Developing a High-Voltage Mechanical Disconnector: Meeting Safety Standards

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MASTER THESIS

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Abstract

This master thesis is conducted in collaboration with Opticept Technologies, a company operating in the Pulsed Electric Field (PEF) treatment industry. PEF treatment necessitates the use of high-voltage machines, and this thesis focuses on exploring a mechanical disconnector that serves as an essential safety feature for such high-voltage systems.

The thesis examines relevant standards and delves into the associated requirements and guiding principles. These requirements and principles are subsequently translated into design criteria that form the fundamental basis for the development process, highlighting their pivotal role in ensuring safety.

The master thesis encompasses a comprehensive development process, encompassing concept generation while considering specific design criteria. Through close collaboration with Opticept, the most promising solutions are further refined and ultimately presented as viable solution, accompanied by further development aspects.

In addition to addressing specific standards and design considerations, the thesis explores broader aspects of product development. It investigates how the constraints imposed by requirements and existing knowledge impose limitations on design freedom. Moreover, it sheds light on the disparities between concept development for these types of safety systems and the approaches taught in the educational system, particularly in the realms of "product realization" and "product development" specializations.

Overall, this master's thesis offers valuable insights into integrating safety standards throughout the development process of mechanical disconnectors utilized in Opticept PEF machines. It underscores the significance of adhering to specific safety requirements and their profound impact on product development.

Keywords: Opticept, Standards, Product development, Disconnector, High Voltage

Sammanfattning

Detta examensarbete genomförs i samarbete med Opticept Technologies, ett företag verksamt inom Pulsed Electric Field (PEF) behandlingsbranschen. PEF-behandling kräver användning av högspänningsmaskiner, och detta arbete fokuserar på att utveckla en mekanisk brytare som fungerar som en väsentlig säkerhetsfunktion för sådana högspänningsystem.

Examensarbetet undersöker relevanta standarder och granskar de associerade kraven och deisgnprinciper. Dessa krav och principer översätts sedan till designkriterier som utgör den grundläggande basen för utvecklingsprocessen och betonar deras avgörande roll för att säkerställa säkerheten.

Examensarbetet omfattar en omfattande utvecklingsprocess, inklusive konceptgenerering med hänsyn till specifika designkriterier. Genom nära samarbete med Opticept förfinas de mest lovande lösningarna och presenteras slutligen som en genomförbar lösning, tillsammans med ytterligare utvecklingsaspekter.

Utöver att behandla specifika standarder och design överväganden utforskar uppsatsen bredare aspekter av produktutvecklingen. Den undersöker hur begränsningarna som ställs av krav och befintlig kunskap sätter gränser för designfriheten. Dessutom belyser den skillnaderna mellan konceptutveckling för säkerhetssystem och de tillvägagångssätt som lärs ut inom utbildningssystemet, särskilt inom områdena "produktrealisering" och "produktutveckling".

Sammanfattningsvis ger detta examensarbetet värdefulla insikter i integrationen av säkerhetsstandarder genom hela utvecklingsprocessen av mekaniska brytare som används i Opticept PEF-maskiner. Den understryker betydelsen av att följa specifika säkerhetskrav och deras djupgående inverkan på produktutveckling.

Nyckelord: Opticept, Standarder, Produktutveckling, Mekanisk brytare, Högspänning

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Lund, May 2023

Hampus Carlqvist

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1 Introduction

This chapter presents the project's background, objectives, and scope and aims to give the reader the context and purpose of this project.

1.1 General information about Opticept

Opticept is a company operating in the food and plant industries, dedicated to the development of advanced technological solutions that foster a sustainable future. The company specializes in two primary domains: PlantTech and FoodTech. PlantTech revolves around enhancing the quality and prolonging the lifespan of mainly floral products, while FoodTech is geared towards extending shelf life, improving quality, and reducing waste in the food industry. A key technology employed by Opticept in their FoodTech endeavors is Pulsed Electric Field (PEF) processing. [1] This innovative technology enables the company to achieve their objectives by utilizing the transformative capabilities of PEF.

Pulsed Electric Field (PEF) technology is an emerging innovation showing potential in the food industry due to its wide range of applications. By subjecting food products to brief electric pulses, PEF effectively creates pores in the cell membrane, leading to transformative changes in the product's properties. Today, PEF finds diverse applications in various food processes.

