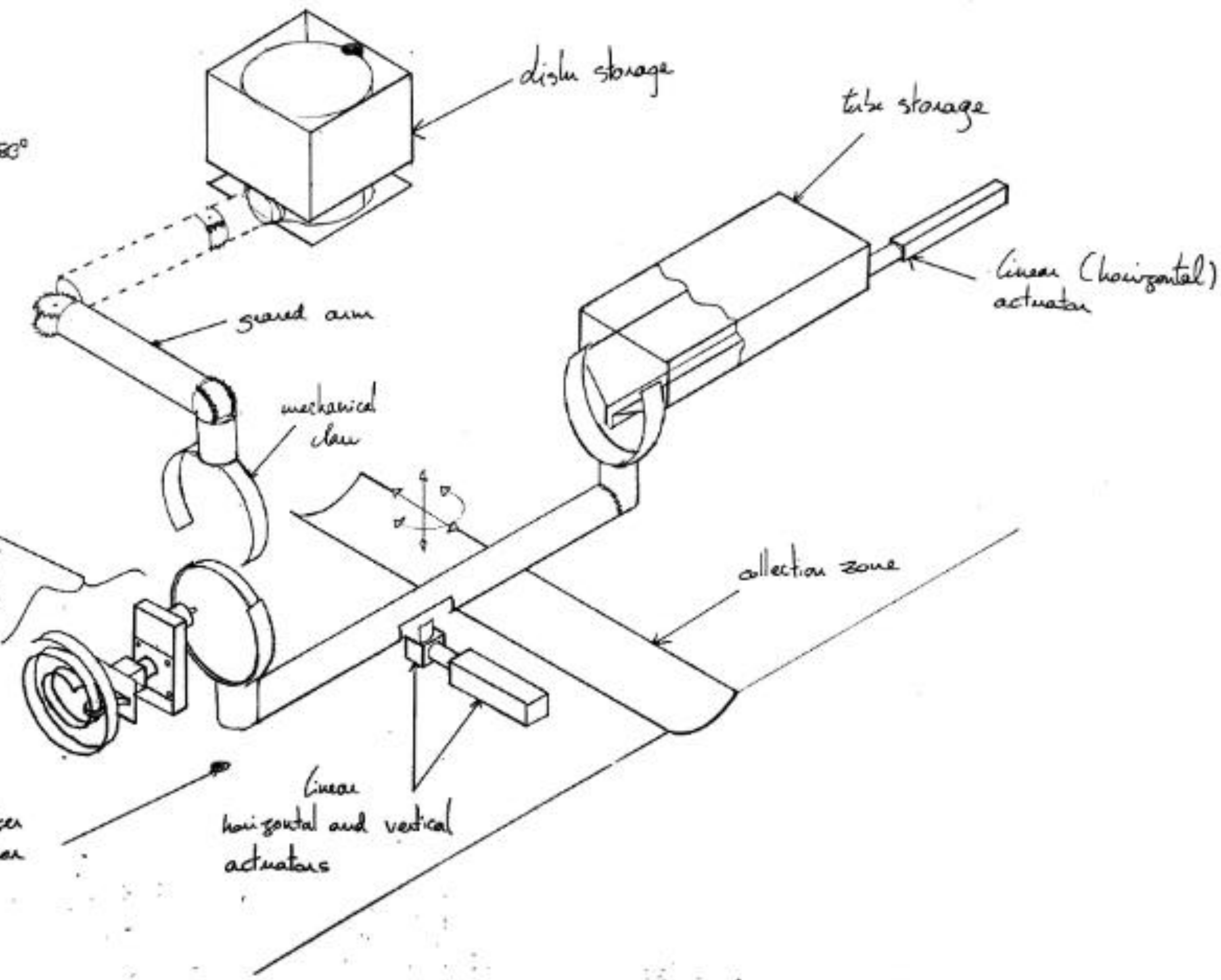
1. • EM transporter retrieves tubes from buffer & transports them to aligner 1
   • Sheets raised from hoppers, pushed onto conveyor belts via 'arms' to arrive at aligners 1 & 2
2. Aligners rotate until sheets lock into known position (2 rotations)
3. EM transporter lowers tubes into sheet 1 holes
4. Expansion guns carry out joints
5. EM transporter releases tubes & returns to buffer while aligner 1 clamps engage
6. Aligner 1 lever rotates such that aligner 1 is above aligner 2
7. Aligner 2 raises to slot tubes into sheet 2 holes
8. 2nd round of expanding guns
9. Aligner 2 lowers
10. Aligner 1 moves to collection point and release clamps



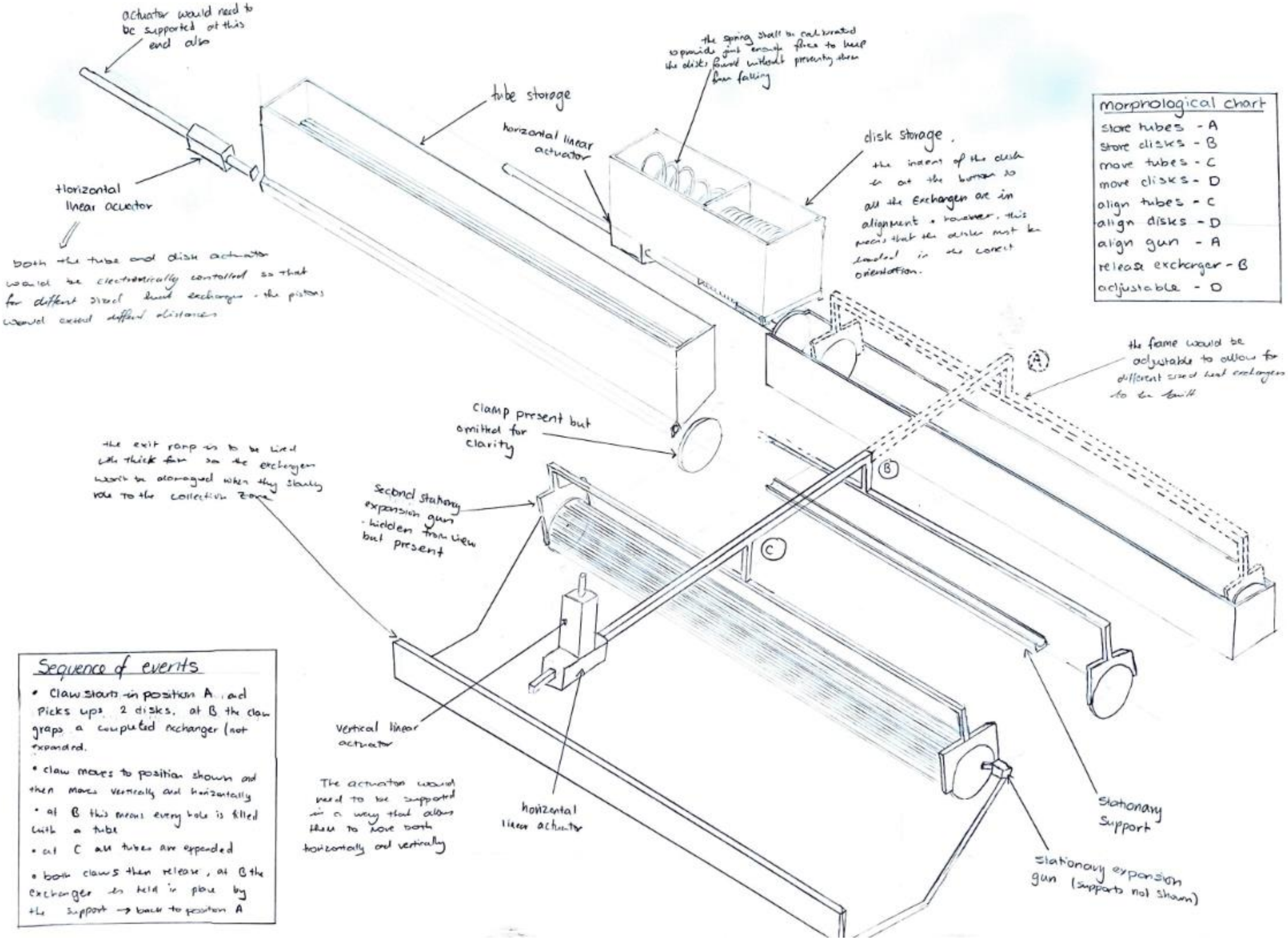
Concept 3

Sequence of Events

- Grared arm drops first sheet to working station. Thu collects second as working station turns 180° and drops it.
- Tubes fall from storage and are placed through two holes into desired place by actuator.
- Working station moves accordingly to desired tube position. (previously programmed path).
- Alignment tool makes expansion tool move together with working station and follows rail path to expand placed tubes. Process should take approx 45 mins.
- Laser verifies tubes are flushed with sheets and if not, provides emergency signal
- Once all tubes expanded from one side, working station rotates and second side is performed.
- Finally, working station turns 90° from initial position and drops assembled one into collection zone.



Concept 4


actuator would need to be supported at this end also
Horizontal linear acuator
tube storage
horizontal linear actuator
disk storage
morphological chart
store tubes - A
store disks - B
move tubes - C
move disks - D
align tubes - C
align disks - D
align gun - A
release exchanger - B
adjustable - D
the frame would be adjustable to allow for different sized heat exchangers to be built
Clamp present but omitted for clarity
Second stationary expansion gun hidden from view but present
Sequence of events
• Claw starts in position A, and Picks ups 2 disks, at B the claw graps a completed exchanger (not expanded.
• claw moves to position shown and then moves vertically and horizontally
• at B this means every hole is filled with a tube
• at C all tubes are expanded
• both claws then release, at B the exchanger is held in place by the support → back to position A
Vertical linear actuator
horizontal linear actuator
Stationary Support
Stationary expansion gun (supports not shown)
A
B
C

MCDA and concept evolution

All criteria are scored out of 5			concept 1		concept 2		concept 3		concept 4	
Code	Criteria	Weight	Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score
a	The machine shall be cost efficient	2	2	4	1	2	4	8	3	6
b	Running time shall be less than 1 hour	3	2	6	3	9	1	3	4	12
c	The machine shall have minimal human intervention	3	3	9	1	3	3	9	3	9
d	Ease of adjustment of length of exchanger	2	3	6	4	8	1	2	2	4
e	Ease of disassembly	2	1	2	2	4	4	8	3	6
f	Precision of alignment	5	4	20	3	15	1	5	2	10
g	Controlled transportation	4	3	12	4	16	1	4	2	8
h	Simplicity of design	1	4	4	1	1	2	2	3	3
i	Minimal custom parts	1	1	1	4	4	3	3	2	2
j	Controlled expansion process	4	4	16	2	8	1	4	3	12
k	Careful exchanger release process	4	1	5	4	16	3	12	2	8
l	Ease of correction of error	5	2	10	3	15	1	5	4	20
Weighted score total				95		101		65		100
Rank				3		1		4		2
% Total				26%		28%		18%		28%

Pair wise comparison:

To determine the weighting used above for the MCDA success criteria, a pairwise comparison was completed. A 1 indicates that the column criteria is more influential than the row criteria.

	a	b	c	d	e	f	g	h	i	j	k	l
a	-	1	1	1	0	1	1	0	0	1	1	1
b	0	-	0	0	0	1	1	0	0	1	1	1
c	0	1	-	0	0	1	1	0	0	1	1	1
d	0	1	1	-	0	1	1	0	0	1	1	1
e	1	1	1	1	-	1	1	0	0	1	1	1
f	0	0	0	0	0	-	0	0	0	0	0	1
g	0	0	0	0	0	1	-	0	0	1	0	1
h	1	1	1	1	1	1	1	-	0	1	1	1
i	1	1	1	1	1	1	1	1	-	1	1	1
j	0	0	0	0	0	1	0	0	0	-	0	1
k	0	0	0	0	0	1	1	0	0	1	-	1
l	0	0	0	0	0	0	0	0	0	0	0	-
total	**3**	**6**	**5**	**4**	**2**	**10**	**8**	**1**	**0**	**9**	**7**	**11**

The criteria were then weighted between 1 and 5 by pair wise ranking and distributed evenly across the different weights.

Concept selection

Although Concept 2 scored highest, when it came to making individual improvements, the prevalent design flaws of this concept (namely the complexity, expense, and practicality of using electromagnets) proved too complex to be resolved. This was particularly due to the additional steps that would have had to be taken to magnetise the exchanger components as they are not naturally magnetic.

Concept 4 came in a remarkably close second and was a simpler machine design. In addition, the group had several ideas on ways to improve the concept. Therefore, this is the concept that we decided to take forward.

Concept evolution

Throughout the process the design of the machine underwent many departures from the initial concept sketch. The major changes are outlined below.

Tube storage:

- removable plates within the tube storage to allow for the position of tubes of different lengths to still be known accurately
- enlarged the storage container to allow for the tubes needed to complete two heat exchangers (less manual labour needed)

Sensors:

- implemented many sensors to improve accuracy and ensure quality of our products e.g warning system

Disk foam:

- altered the disk storage arrangement to allow for there to be a thin layer of foam between each of the disk to prevent damage to the disk in storage. This foam will be loaded in along with the disks when the storage is refilled.

Disk hoppers:

- two disk hoppers were implemented rather than one - removed the need for a long actuator and piston and simplified the machine design
- front of the hopper now lifts to allow for the foam to be removed between each of the disks

Expansion guns:

- one of the expansion guns was moved from station 3 to station 2 - exchanger is connected before moving stations, reducing the risk of parts becoming unaligned during the transportation; marginally increases the cycle time of operation as the two guns are still working simultaneously on different heat exchangers.

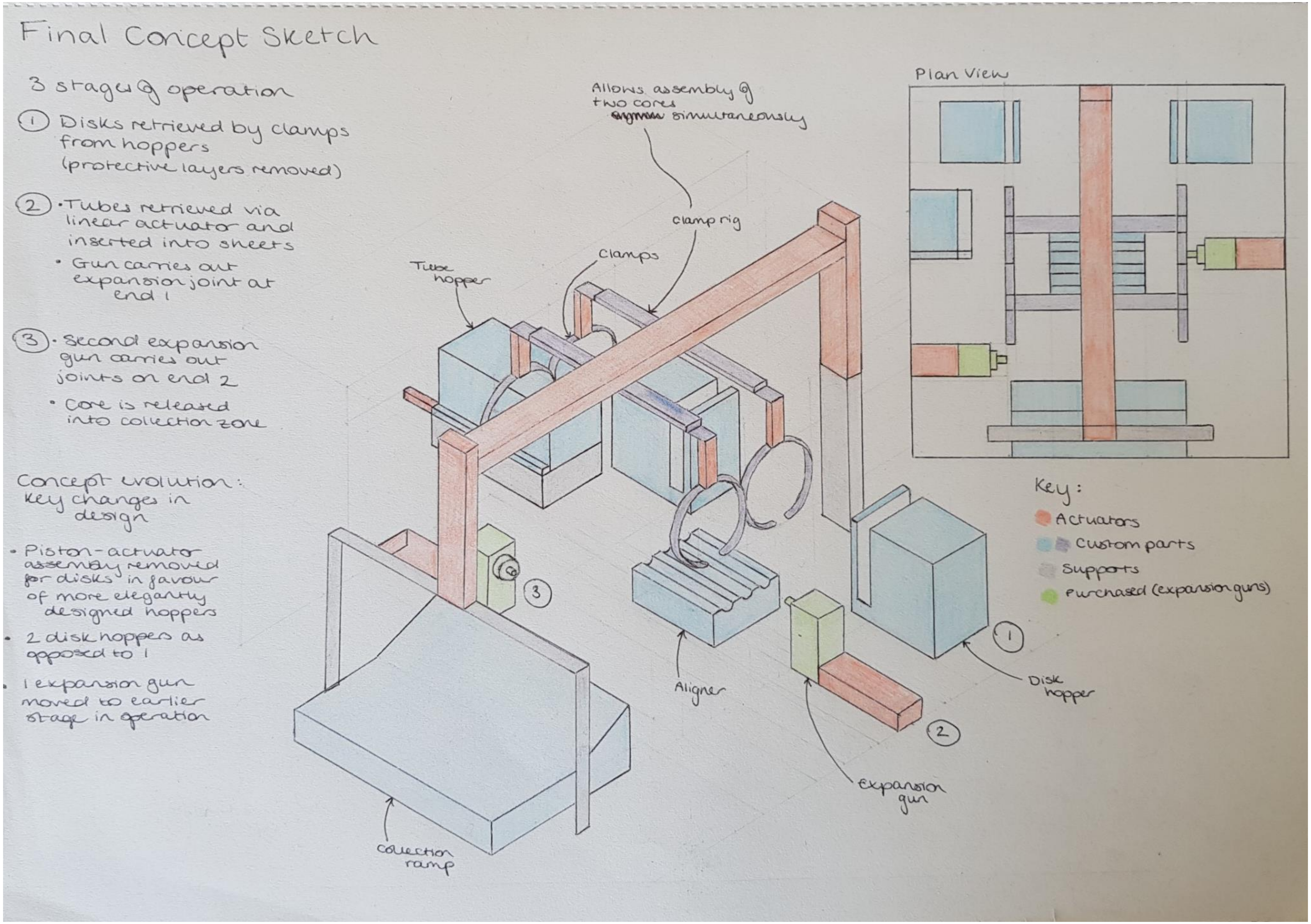
Exit ramp:

- exit ramp was lowered to ensure it was not going to interfere with the clamp system actuators
- gradient of the ramp was reduced to lower the speed the exchanger will enter the collection zone – lowering exit ramp increased distance exchanger falls, had to mitigate this
- thicker layer of foam on the ramp was implemented so that the exchanger will not be damaged

Larger exchanger support:

- stationary support in station 2 was increased in width and its location adjusted so to ensure the exchanger would be securely supported while it was changing clamps
- support will now hold all four of the lowermost tubes

Final concept sketch



Component selection and calculations

* this product has either been updated or added since the parts list was produced for the CAD hand-in on the 22/03/2022.