One notable application of PEF is in winemaking, specifically in the maceration of grape skin. By employing PEF as a pre-treatment, the time and energy required for this process can be significantly reduced, streamlining the winemaking process. Similarly, in olive oil production, PEF can be used in the malaxation of crushed olives, offering efficiency gains and improving overall production. [2]

Beyond process optimization, PEF technology also exhibits antimicrobial properties. It can be employed to eliminate microorganisms, thus enhancing safety, and extending the shelf-life of food products. This feature has the potential to revolutionize food preservation methods and ensure the delivery of safer and longer-lasting consumables to consumers.

Figure 1: CEPT7 BALDER [4]

With its ability to enhance efficiency, improve product quality, and enhance food safety, PEF technology represents a promising advancement in the food industry. As research and development continue to unlock its full potential, PEF is poised to play a pivotal role in shaping the future of food processing and manufacturing. Opticept developed a series known as CEPT (Controlled Environment Pulsed Electric Field Treatment), which harnesses the potential of PEF technology to treat fluids. [3] The project will primarily center around the newest CEPT series, CEPT7 called BALDER, which can be seen in figure 1.

1.2 General information about CEPT7

CEPT7 (BALDER) is the 7 generation of CEPT:s that uses the PEF-treatment for fluids. The CEPT is divided into two main parts, the application module and the control cabinet. In this report the focus will be on the application module.

CEPT7 uses powerful capacitors to perform PEF-treatment. The issue with using capacitors is that once the main switch is turned OFF there is remaining electricity stored in the capacitors. That energy is drained in about 20 min. Under these 20 minutes, the user could get in contact with the electrodes, located in the chamber in the application module. Normally this would not be an issue as the PEF generators don’t pulse out any energy, the issue is that the machine uses IGBT (insulated-gate bipolar transistor), which for safety reasons can’t be trusted, as they are semiconductors. If for some reason, there is a short circuit and the fluid that is undergoing the PEF-treatment is drained from the chamber, the energy from the capacitors will be transferred to the electrodes in the chamber. If a user is doing maintenance and touches the electrodes, they could get a shock. For CE certification there is a condition that no single fault condition should make it less safe for the user, therefore as there could be a short circuit, this needs to be handled with another safety layer.

1.3 Safety Considerations

Opticept prioritizes heavily on the safety of their machines and has the goal of designing the machine in a way where most (if not all) safety concerns are removed. The safest solution would be to disconnect from the power and then ground the electrodes. This is however a complicated solution, as grounding the electrodes imposes difficulties in assembly and maintenance and is an expensive solution compared to the alternative. The alternative solution is to disconnect the power supply from the electrodes and has clear indications if the disconnector is malfunctioning, like visible gaps or ON/OFF indicators. Opticept developed and incorporated this type of disconnector into CEPT7 and will be showcased and explained in the next subsection.

As mentioned, using semiconductor devices is not considered safe, but mechanical solutions and solutions with passive electronic components are allowed, according to relevant safety standards. It is also allowed to use mechanical contactors, there are some on the market, however for these types of voltage and current, they are quite expensive, so other solutions are required.

One potential solution to achieve this is by incorporating a disconnector lever outside the door, which users would be instructed to pull before opening it. This approach would hold the user responsible rather than placing the liability solely on the manufacturer in case of an accident. However, Opticept has determined that relying on users to consistently remember to pull the lever poses a significant risk, as it is prone to human error. Consequently, their objective is to devise a solution where user error does not significantly compromise the safety of the machine.

A safety feature could be employed so that the users can immediately detect any malfunctioning of the disconnector. This can be achieved by implementing measures such as preventing the door from opening or requiring an abnormal amount of force to open it when the disconnector is not functioning properly. Consequently, if the door opens without impediment, it signifies that the disconnector is in a disconnected state.

The machine can reach voltages up to 12 kV, therefore the system is considered a High Voltage (HV) system. [5] Special standards are in place to handle these higher voltages, where clearance and creepage distances become extremely important. The use of a disconnector within an HV system presents a complex problem. Both mechanical and electrical standards need to be considered, resulting in more complex solutions compared to low-voltage systems or strictly mechanical or electrical systems. The relevant standards will be discussed in the standards chapter, and their impact on the design will be described as requirements.