Heat exchanger Core

Tube and Sheet Material: Stainless Steel 304 1.4301. Density is 8,000 kg/m3.

In the following calculations, the tubes were assumed to have their greatest length (1m) to calculate minimal component requirements.

Tube Volume:

$$V_{tube} = \frac{\pi h_{max}(D^2 - d^2)}{4} \qquad \textit{Eq. 1}$$

Where h_{max} is 1m, D is $12.7*10^{-3}$m and d is $10.92*10^{-3}$m. Hence $\mathbf{V_{max,tube}}$ **is** $\mathbf{3.3021*10^{-5}m^3}$.

Tube Mass:

$$M_{tube} = V_{tube} \times \rho_{ss} \qquad \textit{Eq. 2}$$

And so M_{tube} is 264.2g.

Tube Sheet Volume:

$$V_{sheet} = \frac{\pi t}{4}\left(D^2 - 85d^2\right) \qquad \textit{Eq. 3}$$

Where t is $20*10^{-3}$m, D is $210*10^{-3}$m and d is $13.5*10^{-3}$m. Hence $\mathbf{V_{sheet}}$ **is** $\mathbf{4.494*10^{-4}m^3}$.

Tube Sheet Mass:

$$M_{sheet} = V_{sheet} \times \rho \qquad \textit{Eq. 4}$$

And so M_{sheet} is 3.6kg.

-Now considering the assembled core exchanger comprises 85 tubes and 2 tube sheets, the total mass of a single core $\mathbf{M_{core}}$ **is 29.66kg.**

Machine Parts

Table 1: Mass and Material of other machine components and sub-assemblies

Part	Qty.	Material and Density (kg/m^3)	Mass (in kg)
Suspension frame	1	Stainless Steel – 7900	20.5
Pulley mount plate	2	Aluminium alloy – 2600	3
Double Pulley Bracket	2	Aluminium alloy – 2600	0.08
Single Pulley Bracket	4	Aluminium alloy – 2600	0.61
Claws	4	Stainless Steel – 7900	4.35
Claw Control Driver	2	(Catalogue Part)	10.4
Claw and which sub-assembly (neglecting small parts)			38.94

Gantry sub-assembly

Horizontal actuator selection:

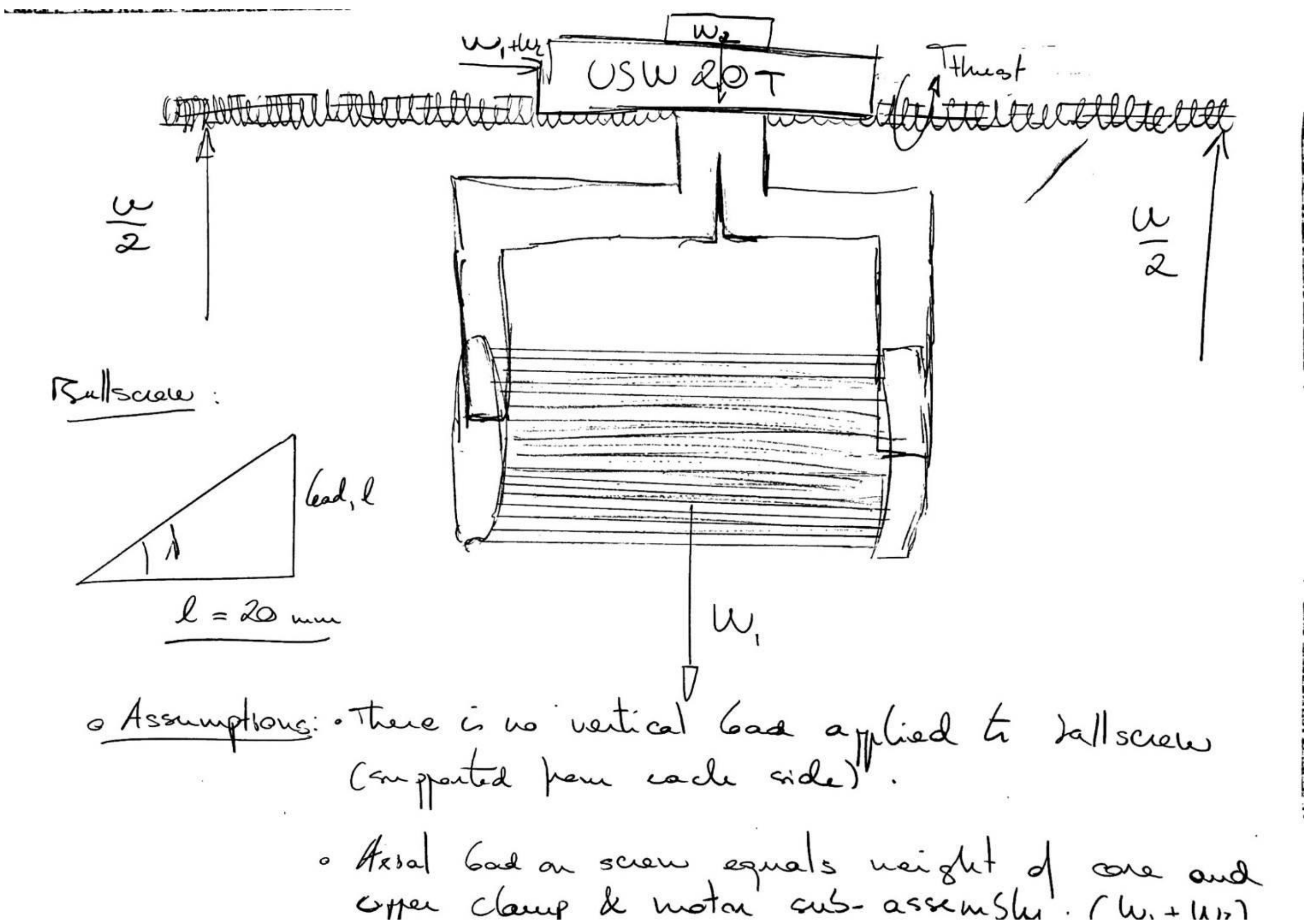


Figure 1: Diagram of fully assembled core supported by horizontal ball screw actuators

Considering there is a point in the machine's working cycle where two fully assembled cores (where only one has the tubes fully expanded on both sides), the axial load exerted by the assembled core and the claw and winch sub-assembly on the ball screw actuator, as demonstrated in Figure 1 is:

$$W = 9.81(2 \times M_{core} + M_{claw,winchSB}) \qquad \text{Eq. 5}$$

And so, this horizontal actuator axial load **W is 963.9N**. Also, the required stroke for the horizontal actuator is 1000mm to accommodate the full length of the machine's core assembling process.

The selection process was based on looking at different catalogues and trying to reach a solution accommodating both load and stroke length requirements. The choice of ball screw driving method was due to the reliability, precision, velocity and load range of this type of actuator. The universal series actuator units of the manufacturer THK provided a good range of ball screw linear units:

Figure 2: THK Universal Series Actuator Catalogue

Table 2: THK USW20T-20-1000A-1B Specifications

Stroke length (mm)	1,000
Maximum thrust load (N)	1,810
Ball screw lead (mm)	20
Motor connecting shaft diameter (mm)	20
Axial maximum speed (m/s)	1
Ball screw maximum speed (rpm)	478
Acceleration and deceleration rate (m/s^2)	2.9
Repeatability (mm)	±0.020
Backlash (mm)	0.05
Weight (kg)	46.4
Running life (km)	20,000
Price estimation (£)	800
Distance between mounts l_b (mm)	1300
Second moment of inertia I (mm^4)	21900
Shaft Young's modulus (GPa)	190

To check if the actuator can withstand the axial load of the core without being damaged, looking at its buckling load P and considering its support factor β to be 2.0 as it is fixed on one end and supported at the other:

$$P = 97.2\ kN \qquad \text{Eq. 6}$$

And so, the axial load applied to the actuator is considerably lower than the ball screw buckling load, meaning there will be no damage to the latter.

As the colour code represents, the selected actuator comprises several satisfying specifications and so the decision was straightforward to make. The downside of the component is the need to integrate a motor on of the ends with a brake to avoid being back driven, increasing its already heavyweight.

Horizontal actuator motor selection*

Required torque to provide axial thrust for ball screw actuators, where l is the lead in the helical threads of the screw, F the axial load applied to the actuator and η the efficiency (considered to be 95%):

$$T_{thrust} = 3.23\ Nm \qquad \text{Eq. 7}$$

Therefore, the motor selection process was based on this thrust torque value, as well as on the maximum speed of the actuator. The type of drive selected was servomotor, due to its high accuracy desirable when moving the core from one position to another, to avoid any tube expansion failures. From the Festo servomotor catalogue, the following driver and gear unit were selected:

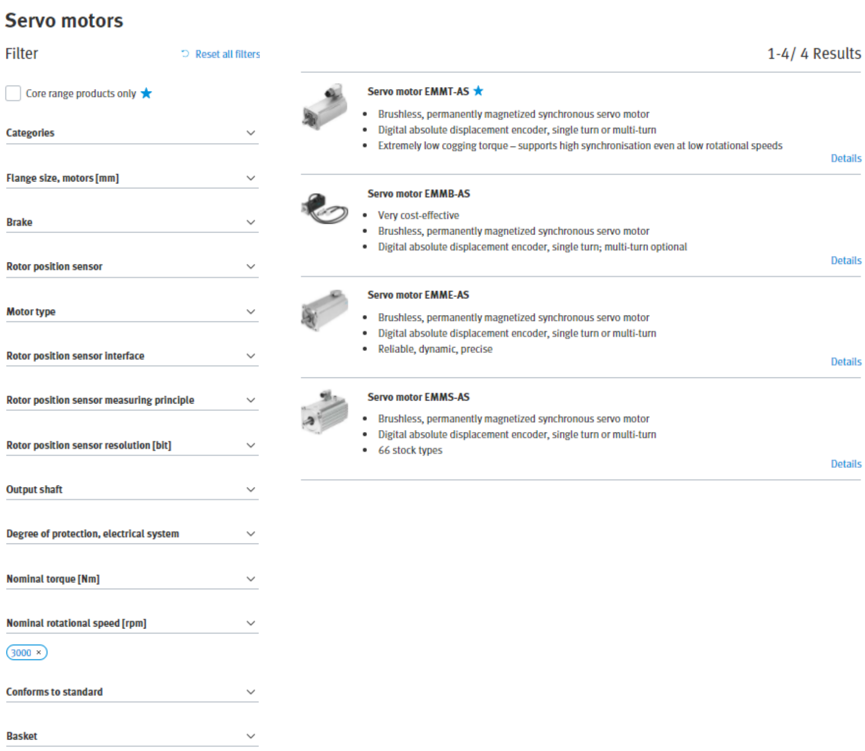


Figure 3: Festo servomotor selection tool

Table 3: EMMT-AS-60-S-LS-RMB servomotor and EMGA-60-P-G5-EAS-60 gear unit specifications

Nominal operating voltage (V)	565
Nominal torque (Nm)	0.6
Nominal rotary speed (rpm)	3000
Integrated brake holding torque (Nm)	2.5
Maintenance	190 years to failure
Gearbox ratio	5:1 (reduction)
New nominal torque (Nm)	3
New nominal speed (rpm)	600
Motor Price (£)	870
Gear Price (£)	394

With the integrated gear unit, the motor can deliver almost perfect torque and speed characteristics, satisfying the actuators needs to operate at maximum axial velocity. The lack of breaking torque is not critical as the actuator is used horizontally.

Vertical actuator selection

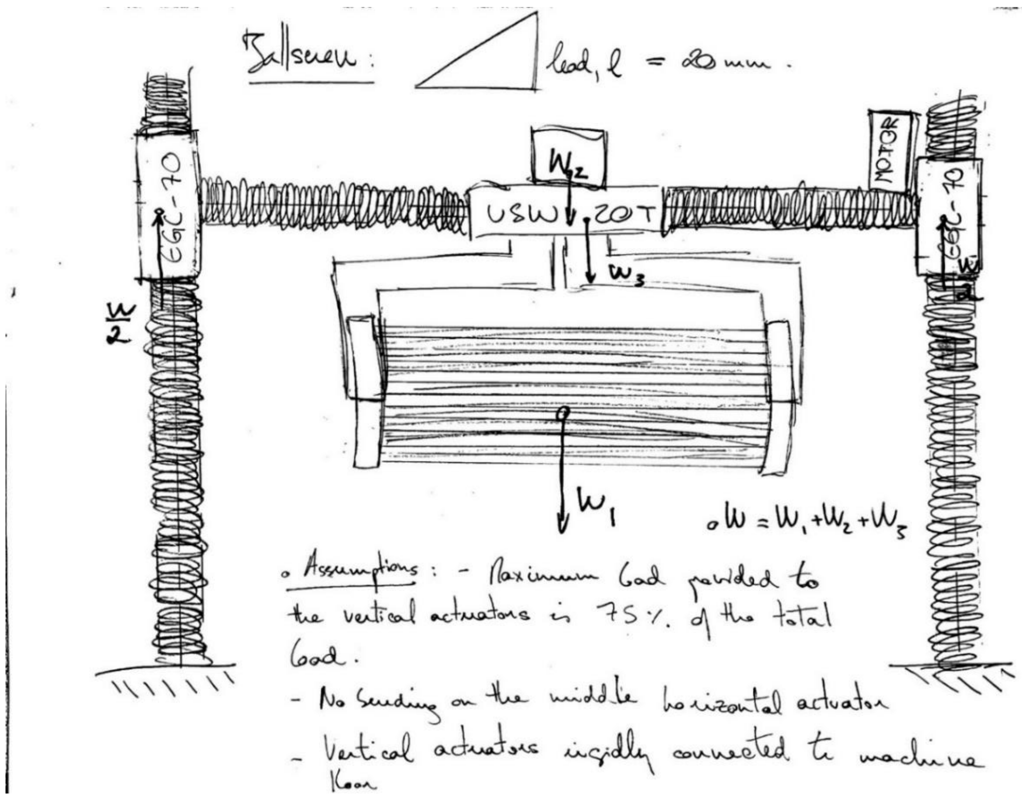


Figure 4: Diagram of vertical actuators supporting exchanger core, horizontal actuator, and claw anf winch sub-assembly

Again, for safety purposes, considering a point in the sequence of events where two fully assembled cores (one of them, not having the tubes fully expanded) apply a vertical load to the actuators. Also considering the load consists of W_1 core weight, W_2 claw and which sub-assembly weight, and W_3 horizontal actuator at this point, 75% of the load is concentrated on of the ball screw systems. Therefore, the axial load capacity required by the actuator is:

$$W = 0.75 \times 9.81(2 \times W_1 + W_2 + W_3) \qquad \text{Eq. 8}$$

And so, this maximum vertical actuator axial load **W is 1064.3N**. Also, the required stroke for the vertical actuator is around 300mm to accommodate the full height of the machine's core assembling process (1.5 times the sheets PCD).

Again, the selection process focused mainly on finding a solution that fits the load and stroke requirements and the choice of a ball screw linear electrical system was also preferred for strength and accuracy. Two options were considered from the Festo Electro-Mechanical selection tools:

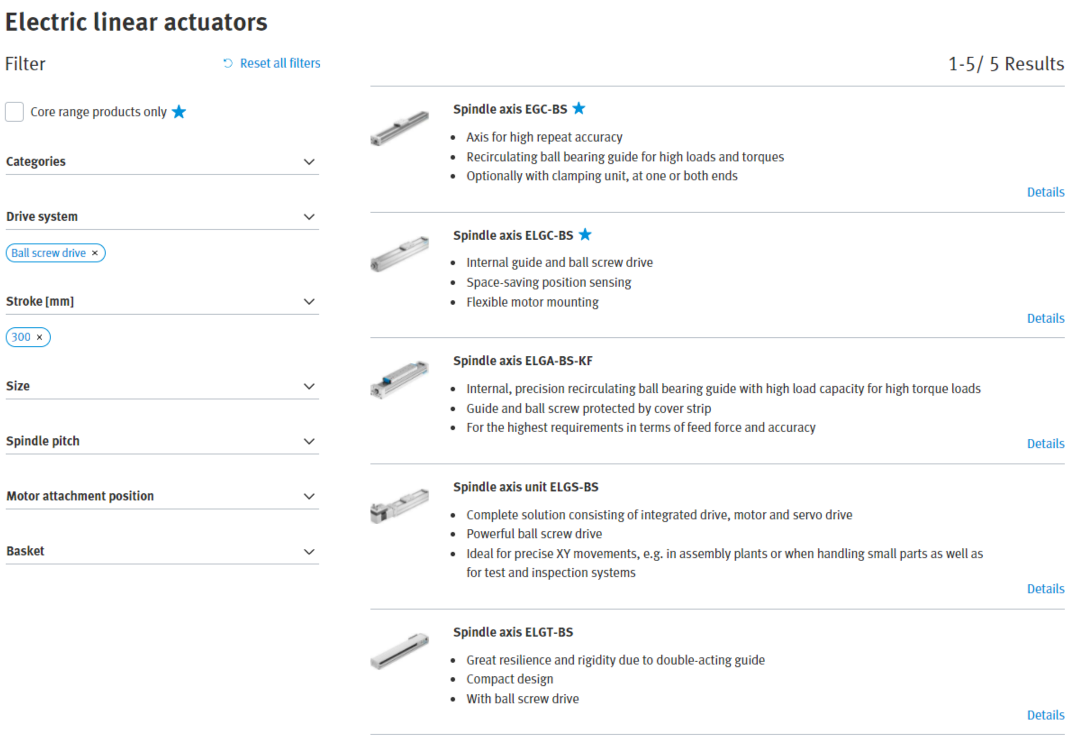


Figure 5: Festo electrical linear actuators selection tool

Table 4: Comparison between two possible actuator solutions

Component	ELGC-BS-KF-45-300-10P	EGC-70-300-BS-10P-KF-0H-ML-GK
Working stroke (mm)	300	300
Lead (mm)	10	10
Spindle diameter (mm)	12	12
Max. acceleration (m/s^2)	15	15
Max. axial speed (m/s)	0.60	0.75
Max rotary speed (rpm)	477	477
Repetition accuracy (mm)	±0.015	±0.020
Max. axial force (N)	600	1850
Running life		
Price (£)	567	1,370
Distance between mounts l_b (mm)	X	340
Second moment of inertia I (mm^4)	X	419000
Young's modulus E (GPa)	X	190

To check if the actuator can withstand the axial load of the core without being damaged, looking at its buckling load P and considering its support factor β to be 2.0, as the ball screw is fixed on end and simply supported on the other:

$$P = \frac{\beta\pi^2 EI}{l_b^2}$$

$$P = \frac{2\pi^2(190 \times 10^9)(419000 \times 10^{-12})}{0.34^2}$$

$$P = 13.6\ MN \qquad \textit{Eq. 9}$$

Again, the buckling load is considerably higher than the axial load applied to the actuator, and so no damage will be caused on the ball screw.