1.4 Current Disconnector

The current disconnector in the CEPT7 is comprised of two distinct components, seen in figure 2. The lower part remains fixed and serves as the point of connection for the high-voltage cables, originating from the application module. Unlike the upper part which is movable and linked to the door through a steel wire. When the door is opened, the disconnector separates. A hooking mechanism engages with the upper part, ensuring that the disconnector does not connect involuntarily. To connect the disconnector, manual intervention is required to detach the hooking mechanism, before closing the door.

Figure 2: Current Disconnector [5]

Opticept has had issues with the steel wire breaking, resulting in unintended reconnection of the disconnector. This poses a safety concern as the disconnector should remain in the disconnected state if any malfunction occurs. Both the upper and lower parts of the disconnector are fabricated using 3D printing technology, which Opticept has mention is a sizable and costly solution. Given that the disconnector relies on gravity for connection, the upper part necessitates significant weight to ensure a secure connection.

Consequently, this places additional strain on the plugs, pins, and 3D-printed parts. To mitigate this, a gas spring is employed, further increasing the weight of the disconnector. As a result, opening the door requires substantial force, placing significant stress on the wire. Due to the combination of high cost and insufficient redundancy in terms of safety, Opticept seeks an alternative solution.

1.5 Problem Description

The objective of this master's thesis is to develop an enhanced mechanical disconnector that offers improved safety compared to the existing disconnector. The main focus is on designing a mechanical disconnector with redundant safety features to ensure that, in the event of a malfunction, the disconnector remains in its OFF state. Additionally, providing a locking mechanism that enables users to securely lock the disconnector in the OFF state.

Throughout the development process, relevant safety standards will be incorporated to guarantee the safety of the solution. These standards will be discussed in detail in Chapter 3, along with other specific requirements outlined by Opticept for the disconnector.

2 Processes and Methods

This chapter covers the processes and methods used in this project. Outlining both the main development process and a complementing process.

The development process adhered to the prescribed steps delineated in the Eppinger and Ulrich product development process. [6] This widely recognized and established approach ensures the systematic and efficient creation of optimal concepts while minimizing resource wastage.

2.1 Eppinger and Ulrich Product Development Process

According to the Eppinger and Ulrich method, the development process consists of six sequential stages. These stages encompass planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up, see figure 3 below.

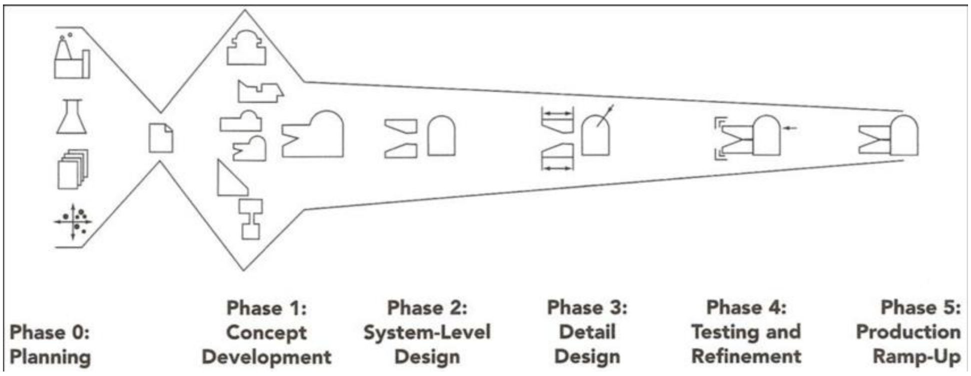


Figure 3: Eppinger and Ulrich development process

2.1.1 Planning

In the beginning weeks of the project, a comprehensive Gantt chart was formulated, encompassing the principal activities to be pursued. The Gantt chart, presented in Appendix A, showcases the planned course of action, including research on pertinent standards, concept development, concept selection, prototyping, testing, and academic objectives. The creation of this chart was informed by discussions held with Opticept, encompassing the project's procedural aspects and anticipated goals. While the initial plan served as a fundamental framework, it is noteworthy that the subsequent execution of the project deviated from the initial projections. Further details regarding the deviations from the original plan are brought up in the discussion part of this report.