As denoted by the colour code, the two solutions found are very similar in their specifications. Nonetheless, they differ in their capability of withstanding axial load, one of the essential criteria of the desired actuator. The selected component was the one capable of withstanding 75% of the total vertical load by itself (considering two actuators required), i.e., EGC-70-300-BS-10P-KF-0H-ML-GK.

Vertical actuator motor selection*

Required torque to provide axial thrust for ball screw actuators, as described in Eq. 7:

$$T_{thrust} = \frac{1064.3 \times 0.01}{0.95 \times 2\pi}$$

$$T_{thrust} = 1.78\ Nm \qquad \textit{Eq. 10}$$

Again, the type of driver selected was a servomotor, and the selection process was based on the torque and rotational speed provided to the ball screw system. Once more form the Festo servomotor catalogue:

Figure 6: Festo DC servomotors catalogue

The same motor and gear unit were selected as for the horizontal actuator, i.e., EMMT-AS-60-S-LS-RMB and EMGA-60-P-G3-EAS-60.

The final torque delivered to the actuator would be higher than the desired value, however this value of 3 Nm would still lie within the acceptable torque range the ball screw can withstand as the following calculations show:

$$T_{thrust,max} = \frac{F_{max} l}{2\pi\eta}$$

$$T_{thrust,max} = \frac{1850 \times 0.01}{0.95 \times 2\pi}$$

$$T_{thrust,max} = 3.01 \qquad \text{Eq. 11}$$

In addition, the break torque provided by the motor (2.5Nm) would be perfect to vertically hold the core when moving it between expansion positions.

Tube Storage sub-assembly

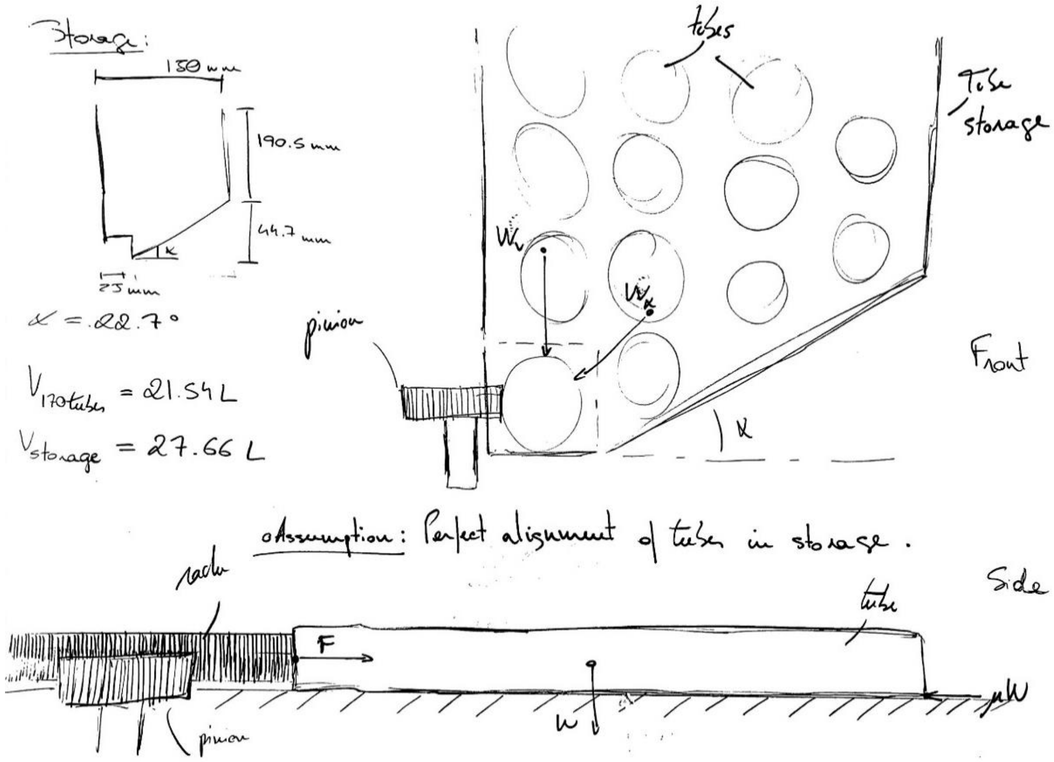


Figure 7: Diagram of Tube, tube storage and tube inserter actuator

Total Load of Tubes

As Figure 7 states, the following calculations assume a perfect alignment of the tubes inside the storage, where they are vertically aligned in columns and equally spaced in rows.

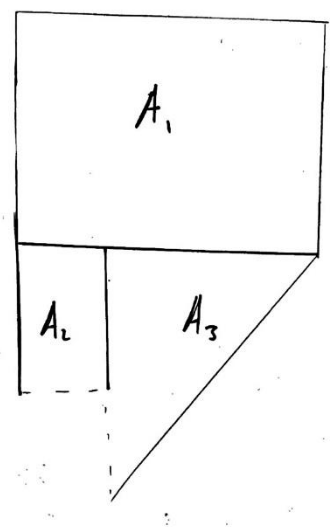


Figure 8: Tube Storage Diagram

By dividing the tube storage into three different sections, an upper rectangular, a triangular and a lower rectangular, the number of tubes per section can be estimated using each of their volumes:

Table 5: Volumes of three sections of tube storage

V_1	24.77 L

V_2	1.04 L
V_3	2.39 L

$$N_{tubes} = integer\left(\frac{V_{section}}{V_{tube}}\right) \quad \textit{Eq. 12}$$

And so,

Table 6: Number of tubes per section of tube storage

N_1	8
N_2	18
N_3	144

Now if the width of the upper rectangular section is 130 mm and the width of a single tube is 12.7mm, then a single row fits 10 tubes. Hence there are 15 rows of tubes in storage where for each, a single tube is vertically aligned with the tube in the inserting position.

Now assuming all the tubes that are not vertically applying a load on the inserting position tube have an angled impact on the latter, acting along the direction of the bottom plane of the tube storage. The total load applied on the tube inserting the tube is:

$$W_{tubes} = W_{tubes.v} + W_{tubes,\alpha}$$
$$W_{tubes} = 9.81((8 + 15)M_{tube} + 147M_{tube} \times \sin{(\alpha)}$$
$$W = 206.64\ N \quad \textit{Eq. 13}$$

Tube inserting velocity and acceleration

A reasonable assumption of time taken for the tube to reach its final position (inserted inside two tube sheets) consists of 1.5 seconds. The distance of travel of the tube is around 1000mm at max. Therefore, the velocity of the tube during this travel period can be estimated to be 0.7m/s. Now, using the kinematic equation for acceleration:

$$a = \frac{v^2 - v_o^2}{2\Delta s}$$
$$a = \frac{0.7^2}{2}$$
$$a = 0.245\ m/s^2 \quad \textit{Eq. 14}$$

Tube Inserter Actuator Selection

The choice of actuator type selected to insert the tubes into the tube sheets to then undertake their first expansion was made based on the machine ergonomics. In other words, the actuator selected would have to be practical, being able to make the tube storage length while not letting any other tube fall into position. A rack and pinion linear arrangement were thought to combine both performance and functional design requirements.

For a horizontal rack and pinion, the required thrust is:

$$F = mg\mu + ma + F_{load} \quad \text{Eq. 15}$$

Now considering the load acting on the tube to be the weight of the tubes above it on the storage, the acceleration to be the previously calculated value and the coefficient of friction between stainless steel and rubber to be 0.64[1].

$$F = 0.64M_{tube}g + 0.245M_{tube} + 206.64$$
$$F = 208.36\ N$$

The selection of a rack and pinion capable of withstanding such load and having a 1000mm "stroke length" while maintaining the speed and acceleration requirements, as well as considering a reasonable price was conducted, particularly going through the Wittenstein Value Linear Systems Catalogue shown below.

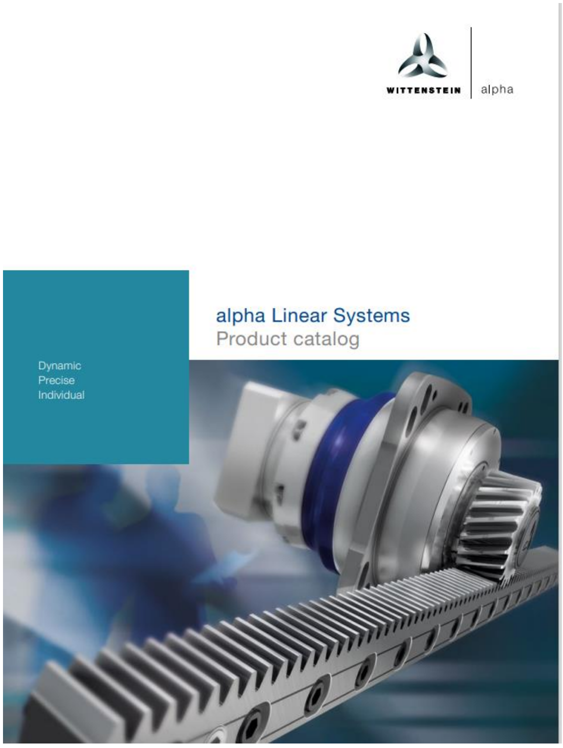


Figure 9: Wittenstein alpha linear systems product catalogue

Table 7: Wittenstein alpha linear value system 2 - NPR

Max. feed force (N)	1890
Max. feed speed (m/s)	1.32
Rack and Pinion module (mm)	1.5
Pinion number of teeth	19
Rack length (mm)	1000
Pinion PCD (mm)	30.3
Price (£)	

The selected rack, ZST 150-221-1000-R1, and pinion, RMK 150-222-1921-016-022, comprised the desired characteristics as shown in Table 7 colour code. Nonetheless, the rack and pinion system must be driven by a motor.

Pinion Driver Selection*

The torque required to drive the given rack and pinion system is:

$$T = F \times r_{pinion}$$
$$T = 208.36 \times 0.01515$$
$$T = 3.16\ Nm \qquad \text{Eq. 16}$$

Similarly, the maximum rotational speed of the pinion is given by:

$$n = \frac{v_{max} \times 60}{\pi d_{pinion}}$$
$$n = \frac{1.32 \times 60}{0.0303\pi}$$
$$n = 832\ rpm \qquad \text{Eq. 17}$$

And so, the motor selection was based on these criteria. The type of driver chosen was a servomotor because of its good accuracy, reliability, and power characteristics. The selection process was done using the Festo-Electromechanical Actuators servomotor selection tool with the following specifications:

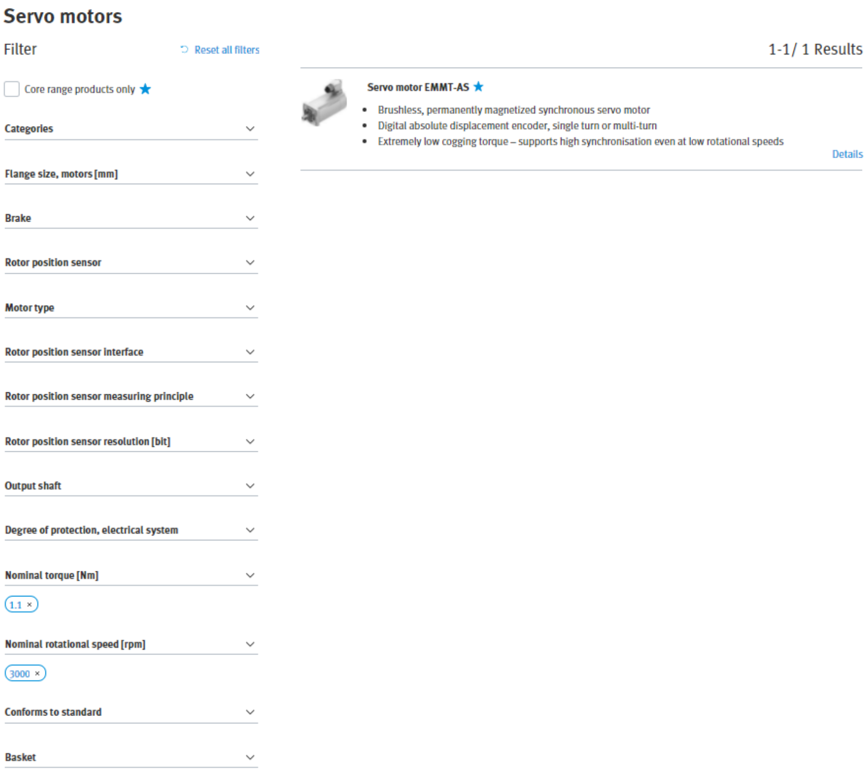


Figure 10: Festo servomotors selection tool

Table 8: EMMT-AS-60-S-LS-RM servomotor specifications

Nominal operating voltage (V)	565
Nominal torque (Nm)	0.64
Nominal rotary speed (rpm)	3000
Maintenance	190 years to failure
Price (£)	689

As the above colour code implies, the EMME-AS-80-M-HS-AMB operating speed is far above the required one. Therefore, the choice of integrating a reduction ratio gearbox was made with the following characteristics:

Table 9: EMGA-80-P-G5-EAS-80 gear unit specifications

Gear unit ratio	5:1
Drive speed (rpm)	3000
Drive torque (Nm)	3.2
Driving speed (rpm)	600
Price (£)	393

And so, the torque and speed characteristics delivered are compatible with the rack and pinion actuator.