2.1.2 Concept Development

The concept development stage is further divided into five distinct stages: identification of customer needs, product specification, concept generation, concept selection, and concept testing. As Opticept endeavors to enhance the safety of its machines, the needs stem directly from their requirements, in combination with the requirements from relevant safety standards.

Concept generation is further divided into five crucial steps: problem clarification, external search, internal search, systematic exploration, and reflection upon the generated solutions and the overall process, as seen in figure 4 below.

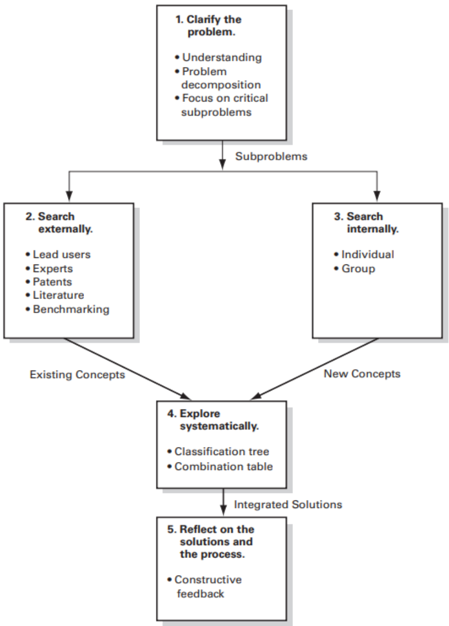


Figure 4: Concept generation phases

The initial step of problem clarification involves getting a comprehensive understanding of the issue at hand and, if necessary, subdividing it into manageable subproblems. This subdivision enables a more focused and systematic approach to problem-solving.

In the external search phase conducting competitive benchmarking is an integral part of the process and is continuously pursued throughout the project. This entails examining existing products and similar solutions in the market to avoid redundant efforts and leverage existing knowledge and best practices. It is worth noting that due to the absence of comparable products, general mechanical principles will be examined instead.

The internal search involves harnessing the collective knowledge and creativity of the project team to generate a diverse array of potential solutions. In this project, the author will develop and present solutions to the development team at Opticept, offering recommendations and advocating for the most promising approaches. This internal search process will be facilitated through meetings, ensuring an iterative and collaborative decision-making process.

The systematic exploration stage is dependent on the complexity of the problem. Once a broad range of solutions has been generated through internal search, especially when the problem has been subdivided into subproblems, systematic exploration is conducted. While a concept classification tree is commonly used, it will not be employed in this project. Instead, the divisions themselves enable individual selection of the solutions.

The following step entails reflecting upon both the selected solution and the overall process employed. While reflection should ideally occur throughout the process, a final assessment is essential to ensure the exploration of all possible solutions and avoid overlooking potential alternatives.

After generating a range of solutions, the next stage involves concept selection, often accomplished through a concept scoring matrix. This method enables the scoring of solutions, expediting the process of narrowing down the options. One or more concepts are then chosen to be further refined and tested. Given the time constraints of this project, a single concept will be selected for progression into the system-level design phase.

2.1.3 System-Level Design

The system-level design phase encompasses defining the architectural framework and specifying all components. Key components are preliminarily designed, encompassing functional specifications, assembly processes, and the geometric layout of the product.

2.1.4 Detail Design

In the detail design phase, comprehensive and detailed drawings are created, encompassing the complete geometry with tolerances, material selection, and the inclusion of standard parts to be sourced from specific suppliers. Considerations such as material selection, production techniques, cost, and performance play pivotal roles in this phase.

2.1.5 Testing and Refinement

During the testing and refinement phase, the initial version of the product undergoes evaluation to determine its alignment with key customer needs and its functionality according to design specifications. Safety features are specified by relevant standards, and similar tests conducted on Opticept existing disconnector are performed to identify potential enhancements in the new concept. This phase involves constructing and evaluating multiple pre-production versions of the product, with early prototypes utilizing production-intent parts, albeit not necessarily produced using the intended manufacturing processes. If required, refinements are made to the concept based on the outcomes of the testing phase.