Expansion Gun sub-assembly

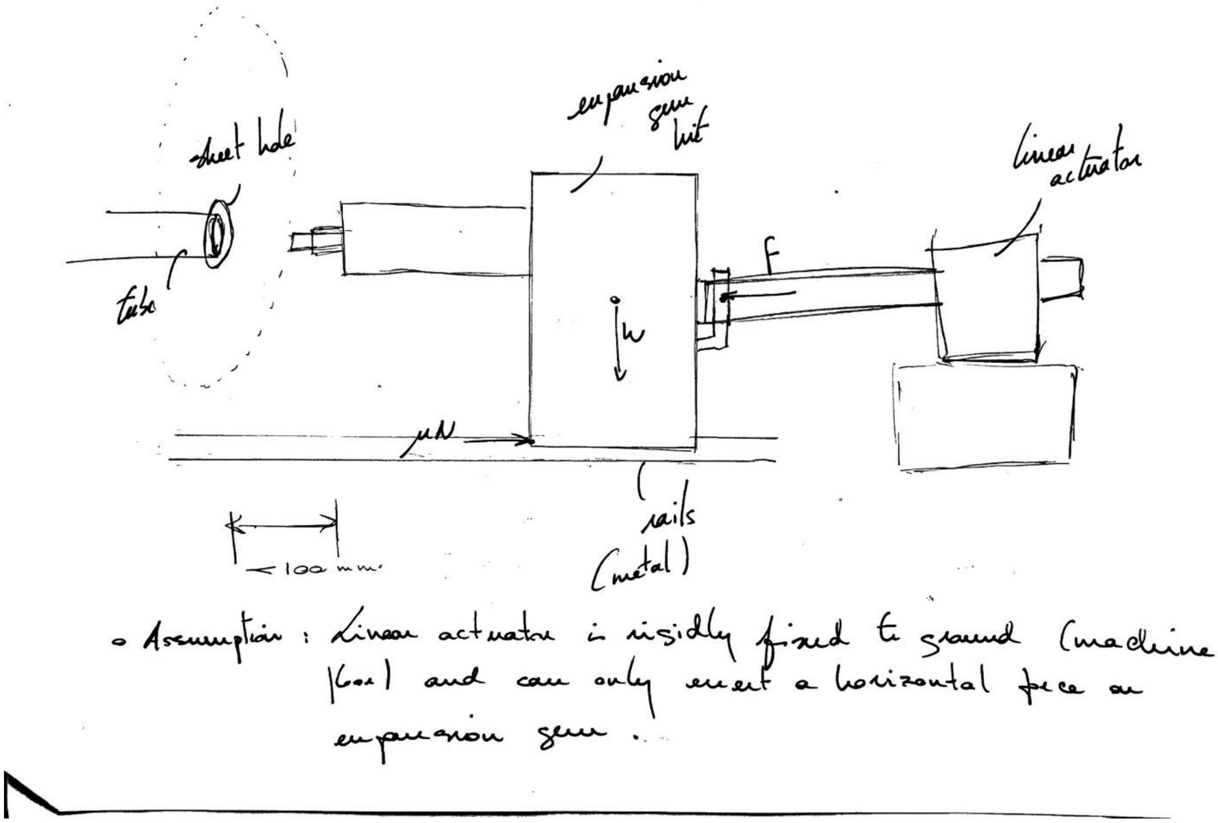


Figure 11: Diagram of Expansion unit and linear actuator

Linear Actuator Selection

The total weight of an expansion gun unit is 10 kg [2]. Also, given that the rails where the expansion unit slides are made of aluminium and considering the gun case to be made of steel, the coefficient of friction between both can be assumed to be 0.5[1]. And so, the force required by the linear actuator to push the expansion gun is:

$$F = \mu N$$
$$F = \mu g W_{e.unit}$$
$$F = 0.5 \times 9.81 \times 10$$
$$F = 42.05\ N \qquad \text{Eq. 18}$$

And so, the type of actuator chosen was linear electrical since the axial force is considerably low. A stroke length of 100 mm was set as an upper boundary and a moderate linear speed was desired to avoid any unexpected collisions with the metal sheets or tubes. From the Elero linear solutions catalogue, the following “push-rod” actuator was selected:

Figure 12: Elero linear actuator "Junior" catalogue

Table 10: Elero Junior 1A specifications

Nominal axial load (N)	50
Nominal speed (m/s)	0.55
Stroke length (mm)	100
Operating voltage (V)	24
Maintenance	Maintenance free – long life cycle
Price (£)	680

The actuator is electrically driven and so the only extra parts that need to be bought are cables, to connect the former to the machine's control unit.

Disk Storage sub-assembly

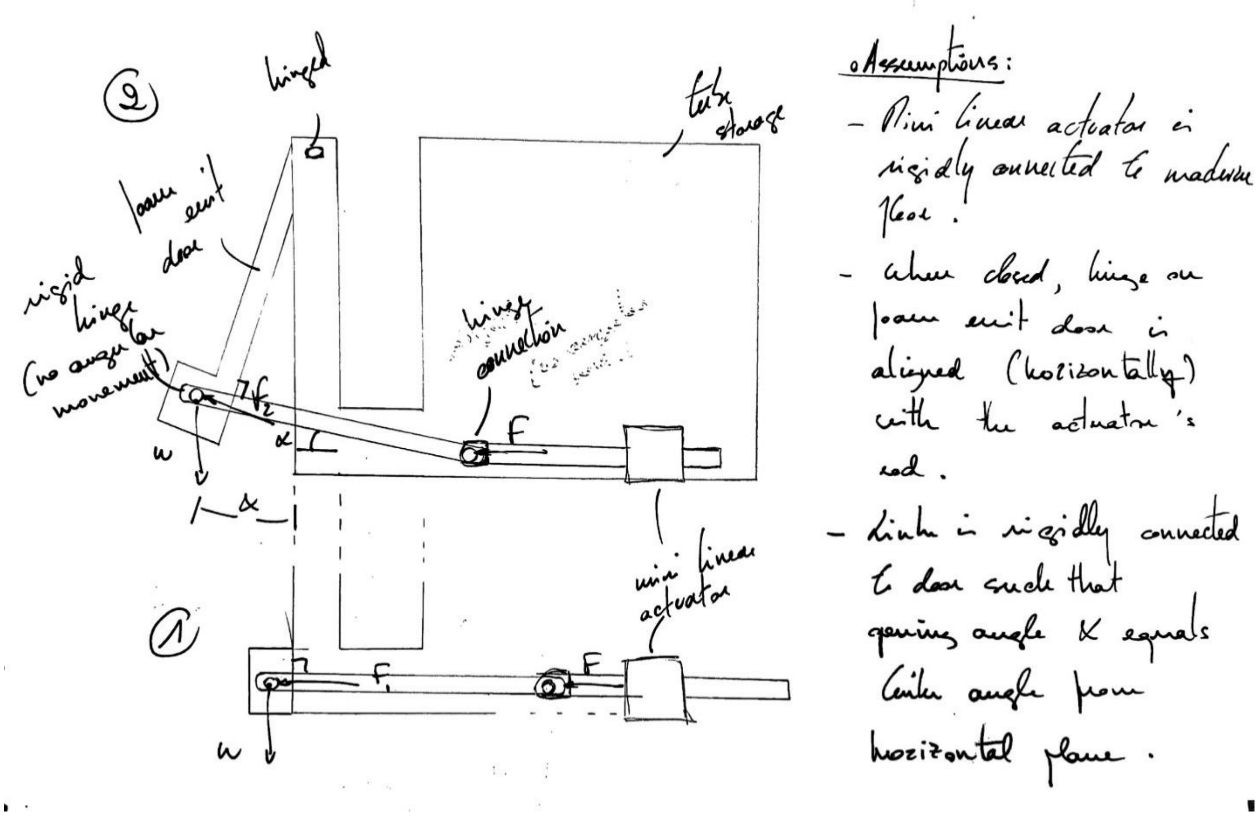


Figure 13: Diagram of disk storage sub-assembly

Foam Door Linear Actuator Selection

The foam exit door is made of cork (strong, durable and very light), whose density is 180 $kg.m^3$ [3]. Therefore, the mass of this door m_{door} is 0.1kg. For the following calculations, the weight of the link between the door and the actuator rod was assumed to be negligeable, as well as the hinge pins weight.

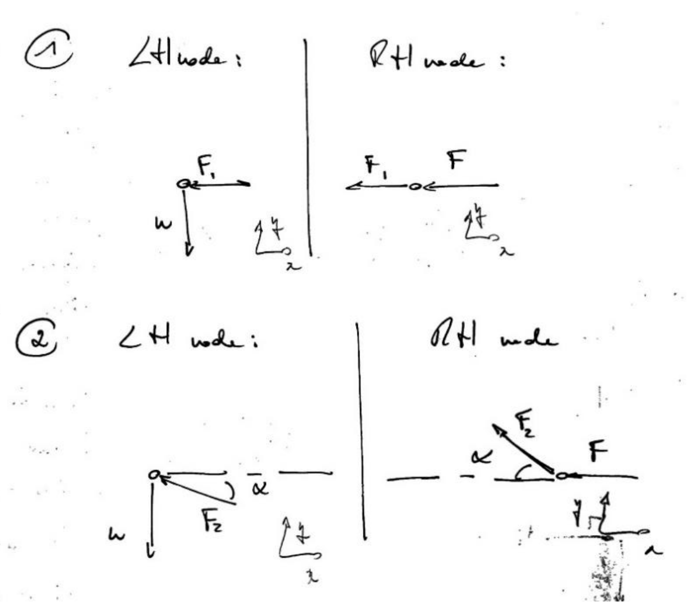


Figure 14: Forces at nodes of link between actuator rod and foam exit door

For the first scenario, where the door is closed:

$$F = F_1 = 0$$

Now for the second scenario, assuming the door is opened at its maximum angle (α = 20º), solving vertically for the left-hand node:

$$F_2 \sin(\alpha) = W$$

$$F_2 = \frac{W}{\sin(\alpha)} \qquad \text{Eq. 19}$$

And then solving horizontally for the right-hand node:

$$F = -F_2 \cos(\alpha)$$

$$F = -W \frac{\cos(\alpha)}{\sin(\alpha)}$$

$$F = -m_{door} g \frac{\cos(\alpha)}{\sin(\alpha)}$$

$$F = 2.6\ N \qquad \text{Eq. 20}$$

Considering the axial load applied is extremely low, the need for a big actuator was thought to be unnecessary and thus, an electrical miniature linear actuator was selected using the manufacturer Xeryon's selection tool as follows:

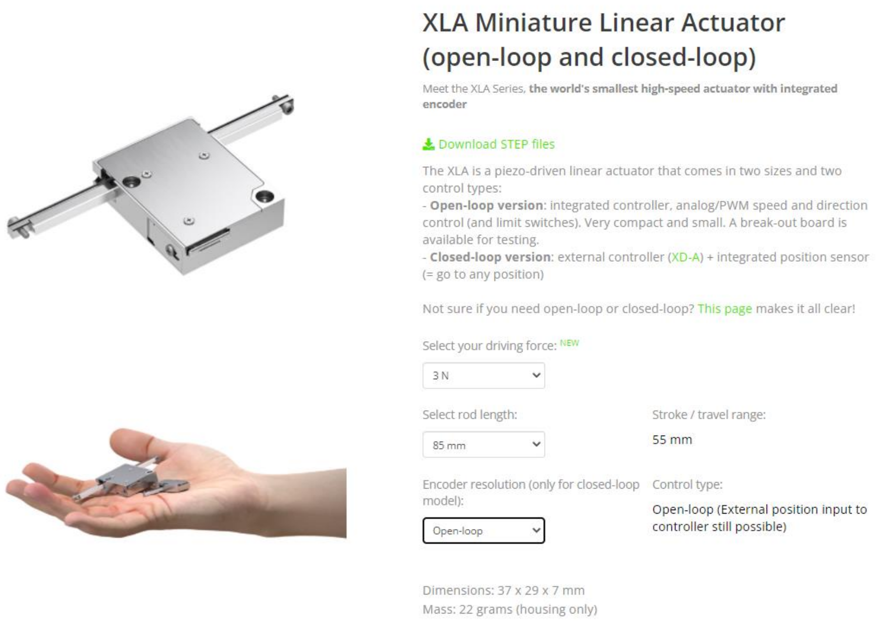


Figure 15: Xeryon miniature actuator selection tool

Control system type	Closed loop
Operating voltage (V)	12
Stroke length (mm)	55
Driving force (N)	3
Repeatability and accuracy (μm)	1.25

Max. operating speed (m/s)	1
Lifetime	1 million cycles
Price (£)	240

As the colour scheme implies, the chosen actuator can perform the foam door opening with providing accurate feedback on the door position. Being so small, the actuator does not need an additional motor to drive it, only cables directly connecting it to the machine control system.

Disk Spring Stiffness Calculation*

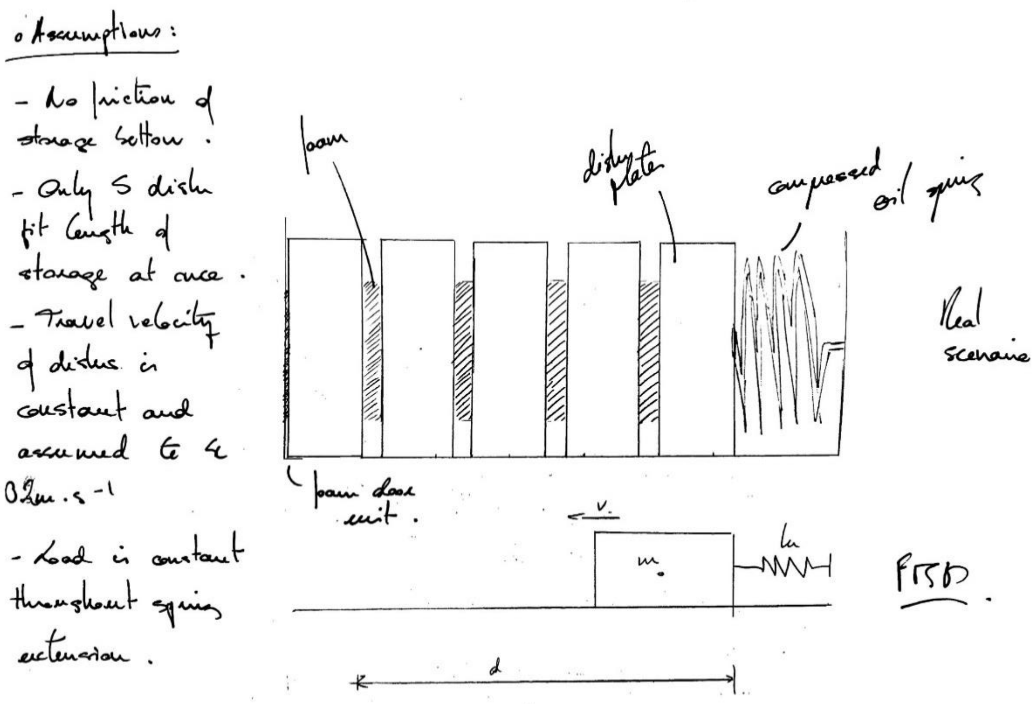


Figure 16: Diagram of spring and tube sheets

To satisfy the energy balance equation, the total energy stored by the spring must equal the energy taken by the disks to move from storage position to collection position. To clarify, the total travelled distance by the final disk is: 112 mm, only four in five disks need to travel into collection position and the velocity of travel was assumed to be 0.2 m/s. Therefore, the spring stiffness can be estimated by:

$$PE_{spring} = KE_{disks}$$

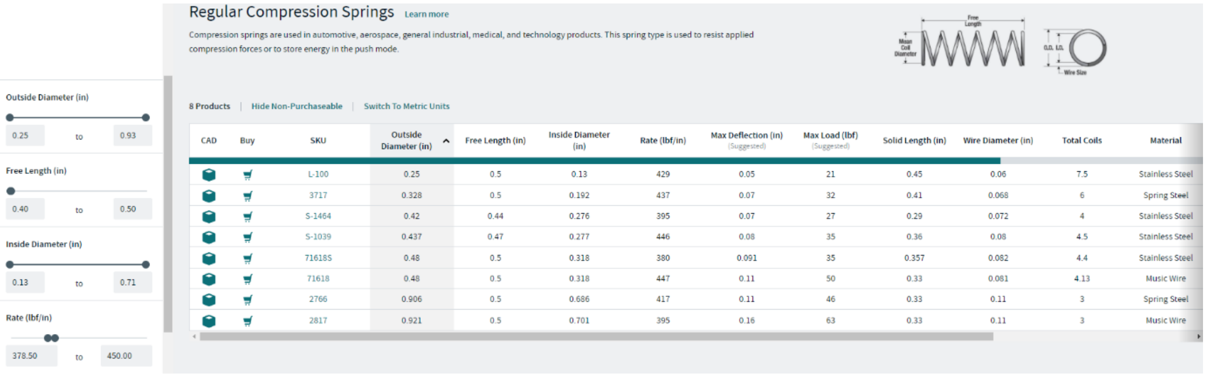
$$\frac{kx^2}{2} = \frac{mv^2}{2}$$

$$k = \frac{mv^2}{x^2}$$

$$k = \frac{4 \times 3.6 \times 0.2^2}{0.112^2}$$

$$k = 45.92\ N.m^{-1} \qquad \text{Eq. 21}$$

And so, from the spring stiffness and spring free length, the following coil spring was selected using the MW components selection tool:



Regular Compression Springs Learn more

Compression springs are used in automotive, aerospace, general industrial, medical, and technology products. This spring type is used to resist applied compression forces or to store energy in the push mode.

Outside Diameter (in) 0.25 to 0.93

Free Length (in) 0.40 to 0.50

Inside Diameter (in) 0.13 to 0.71

Rate (lbf/in) 378.50 to 450.00

8 Products | Hide Non-Purchaseable | Switch To Metric Units

CAD	Buy	SKU	Outside Diameter (in)	Free Length (in)	Inside Diameter (in)	Rate (lbf/in)	Max Deflection (in) (Suggested)	Max Load (lbf) (Suggested)	Solid Length (in)	Wire Diameter (in)	Total Coils	Material
		L-100	0.25	0.5	0.13	429	0.05	21	0.45	0.06	7.5	Stainless Steel
		3717	0.328	0.5	0.192	437	0.07	32	0.41	0.068	6	Spring Steel
		S-1464	0.42	0.44	0.276	395	0.07	27	0.29	0.072	4	Stainless Steel
		S-1039	0.437	0.47	0.277	446	0.08	35	0.36	0.08	4.5	Stainless Steel
		71618S	0.48	0.5	0.318	380	0.091	35	0.357	0.082	4.4	Stainless Steel
		71618	0.48	0.5	0.318	447	0.11	50	0.33	0.081	4.13	Music Wire
		2766	0.906	0.5	0.686	417	0.11	46	0.33	0.11	3	Spring Steel
		2817	0.921	0.5	0.701	395	0.16	63	0.33	0.11	3	Music Wire

Figure 17: MW Components compression springs selection tool

Table 11: 73092 Century Spring specifications

Material	Tempered oil
Free length (mm)	127
Spring rate (N/m)	45.4
Outside diameter (mm)	61.9
Number of coils	8.87
Price (£)	39.41

The chosen part is not perfect but provides good enough characteristics to be used and fits well within the tube storage dimensions.

Claw and winch sub-assembly

Suspension Frame Stress Calculations

The component under the most stress in the machine is the stainless-steel frame supporting the claws that hold the exchanger and move it along the expansion process. To predict if this component could withstand the required 10 years of machine functioning, the following calculations were made:

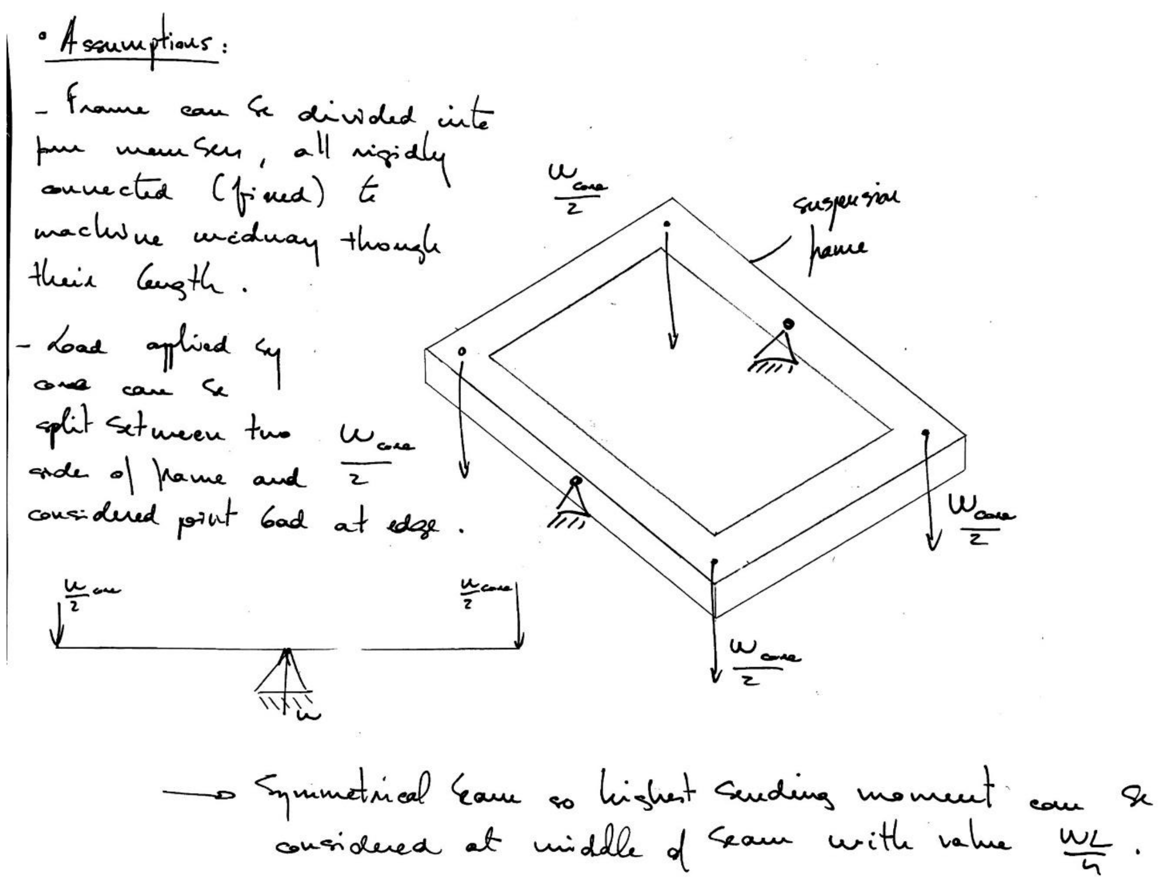


Figure 18: Diagram of suspension frame and loads

Given the beam is symmetrical, the reaction force at the fixed point is:

$$\sum F_y = 0$$

$$R = \frac{W}{2} + \frac{W}{2} = W \qquad \text{Eq. 22}$$

And again, for a symmetrical beam, the maximum bending moment can be estimated for the longest member in the frame as:

$$BM_{max} = \frac{Wl}{4}$$

$$BM_{max} = \frac{W_{core} l_{frame}}{4}$$

$$BM_{max} = \frac{292 \times 1}{4} = 73\ Nm \qquad \text{Eq. 23}$$

Therefore, considering the stainless-steel frame to have a squared cross section, as shown below, the maximum stress can be deduced:

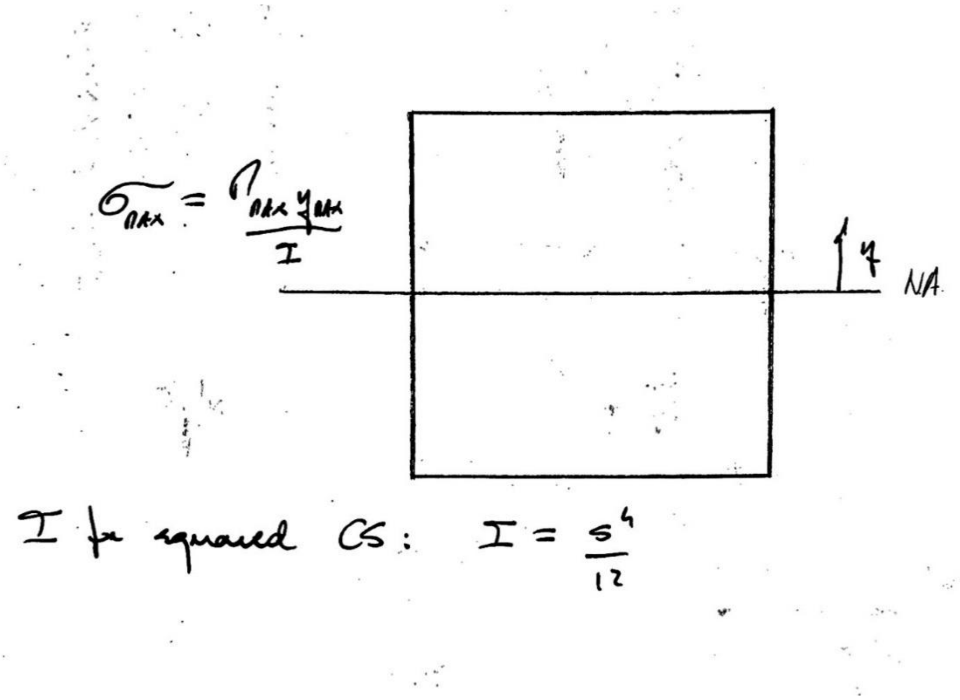


Figure 19: Diagram of suspension frame cross section

As shown above, the second moment of area of the cross section is:

$$I = \frac{s^4}{12}$$
$$I = \frac{0.02^4}{12}$$
$$I = 1.33 \times 10^{-8}\ m^4 \quad \text{Eq. 24}$$

And so, considering the largest distance from the neutral axis to be 10 mm:

$$\sigma_{max} = \frac{M_{max} y_{max}}{I}$$
$$\sigma_{max} = \frac{73 \times 0.01}{1.33 \times 10^{-8}}$$
$$\sigma_{max} = 54.9\ MPa \quad \text{Eq. 25}$$

Considering the material of the suspension frame to be stainless steel, the following properties can be obtained [5]:

Table 12: Stainless Steel fatigue properties

Tensile stress σ_T (MPa)	618
Endurance stress σ_e (MPa)	293

From this, the mean stress in the cross section can be estimated by considering the case where no load is applied to the arm of the suspension frame (no core being held) and thus the minimum stress is 0:

$$\sigma_{mean} = \frac{\sigma_{min} + \sigma_{max}}{2}$$

$$\sigma_{mean} = \frac{54.9}{2} = 27.45 \quad \text{Eq. 26}$$

And now a mean stress factor can be determined:

$$k_m = 1 - \frac{\sigma_{mean}}{\sigma_T}$$

$$k_m = 1 - \frac{27.45}{618}$$

$$k_m = 0.95 \quad \text{Eq. 27}$$

Now, considering a reliability factor of 0.814 for 99% reliability, the new endurance strength of the suspension's material can be determined:

$$\sigma_e' = \sigma_e k_m k_r$$

$$\sigma_e' = 293 \times 0.95 \times 0.814$$

$$\sigma_e' = 226.6\ MPa \quad \text{Eq. 28}$$

Now, because the maximum stress in the suspension frame is lower than the endurance stress, then the part is estimated to have an infinite life, perfectly suiting the design specification.

Claw Spring Stiffness Calculations*

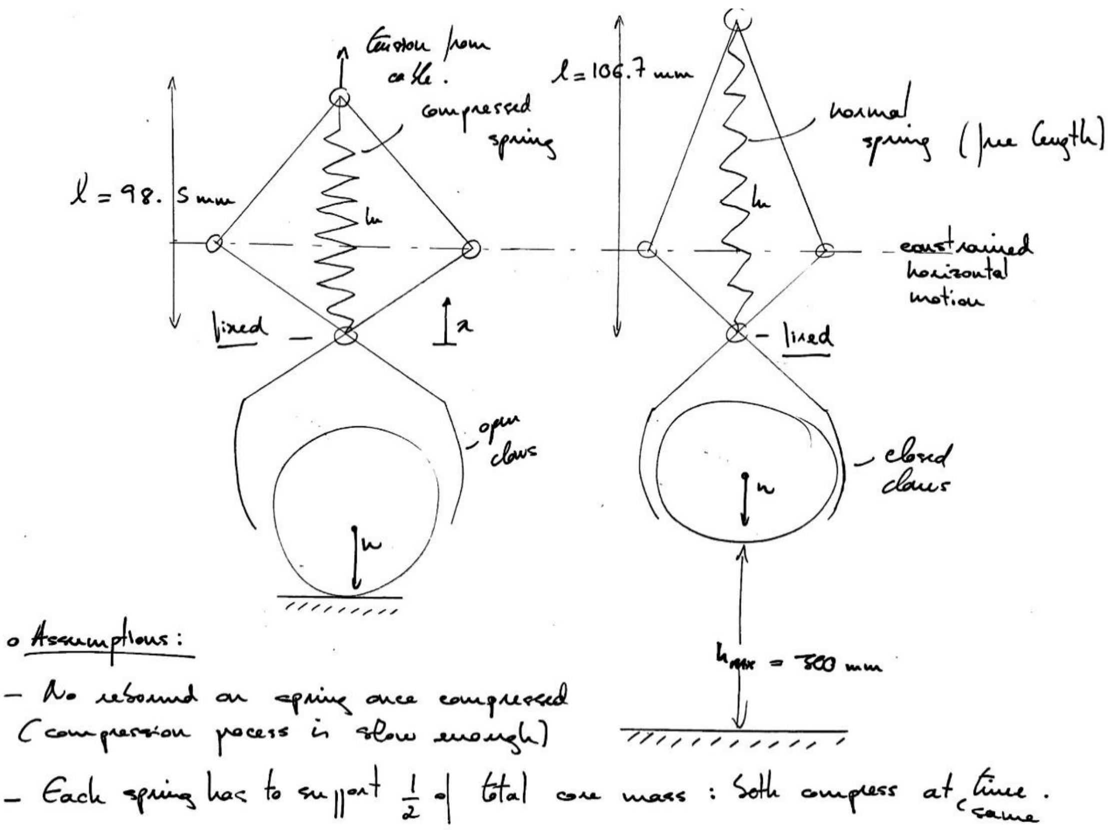


Figure 20: Diagram of core holding process

Again, to determine the stiffness of the spring used to close the claws and pick up the heat exchanger core. Note that the compression process should be made as slow as possible to avoid any spring rebound. Also note that the maximum load an individual can carry is half the mass of an assembled actuator. Similarly, the maximum height of the claw (above machine ground) is 300 mm and the distance travelled by the spring when compressed is 8.2 mm. Therefore:

$$PE_{spring} = PE_{core}$$

$$\frac{kx^2}{2} = mgh_{max}$$

$$k = \frac{2mgh_{max}}{x^2}$$

$$k = \frac{2 \times \frac{29.66}{2} \times 9.81 \times 0.3}{0.0082^2}$$

$$k = 1.29\ MN/m \qquad \text{Eq. 29}$$

And so based on this stiffness value and on the free length of the spring (98.5 mm), the following coil spring was selected, again using the MW Components selection tool:

Table 13: D-307816 Century Spring specifications

Material	Chrome Silicon
Free length (mm)	102
Spring rate (MN/m)	1.22
Outside diameter (mm)	50
Max deflection (mm)	22
Price (£)	58

The spring rate is a little under the required value but given the shape of the claw when enclosing the tube sheet, the load will be slightly distributed along the claw, and so the spring may be relaxed.

Clamp driver selection and calculations:

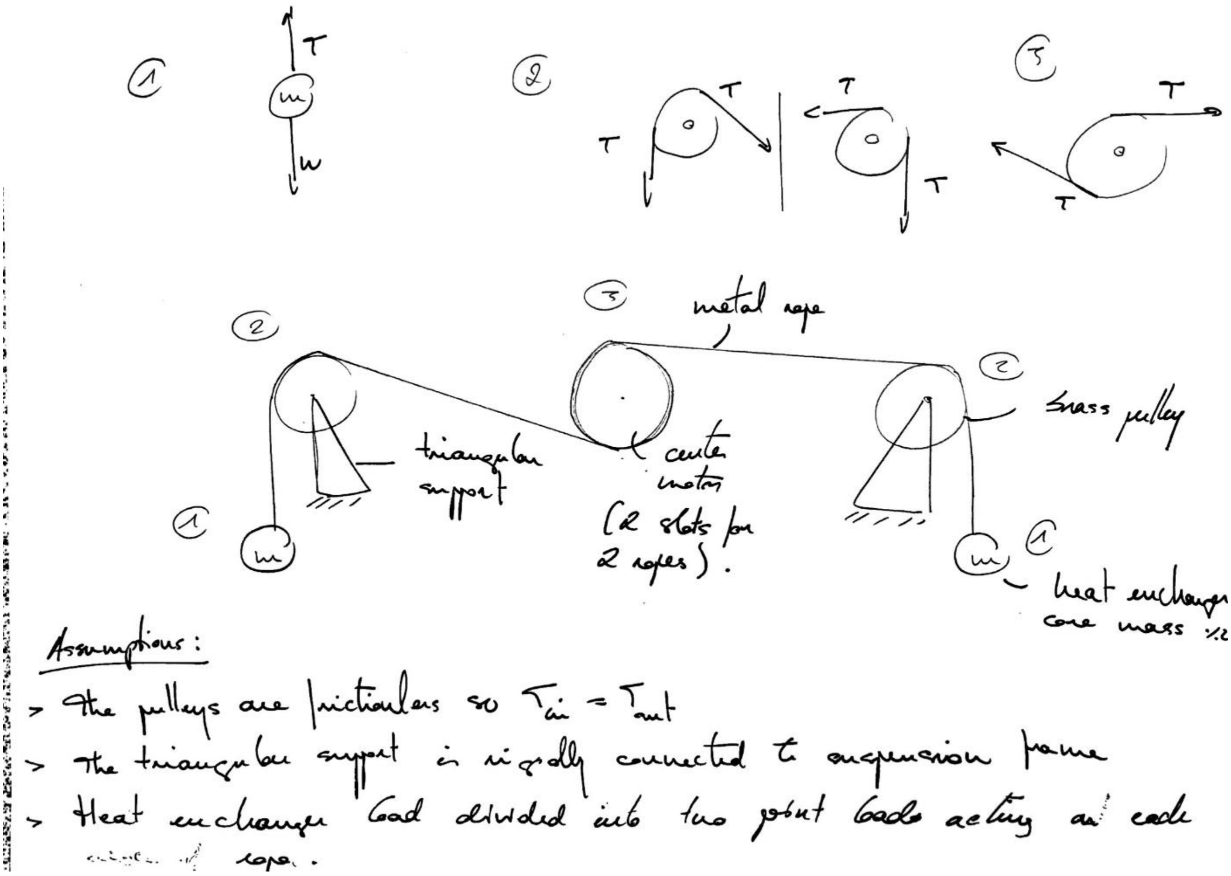


Figure 21: Diagram of rope and pulley system

From small diagrams 1,2 and 3, the tension applied to the centre pulley (connected to the motor) is:

$$T = 2W$$
$$T = 2 \times \frac{gM_{core}}{2}$$
$$T = 291\ N \qquad \text{Eq. 30}$$

Now, for a centre pulley radius of 40 mm, the torque τ is:

$$\tau = F \times r$$
$$\tau = 291 \times 40 \times 10^{-3}$$
$$\tau = 11.7\ Nm \qquad \text{Eq. 31}$$

Now, the type of drive needed for this clamp system is non-linear, since it will have to pulse displacements, followed by a brake. Therefore, a stepper motor was selected based on the torque calculations, given that it provides full torque at stall, and operates in a pulse form. A brake was added following the motor. From Anaheim Automation solutions:

Table 14: 42N112S-CB8 stepper motor specifications

Nominal voltage (V)	5
Nominal Power (W)	680
Step Angle (deg.)	1.8
Holding Torque (Nm)	22.2
Nominal Torque (Nm)	14.1
Nominal Speed (rpm)	450
Shaft diameter (mm)	19.1
Price (£)	900

Table 15: BRK-28H-1150-024-375-IP54 friction brake specifications

Max break torque (Nm)	11
Price (£)	200

The combined motor and brake provide a reliable solution to clamp the heat exchanger and move it around as needed.

Speed and Precision Calculations

Speed Calculations

Table 16: Speed and time data for a single core assembly

Part	Action	Speed (m/s)	Time (s)
Vertical Actuator	Lower 300 mm	0.75	0.45
Claws	Clamp tube sheet	4	Negligeable
Vertical Actuator	Raise disks 300 mm	0.75	0.45
Horizontal Actuator	Move disks to 360 mm from current position	0.75	0.48
Vertical Actuator	Lower disks 300 mm	0.75	0.45
Rack and Pinion	Place disk inside sheets 85 times (1m travel max)	1.9	45.05
Expansion gun	Expand tubes 85 times	?	595
Control system	Pause 85 times	0	3.09
Horizontal and Vertical Actuators	Move cores in expansion path	0.75	2.42
Claws	Unclamp tubes	4	Negligeable
Vertical Actuator	Raise 300 mm	0.75	0.45
Horizontal Actuator	Return 360 mm to initial position	0.75	0.45
Vertical Actuator	(2nd core starts here) Lower 300 mm	0.75	0.45
Claws	Clamp/Re-clamp disks	4	Negligeable
Vertical Actuator	Raise disks 300 mm	0.75	0.45
Horizontal Actuator	Move disks to 360 mm from current position	0.75	0.48
Vertical Actuator	Lower disks 300 mm	0.75	0.45

Expansion gun actuator	Insert gun inside tube (20 mm) 85 times	0.55	3.09
Expansion gun	Expand tubes 85 times	?	595
Horizontal and Vertical Actuators	Move cores in expansion path	0.75	2.42
Claws	Unclamp tubes	4	Negligeable
TOTAL TIME TAKEN (s and min)			**1250.63 / 20 min 50.64 s**

Precision Calculations

For the expansion process:

-Vertical actuator has 0.020 mm accuracy

-Horizontal actuator has 0.020 mm accuracy

-Diameter of holes in tube sheet tolerance is ±0.05 mm

-Outer diameter of tube tolerance is ±0.100 mm

-Position of any hole centre offset from required position tolerance is ±0.050 mm

If everything goes wrong, the total offset distance from the planned (and assumed by the control unit) alignment of the tubes and tube holes is then: 0.09 mm

Then if the radius of the holes in the tube sheet is 6.725 mm, and the tubes are 6.4 mm, then the maximum radial distance of the tubes OD from the required position is 6.49 mm.

Luckily, this value still allows the tubes to be fitted and expanded inside the tube sheets, so no expansion errors are expected to happen due to misalignment.

Sensing solutions

Disk position sensor

To detect if the disks are in position in the storage, and ready to be collected, a metal detecting proximity sensor was chosen. The material of the floor would have to be changed so as not to confuse the sensor.

Table 17: IQ40-20BDOKC0K inductive proximity sensor specifications

Sensing range (mm)	20
Electrical wiring	DC 2-wire
Switching frequency	150 Hz
Price (£)	41

Foam detecting sensor

To detect if the foam is out of disk storage once the latter are clamped and moved, a small motion detecting sensor is placed underneath the storage.

Table 18: NCV50B-11ECO100100 non-contact motion sensor specifications

Sensing range (mm)	50
Supply voltage (V)	12
Digital output	Type-dependant
Price (£)	3,450

Clamping force sensor

Load cell to determine clamping force of claws and simultaneously make sure the core is rightfully held and moved around by the gantry system.

Table 19: Miniature button load cell specifications

Load capacity (N)	500 N
Output signal	Wireless Transmitter
Price (£)	545

Tube position sensor

Again, metal detecting proximity sensor to check if tubes have fallen out of storage and are ready to be inserted into sheets. This technology would require the sliding platform at the bottom of the machine to be made of a non-metal material so as not to confuse the sensor. Same sensor as for disk storage so price is £41.

Expansion process sensor

To monitor the expansion process, two photoelectric sensors will be placed at each side of the tube sheet, perpendicular to the tubes. The sensor issues laser technology and detects if the tubes are offset from the tube sheet (to inserted or not too much) by monitoring reception of photoelectric signal from the receivers. It can be adjusted to match the different tube sizes.

Table 20: WTT2SL-2P1192 photoelectric sensor specifications

Sensing range (mm)	800
Light spot diameter (mm)	10
Supply voltage (V)	10
Type of output	Analogue - cable
Price (£)	198

Gantry system linear sensors

The horizontal and vertical actuators are monitored by a linear encoder, having to be integrated in them along with a magnetic tape. The magnetic technology of the encoder able to provide very accurate position feedback to the machine's control unit.

Table 21: TTK70-AXA0-K02 linear encoder specifications

Maximum measuring length (mm)	<3920
Resolution (µm)	1
Maximum traversing speed (m/s)	10
System accuracy (µm)	10
Supply voltage (V)	4.5
Price (£)	650.85

Machine control unit and user interface

Control unit

Despite not having mentioned the machine's control unit previously, it can be stated that every sensor, and motor is directly connected to the machine's control unit. This part contains a PI controller that operates the machines sub-assemblies based on feedback provided by the sensors. The power supply coming from this unit is used to drive all the motors and actuators considering their specific required voltages. Finally, this control unit is where the machine can be programmed to accommodate different lengths of the tubes, even if the changes in the machine's sub-assemblies still must be taken into consideration when altering the product cycle.

User interface

The user interface was not modelled; however, it is imagined having three buttons and a display screen. The display unit informs the user of the current product cycle and on the running time since the latter has been altered. The first button corresponds is used for general errors in the machine, informed to the technicians by an alerting light and can be turned off manually once these errors are found and fixed. The second button is used when another light goes on, telling the technicians the disk storage is empty and needs refilling. Once the disks are refilled, the technician presses the button and the machine's control unit knows the storage is now full. A similar process happens for the third button, but considering the foam tank, for the foam that fall from the disk storage.

Costing

part name	price per uni	quanity	price	reference
plate storage sub assy	**378.03**	**1**	**378.03**	
disk reservoir	15	2	30	bespoke
M5 bolts	0.02	8	0.16	https://www.screwfix.com/p/easyfix-bzp-steel-set-screws-m5-x-8mm-100-pack/4239h
M5 nut	0.05	8	0.4	https://www.screwfix.com/p/easyfix-a2-stainless-steel-hex-nuts-m5-100-pack/2639t
motor platform	6	2	12	https://moodle.bath.ac.uk/pluginfile.php/1344258/mod_resource/content/1/Item_PriceList.pdf
mini electric actuator	240	2	480	Model and pricing from Xeryon - https://xeryon.com/products/mini-linear-actuators/?utm_source=bing&utm_campaign=Linear+Stages&utm_medium=ppc&utm_term=mini%20linear%20actuator&hsa_kw=mini%20linear%20actuator&hsa_mt=e&hsa_tgt=kwd-84387798373503:loc-188&hsa_src=o&hsa_ad=&hsa_ver=3&hsa_cam=8276589006&hsa_net=adwords&hsa_acc=6676083437&hsa_grp=1350200735091874
actuator rod	9.27	2	18.54	https://moodle.bath.ac.uk/pluginfile.php/1344258/mod_resource/content/1/Item_PriceList.pdf
foam gates	3.67	2	7.34	https://moodle.bath.ac.uk/pluginfile.php/1344258/mod_resource/content/1/Item_PriceList.pdf
disk thruster	4.2	2	8.4	https://www.themetalstore.co.uk/products/16swg-1-6mm-thick-mild-steel-rectangular-box-section
coil spring	39	2	78	Model and pricing from MS Components - https://datasheets.globalspec.com/ds/64/CenturySpringCorp/56E43252-7735-4039-90E9-45AEA3C00A1A
piston head	10	2	20	bespoke
connecting shaft	6.27	2	12.54	https://moodle.bath.ac.uk/pluginfile.php/1344258/mod_resource/content/1/Item_PriceList.pdf
dowel pin	3.55	4	14.2	https://moodle.bath.ac.uk/pluginfile.php/1344258/mod_resource/content/1/Item_PriceList.pdf
proximity sensor	41	1	41	Pricing from SICK sensors - https://www.sick.com/gb/en/inductive-proximity-sensors/inductive-proximity-sensors/iqg/iq40-20bdokc0k/p/p653889
motion sensor	3,450	1	3450	Pricing from SICK sensors - ff_data=JmZmX2lkPXA2NTkyNTQmZmZfbWFzdGVySWQ9cDY1OTI1NCZmZl90aXRsZT1OQ1Y1MEItMTFFQzAxMDAxMDAmZmZfcXVlcnk9JmZmX3Bvcz0zJmZmX29yaWdQb3M9MyZmZl9wYWdlPTEmZmZfcGFnZVNpemU9MjQmZmZfb3JpZ1BhZ2VTaXplPTI0JmZmX3NpbWk9OTcuMA==
claw and winch sub-assembly	**2969.99**	**1**	**2969.99**	
clamp mechanism connection hook	2.95	4	11.8	https://www.thesafetysupplycompany.co.uk/p/8773319/045t-wll-galvanised-large-bow-shackle-cw-type-a-screw-collar-pin---38-x-12---conforms-to-bs-3032---gt-htlbg45.html
claw spring	58	4	232	Pricing from MW Components - https://www.mwcomponents.com/shop/sp-dm-a-00045?variant=391821
clamp short arm	0.12	8	0.96	https://www.themetalstore.co.uk/products/2mm-thick-2b-finish-304-grade-stainless-steel-sheet
slider pin track	1.5	4	6	https://www.themetalstore.co.uk/products/2mm-thick-2b-finish-304-grade-stainless-steel-sheet
slider pin	3.65	8	29.2	https://www.cromwell.co.uk/shop/fasteners/dowel-pins/8x50mm-metric-extractable-dowel-pin-c-w-air-flat/p/QFT6500242A
clamp mechanism crossing pin	3.65	4	14.6	https://www.cromwell.co.uk/shop/fasteners/dowel-pins/8x50mm-metric-extractable-dowel-pin-c-w-air-flat/p/QFT6500242A
clamp long arm	0.45	8	3.6	https://www.themetalstore.co.uk/products/2mm-thick-2b-finish-304-grade-stainless-steel-sheet
suspension frame	9.93	1	9.93	https://www.themetalstore.co.uk/products/2-0mm-thick-mild-steel-sheet
cable	0.65	4	2.6	https://www.tcfixings.co.uk/product/5mm-galvanised-steel-wire-rope-10-metre/17618?msclkid=c35dd7195f8110e64384b55b15a8d1f1
double pulley bracket	49	2	98	Pricing from Expertfitness - https://www.gymparts.co.uk/steel-pulley-bracket-and-90mm-double-pulleys-swivel-or-fixed-back-to-back/p10411
single pulley bracket	8.29	4	33.16	https://www.themetalstore.co.uk/products/2-0mm-thick-mild-steel-sheet
pulley mount plate	8.29	2	16.58	https://www.themetalstore.co.uk/products/2-0mm-thick-mild-steel-sheet
double pulley	145	2	290	Pricing from safety supply company - https://www.thesafetysupplycompany.co.uk/Listing/Category/?categoryId=4534189&page=1&sortItem=2&sortDirection=1&utm_source=bing&utm_medium=cpc&utm_campaign=Generic%20-%20Working%20At%20Height%20-%20Equipment%20-%202021%20New%20-%20(manual)&utm_term=double%20pulley&utm_content=Pulleys
single pulley	5.39	4	21.56	https://www.wireropeshop.co.uk/brass-nickel-plated-sheave-pulley-wheel/
claw driver motor	900	2	1800	Model and pricing from Anaheim Automation (Manufacturer) - https://www.anaheimautomation.com/products/stepper/stepper-motor-item.php?sID=22&pt=i&tID=75&cID=19
claw driver brake	200	2	400	Model and pricing from Anaheim Automation - https://www.anaheimautomation.com/manuals/accessories/L010464%20-%20BRK-28H-1150-024-375%20Product%20Sheet.pdf
miniature load cell	545	2	1090	Pricing from LoadCellShop - https://www.loadcellshop.co.uk/load-cells/miniature-button-load-cells/miniature-button-load-cell-up-to-2kn-detail
tube storage assy	**1309.12**	**1**	**1309.12**	
tube storage	20	1	20	Bespoke
rack and pinion	190	1	190	Model from Wittenstein (Manufacturer) - https://www.wittenstein.co.uk/products/linear-systems/system-solutions/value-linear-systems/
rack mount	13.05	1	13.05	https://cpc.farnell.com/c/electrical-lighting/enclosures-racks-accessories/cabinet-rack-accessories/rack-mount-fan-trays/19-rack-mounts
pinion driver motor	689	1	689	Model and pricing from Festo GB - https://www.festo.com/gb/en/a/5242197/?siteName=Festo+GB
pinion driver gear	393	1	393	Model and pricing from Festo GB - https://www.festo.com/gb/en/a/2297690/
tube storage divider	4	2	8	https://moodle.bath.ac.uk/pluginfile.php/1344258/mod_resource/content/1/Item_PriceList.pdf
M3 screws	0.07	12	0.84	Model and pricing from Screwfix - https://www.screwfix.com/p/easyfix-bright-zinc-plated-pan-head-machine-screws-m3-x-20mm-25-pack/5875j
proximity sensor	41	3	123	Pricing from SICK sensors - https://www.sick.com/gb/en/inductive-proximity-sensors/inductive-proximity-sensors/iqg/iq40-20bdokc0k/p/p653889
exchanger assembly and first expansion subassembly	**435.8**	**1**	**435.8**	
exchanger support	7	1	7	bespoke
rails - long	15	2	30	Pricing from Sliding Systems - https://gsf-promounts.com/product/r32-radial-rail-9-56kg-rail-only/
M3 screws	0.07	40	2.8	Model and pricing from Screwfix - https://www.screwfix.com/p/easyfix-bright-zinc-plated-pan-head-machine-screws-m3-x-20mm-25-pack/5875j
light gate sensor + receiver	190	2	380	Model and pricing from SICK sensors - https://www.sick.com/gb/en/photoelectric-sensors/photoelectric-sensors/powerprox/wtt2sl-2p1192/p/p532248?ff_data=JmZmX2lkPXA1MzIyNDgmZmZfbWFzdGVySWQ9cDUzMjI0OCZmZl90aXRsZT1XVFQyU0wtMlAxMTkyJmZmX3F1ZXJ5PSZmZl9wb3M9MSZmZl9vcmlnUG9zPTIxJmZmX3BhZ2U9MSZmZl9wYWdlU2l6ZT04JmZmX29yaWdQYWdlU2l6ZT04JmZmX3NpbWk9OTQuMA==
sensor support	2	8	16	bespoke

second expansion process assy	**1114.28**	**1**	**1114.28**	
ramp	20	1	20	bespoke
light gate sensor + reciver	190	2	380	Model and pricing from SICK sensors - https://www.sick.com/gb/en/photoelectric-sensors/photoelectric-sensors/powerprox/wtt2sl-2p1192/p/p532248?ff_data=JmZmX2lkPXA1MzIyNDgmZmZfbWFzdGVySWQ9cDUzMjI0OCZmZl90aXRsZT1XVFQyU0wtMlAxMTkyJmZmX3F1ZXJ5PSZmZl9wb3M9MSZmZl9vcmlnUG9zPTIxJmZmX3BhZ2U9MSZmZl9wYWdlU2l6ZT04JmZmX29yaWdQYWdlU2l6ZT04JmZmX3NpbWk9OTQuMA==
sensor support	2	2	4	bespoke
M3 screws	0.07	4	0.28	Model and pricing from Screwfix - https://www.screwfix.com/p/easyfix-bright-zinc-plated-pan-head-machine-screws-m3-x-20mm-25-pack/5875j
rails - short	15	2	30	Pricing from Sliding Systems - https://gsf-promounts.com/product/r32-radial-rail-9-56kg-rail-only/
expansion gun actuator	680	1	680	Model and pricing from hepcomotion (Manufacturer) - https://www.hepcomotion.com/product/electric-actuators/elero-electric-actuator-range/?tab=technical
gantree sub assy	**9282**	**1**	**9282**	
horizontal actuator for gantree	800	1	800	Model and Pricing from USW - https://www.thk.com/?q=us/node/13678
actuator motor for gantree	870	3	2610	Model and pricing from Festo GB - https://www.festo.com/gb/en/a/5242199/?q=~:sortByFacetValues-asc
actuator motor gear for gantree	394	3	1182	Model and pricing from Festo GB - https://www.festo.com/gb/en/a/2297687/?siteName=Festo+GB
vertical actuator for gantree	1370	2	2740	https://www.festo.com/gb/en/a/3013390/?q=~:sortByFacetValues-asc~:CC_Drive_type_C_FP_GLOBAL~:CC_Drive_type.BS~:CC_Stroke_mm_C_FP_GLOBAL~:300.0
linear encoder for actuators	650	3	1950	Pricing from SICK encoders - https://www.sick.com/gb/en/encoders/linear-encoders/ttk70/ttk70-axa0-k02/p/p239840?ff_data=JmZmX2lkPXAyMzk4NDAmZmZfbWFzdGVySWQ9cDIzOTg0MCZmZl90aXRsZT1UVEs3MC1BWEEwLUswMiZmZl9xdWVyeT0mZmZfcG9zPTEmZmZfb3JpZ1Bvcz0xJmZmX3BhZ2U9MSZmZl9wYWdlU2l6ZT0yNCZmZl9vcmlnUGFnZVNpemU9MjQmZmZfc2ltaT05Ny4w
expander gun assy	**21378.64**	**2**	**42757.28**	
tube expander	10000	2	20000	Model and pricing from assignement brief
tube expander linear actuator	680	2	1360	Model and pricing from Elero Junior - https://www.elero-linear.de/de/produkte/linearantriebe/junior-1/
tube expander actuator support	3	1	3	Bespoke
gun to actuator adapter	2	1	2	Bespoke
gun actuator mount	2	2	4	Bespoke
gun to rail adapter	9	1	9	Bespoke
M8 screw	0.08	8	0.64	Pricing from Screwfix - https://www.screwfix.com/c/screws-nails-fixings/bolts/cat840086?boltsize=m8
frame	**1020**	**1**	**1020**	
nuts and bolts	0.02	1000	20	Model and pricing https://www.screwfix.com/p/easyfix-bzp-steel-set-screws-m5-x-8mm-100-pack/4239h
frame	1000	1	1000	Bespoke
TOTAL MACHINE PRICE			**59266.5**	

References for calculations

[1] - Edge, E., 2022. Coefficient of Friction Equation and Table Chart. [online] Engineersedge.com. Available at: <https://www.engineersedge.com/coeffients_of_friction.htm> [Accessed 23 February 2022].

[2] – Brief Document

[3] - Edge, E., 2022. Coefficient of Friction Equation and Table Chart. [online] Engineersedge.com. Available at: <https://www.engineersedge.com/coeffients_of_friction.htm> [Accessed 23 February 2022].

Method of Operation Storyboard

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Stage 1

- Plates are stored in plate storage sub-assembly, a number of them are placed inside and kept at the front by a spring in the back of the box.
- Claw and winch sub-assembly lowers (whilst claws are open) over plate storage sub-assembly plate slots.
- Alpha claw system is applied via actuators and claws close around the plates which are at the front of each plate storage subassembly.

(Foam gate and foam transparent for visual clarity of plate position.)

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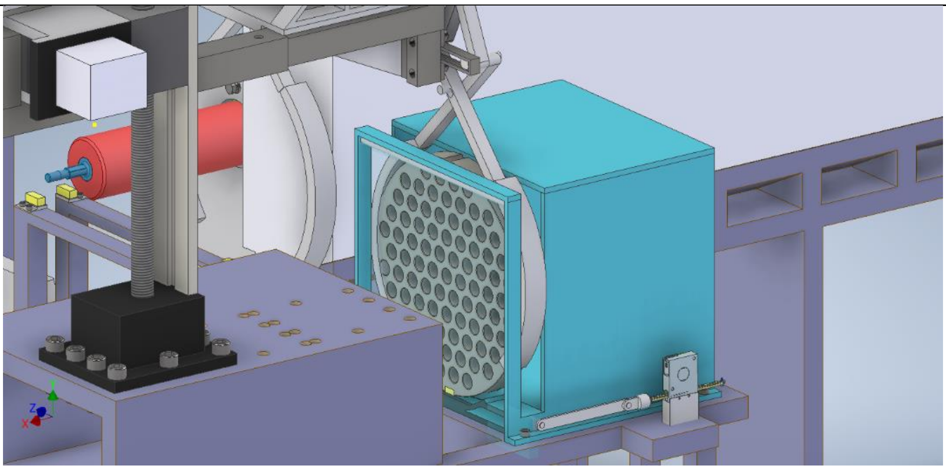
<td></td>
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Stage 2

- Mini Electrical Actuator pushes foam gates of plate storage sub-assembly open to allow protective foam to drop down into box below (box built into frame).

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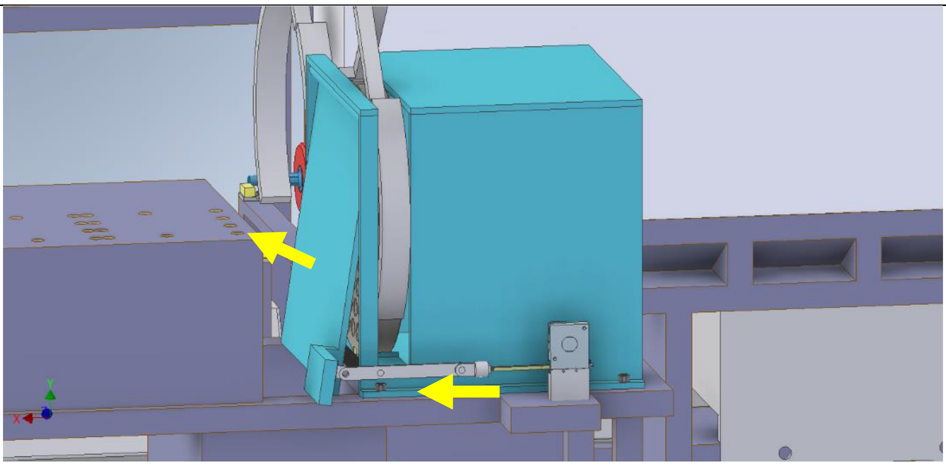
<td></td>
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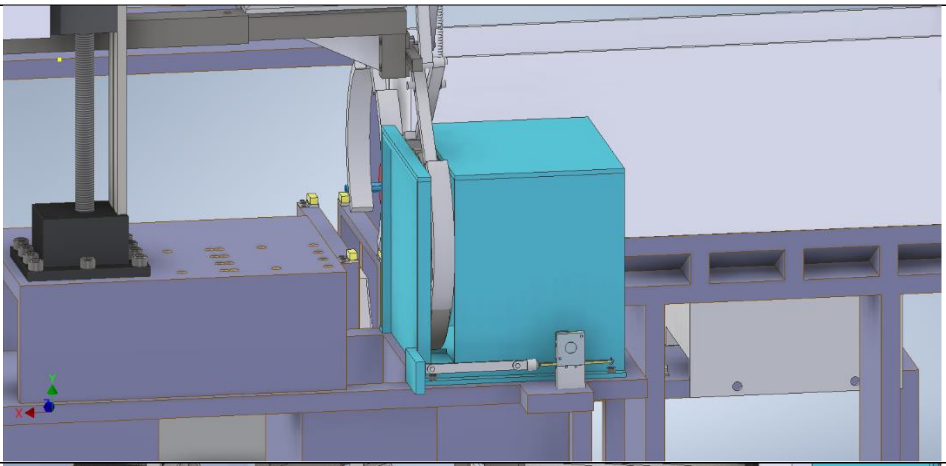
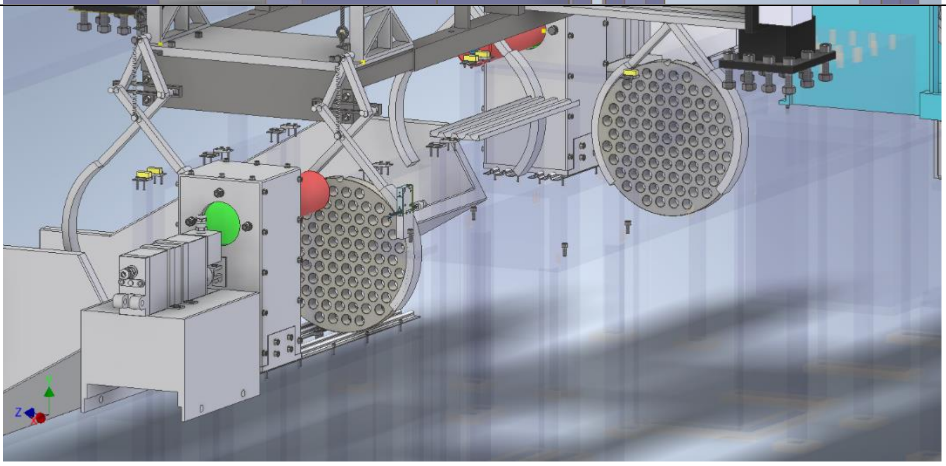
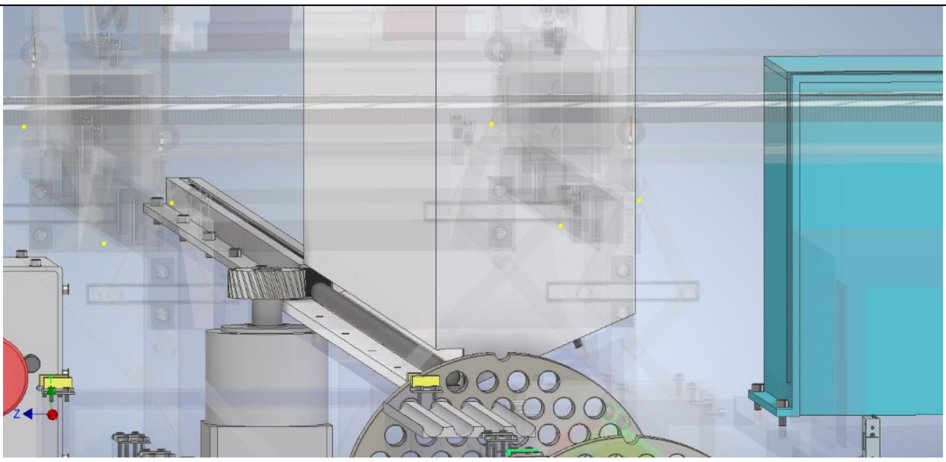
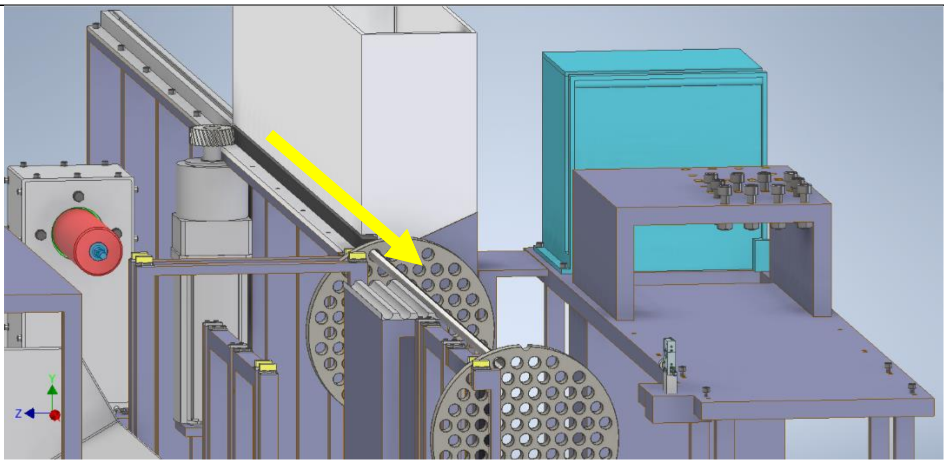
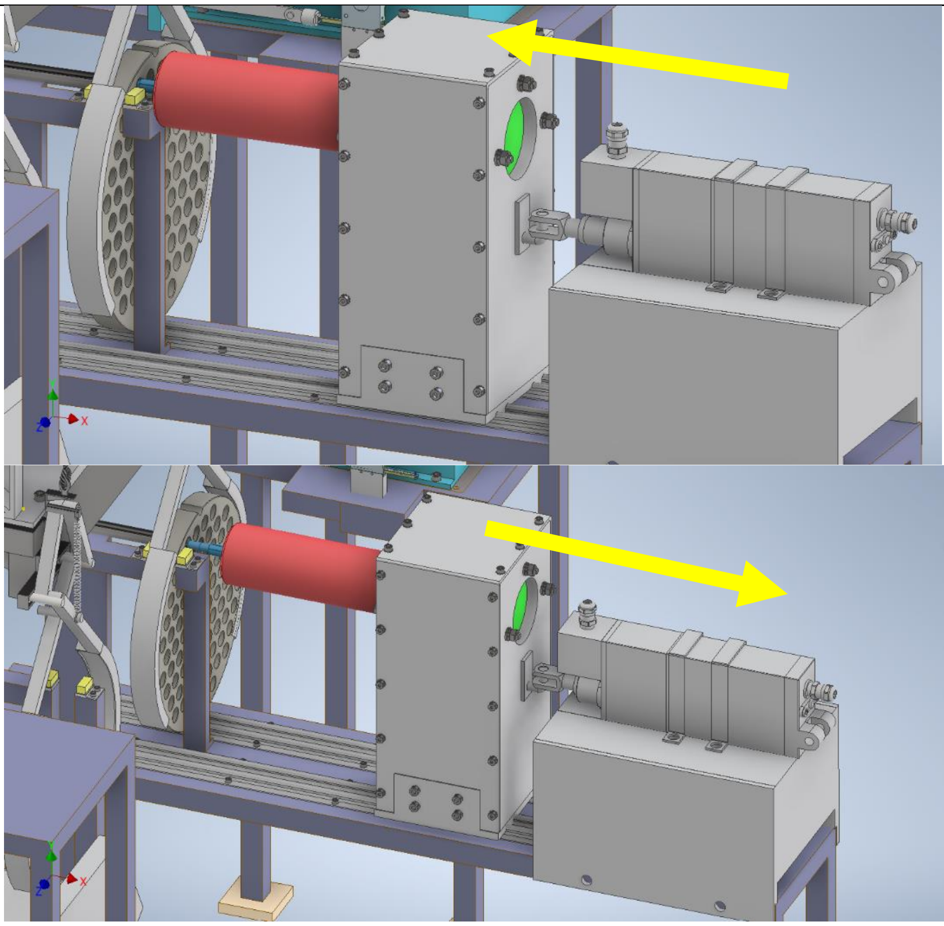
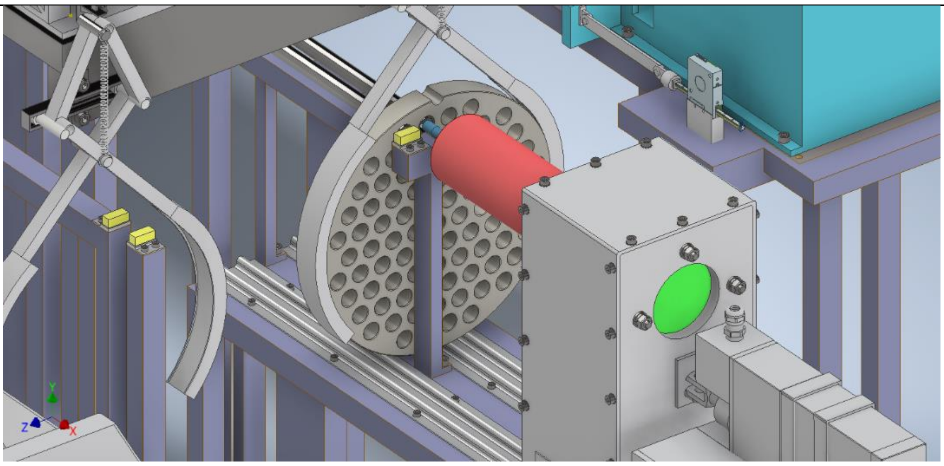
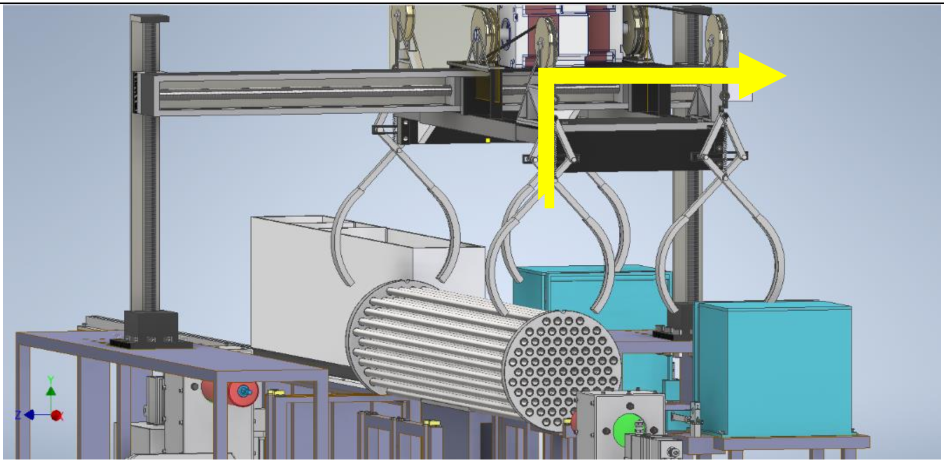
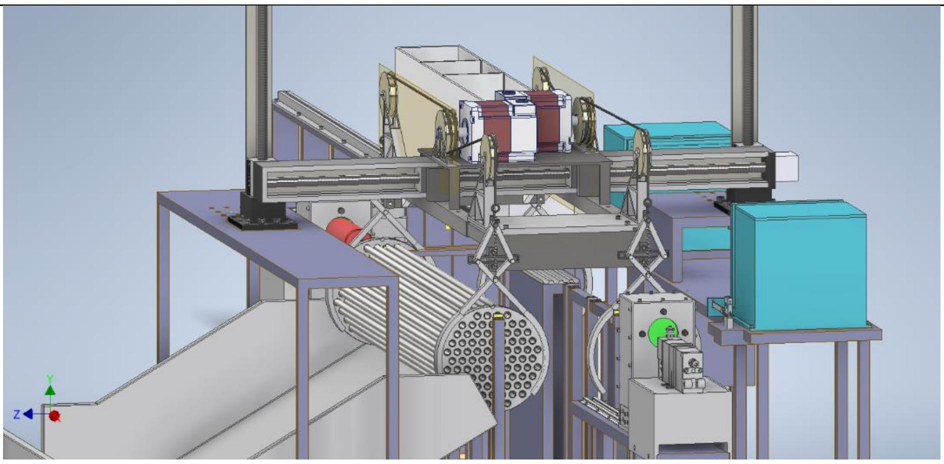
Stage 3 • Mini Electrical Actuator retracts which closes foam gates of plate storage sub-assembly	
Stage 4 • Claw and winch sub-assembly moves assembly to Station 2 via linear actuators whist holding plates. • (Beta claw system now at Station 3 to complete stages 10-12) (Frame transparent for visual clarity.)	
Stage 5 • Rack is retracted into rack mount by pinion, and first tube drops down to the tube storage slot, lining up with the first hole on the top row of the plates. (Frame and Claw and winch sub-assembly transparent so that rack and pinion, and tube storage can be seen.)	

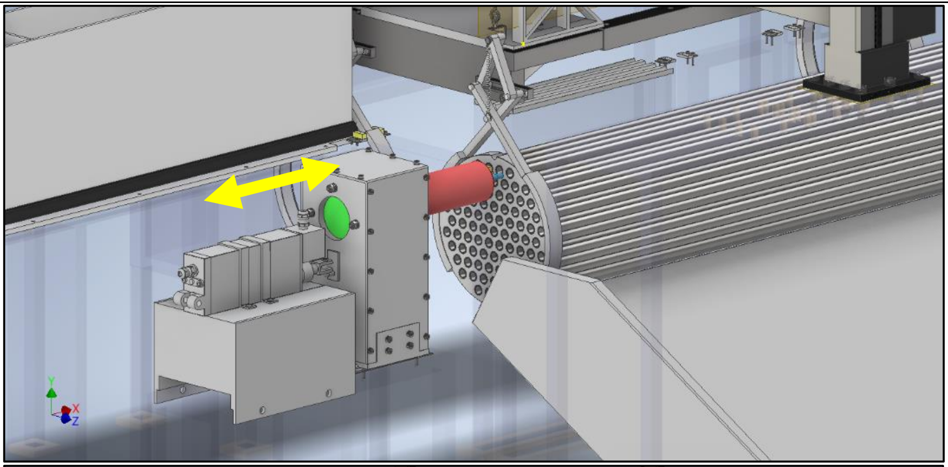
Stage 6 • Piston drives rack forwards, pushing the first tube through hole 1 of both plates. • The tube is guided and supported in the middle by the outer most groove in the exchanger support. (Claw and winch sub-assembly invisible so that tube can be seen.)	
Stage 7 • Expansion gun 1 moves forward via linear actuator into hole 1 of plate 1 (the plate farthest from the tube storage sub-assembly) and completes the expansion of the joint. • Expansion gun is mounted on rails to ensue consistent alignment and smooth movement. • Expansion gun retracts to its original position via the linear actuator.	

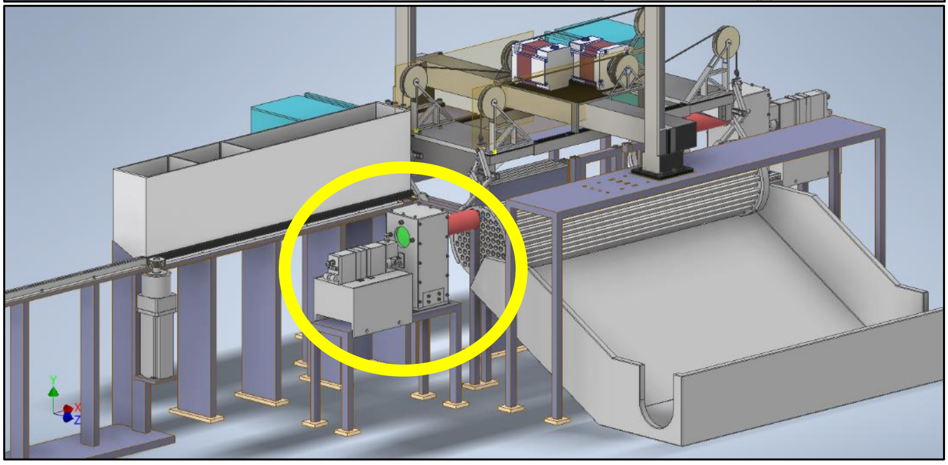
Stage 8 • Claw and winch sub-assembly moves (via gantry sub-assembly actuators) such that the expanding gun is aligned with hole 2 in the pate (directly next to hole 1). • Stages 5-7 are repeated up to hole 85.	
Stage 9 • Core is left resting on exchanger support whilst gantry sub-assembly moves back to its initial position at stage 1. The set of claws which have been used so far return to the plate storage sub-assembly to repeat stages 1 to 7	
Stage 10 • Claw and winch sub-assembly is lowered and takes hold of the plates (the same movement as in stage 1 but positioned at station 2) • Gantry assembly moves the claw and winch system to Station 3 via linear actuators as seen in Stage 4 whilst holding the plates in each claw.	

Stage 11

- Stages 6 and 7 are repeated for the expansion of the tubes already positioned in the holes of plate 2 via the second expanding gun.
- The order and timing simultaneous with the first expansion as the claw and winch system moves as one assembly.
- (Beta claw system now at Station 2 for stages 5-8)

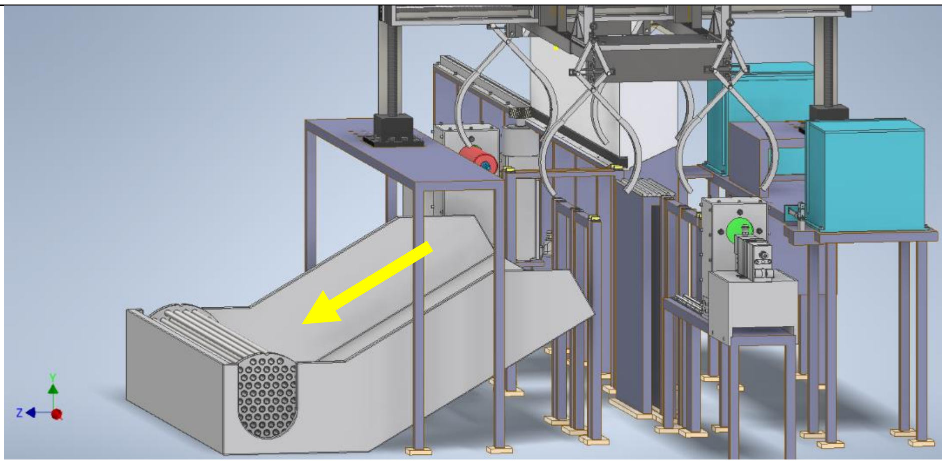
(Frame transparent for clarity of view.)
(Far out view to navigate orientation.)



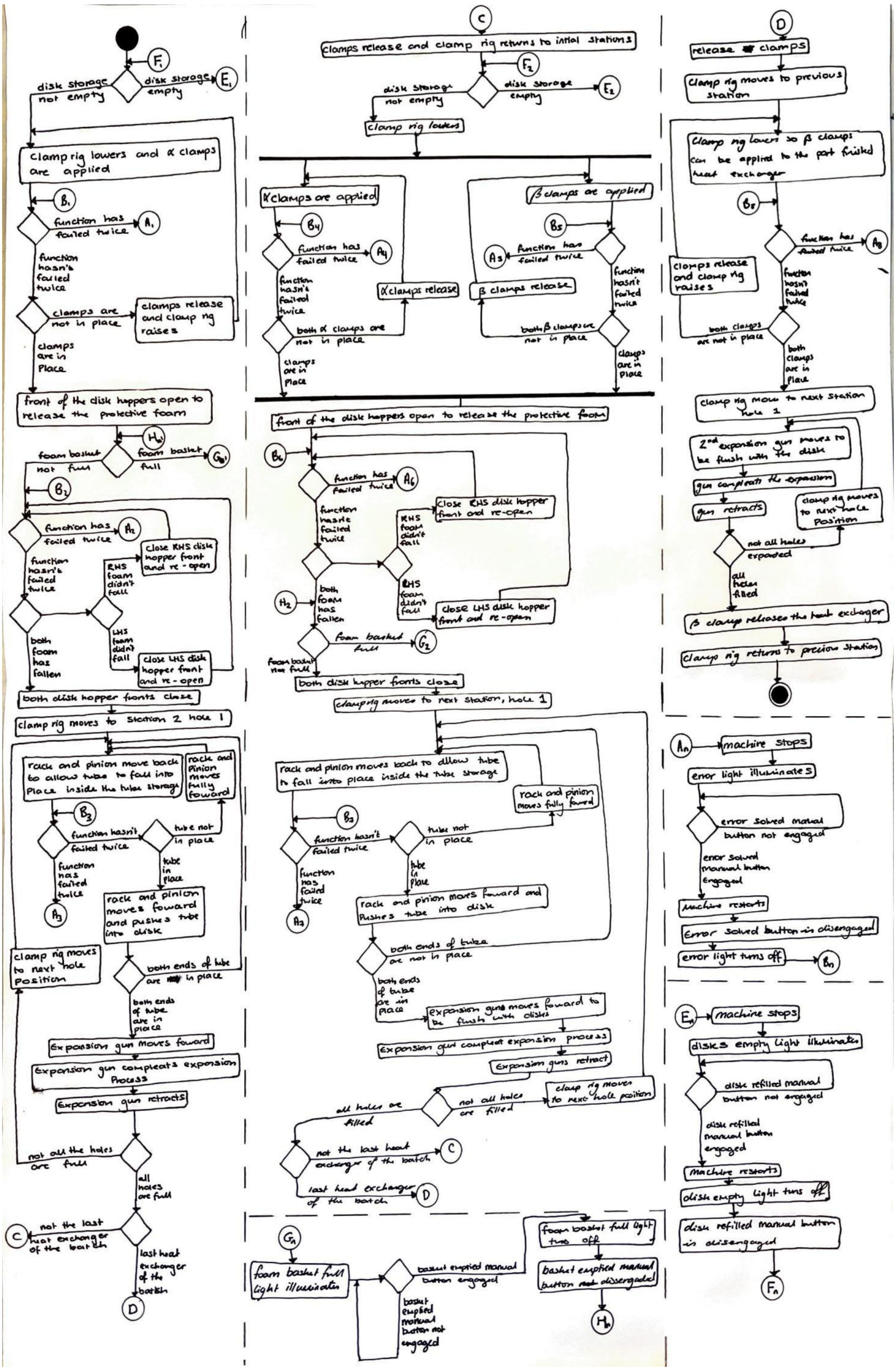


Stage 12

- Claw and winch sub-assembly releases the plates (by opening both claws) and the heat exchanger rolls down ramp to collection point.
- The ramp is padded by thick foam to cushion the exchanger as it rolls. There is extra foam at the bottom of the ramp and ramp sides.



UML activity diagram



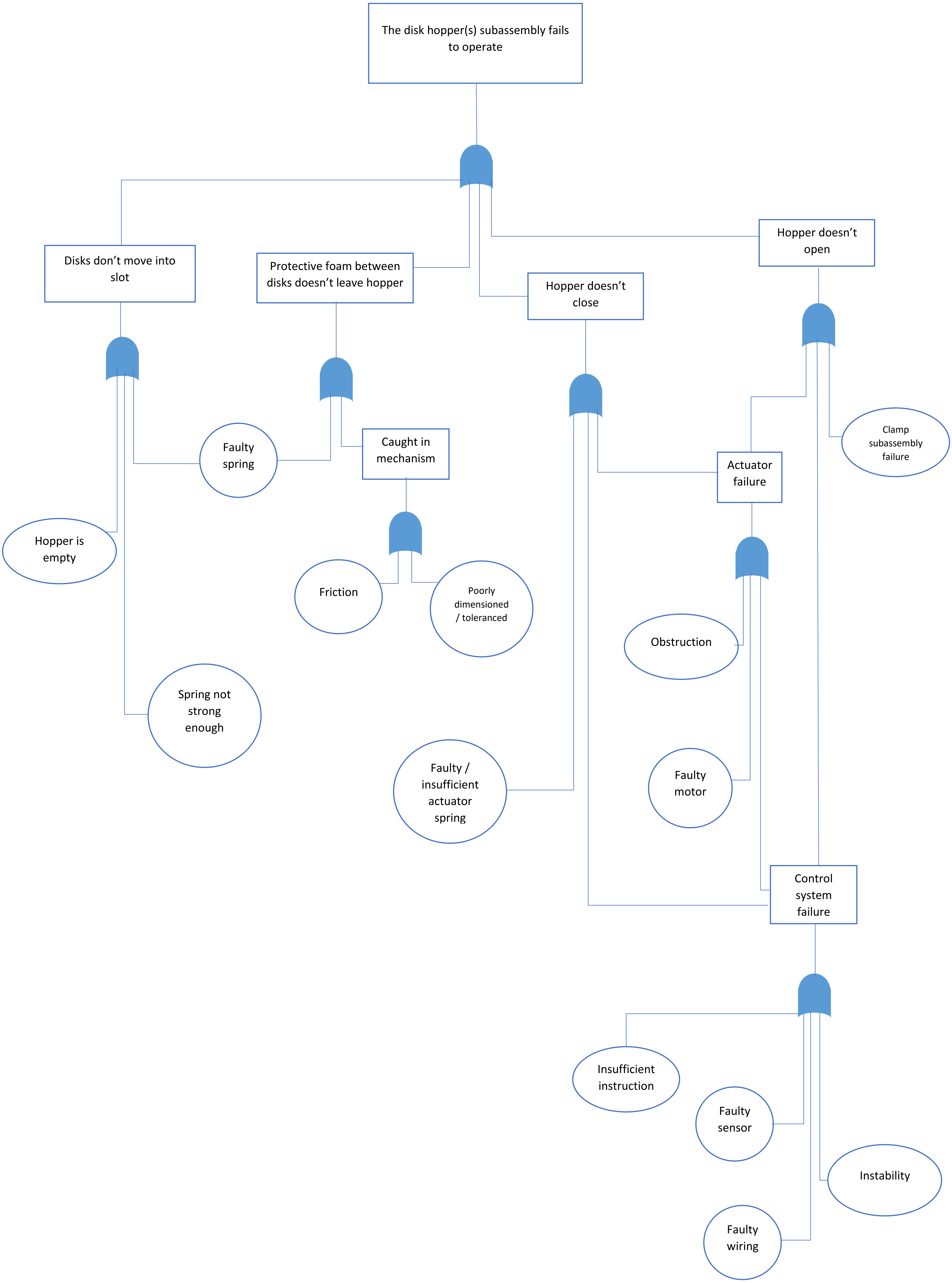
FMECA and fault tree

Item	Part	Failure mode	Cause	Effect	F	I	S	D	R	Sum	How can failure be eliminated or reduced
1	Ballscrew linear actuator	Bending/deformation	Loading too large	Inoperable	1	2	5	2	5	15	Using appropriate safety factors in load calc.
		Screw thread wear	Loading too large	Reduced performance	4	1	1	5	5	16	Lubrication to reduce friction
2	Pulley	Fails laterally	Large lateral movement	Inoperable	2	4	5	1	2	14	Ensuring proper alignment of components
		Wear	Friction	Reduced performance	2	1	1	4	2	10	Lubrication to reduce friction
3	Cable	Fails axially	Loading too large	Inoperable	2	5	5	1	4	17	Appropriate thickness of cable selected for load
		Becomes misaligned with pulley	Large lateral movement	Requires intervention	1	3	3	1	2	10	Ensuring proper alignment of components
		Deformation	Loading too large	Reduced performance	2	2	2	3	4	13	Appropriate thickness of cable selected for load
4	Clamp	Deformation	Misalignment	Poor or no performance	2	2	4	2	3	13	Strengthening joints and ensuring alignment
5	Support frame	Deformation	Loading too large	Poor or no performance	1	5	4	1	5	16	Appropriate reinforcement of support structure
		Buckles/fails	Loading too large	Inoperable, damage to other componen	1	5	5	1	5	17	Appropriate reinforcement of support structure
6	Nuts and bolts	Thread stripped	Loading too large	Unstable system	1	4	3	5	2	15	Selection of bolts based on loading calculations
		Lateral failure (head of bolt lost)	Large lateral movement	Unstable system	1	4	3	5	2	15	Selection of bolts based on loading calculations
		Loosening	Vibration	Unstable system, further vibration	2	3	3	5	1	14	Regular maintenance, dampers installed if vibration present
	Analysis criteria										
F	Probability of occurrence /5										
I	Probability of injury /5										
S	Severity of impact on operation /5										
D	Difficulty of detection /5										
R	Repair difficulty /5										

FMECA carried out to assess the reliability of the clamp rig assembly.

Two most concerning points of fault highlighted were the cable failing axially and the support frame buckling. Both of these can be mitigated with correct stress calculations and corresponding component selection and reinforcement to perform effectively.

Fault tree carried out to assess the reliability of the disk hopper subassembly. Much of these potential errors can be mitigated through thorough design considerations ie control system logic, component calculations, dimensioning.


The disk hopper(s) subassembly fails to operate
Disks don't move into slot
Protective foam between disks doesn't leave hopper
Hopper doesn't close
Hopper doesn't open
Faulty spring
Caught in mechanism
Hopper is empty
Friction
Poorly dimensioned / toleranced
Actuator failure
Clamp subassembly failure
Obstruction
Spring not strong enough
Faulty / insufficient actuator spring
Faulty motor
Control system failure
Insufficient instruction
Faulty sensor
Instability
Faulty wiring

Solution specification

- Workspace required: 3.8m x 1.6m x 1.3m
- Total time to assemble a core: 21 minutes
- Operation conditions: 20 degrees, 1 atm
- 2 people to operate
- Maintenance requirement: general maintenance every 3 months
- Ease of use: operated via control panel
- Adjustable for 600, 800 and 1000mm cores
- Requires refilling every 2 cores produced
- Safety features: cage around system, sensors to abort operation, secure fastenings
- Overall cost: £59,266.50