2.1.6 **Production Ramp-Up**

Due to time constraints, the production ramp-up phase, involving workforce training and addressing any outstanding issues using the intended production system, will not be incorporated into this project. Consequently, the product will not be manufactured using the intended production system to train the workforce and resolve any remaining production-related challenges.

2.2 Adjustment to the process

The Ulrich and Eppinger development process does not deal with standard requirements that need to be met. This would result in a faulty scoring matrix, as concepts that would score low on the requirements set by the standard (meaning that they do not meet those requirements) could still be considered viable concepts. This should not be the case, as the standards are created to protect the user from harm, concepts that do not meet these standards should not be further developed.

Therefore, in addition to the Ulrich and Eppinger development process, the Systematic Design Approach by Pahl and Beitz, will be incorporated to complement the overall design method. [7]

This approach enables the systematic consideration of requirements from both the standards and Opticept. The requirements from the standards and Opticept can be divided into demands and wishes. Where the demands are non-negotiable conditions, mainly form a safety concern and can be interpreted as Yes or No requirements. While the wishes are more subjective and should be taken into consideration whenever possible. All requirements from the standards are considered as demands. While some of the requirements from Opticept are wishes.

The standards utilized for this process will be brought up in the next chapter.

3 Standards and requirements

In this chapter, the relevant standards and requirements from Opticept will be brought up and discussed.

3.1 Standards

Electrical products sold in Europe are required to possess a CE certification, signifying their compliance with essential safety, health, and environmental prerequisites established by European directives and regulations. [8] Standards are created to meet these directives and regulations. Offering guidance about design, manufacturing, risk assessment, and testing. [9] These standards aren’t a legal requirement, but the CE certification is. Thereby, adhering to these standards guarantees that the product meets the minimum safety requirements.

It is important to note that Opticept's mission is not only to fulfill the minimum safety requirements, but to surpass them. Nonetheless, these standards provide a solid foundation for ensuring safety, thereby ensuring that no safety concerns are overlooked.

Different standards are applicable depending on the type of product. In the case of high-voltage machines, specific standards have been established. Opticept, having previous experience in designing and manufacturing a disconnector that complied with the required standards, has provided the relevant standards as points of reference.

It is worth noting that while not all of the standards employed in this project are exclusively specific to high-voltage machines, the general principles of safety outlined in these standards still hold significance for this project.

Five standards have been provided by Opticept and are displayed below:

1. IEC 60204-11:2000 – Safety of machinery – Electrical equipment of machines – Part 11: Requirements for HV equipment for voltages above 1000 V a.c. or 1500 V d.c. and not exceeding 36 kV. [10]

2. RoHS – Restriction of Hazardous Substances in Electrical and Electronic Equipment. [11]

3. IEC 61010-1 Standard: Safety requirements for electrical equipment for measurement, control, and laboratory use - Part 1: General requirements. [12]

4. ISO 13849-1 Safety of Machinery–Safety-related parts of control systems – Part 1: General principles for design [13]

5. ISO 13849-2 Safety of Machinery – Safety-related parts of control systems – Part 2: Validation [14]

The IEC 60204-11:2000 standard has been superseded by a more recent version, IEC 60204-11:2018. However, the significant technical changes introduced in the new version are available without the need to purchase it. These changes do not impact this project, and the newer version will not be utilized.

The initial phase of the project entails identifying the relevant standards that are applicable to the disconnector. However, it is important to acknowledge that due to copyright restrictions, only the interpreted requirements are presented and discussed. These interpreted requirements aim to explain how the actual standards will impact the design.

3.2 Standard IEC 60204-11:2000 and its interpreted requirements

Table 1: Interpreted Requirements from EIC 60204-11:2000

Standard IEC 60204 -11:2000	**Interpreted requirement**
5.2.2	A disconnector device that can be interlocked must be present in the machine.
5.2.3.1	1. Visible gap or position indicator when in OFF position 2. Needs to be able to lock it in the OFF position. 3. It should disconnect all live conductors of its power supply circuit.
5.3 & 5.5	The solution should ensure that it is disconnected and remains so while the door is open. It should also provide a mechanism to lock it in the disconnected state, such as using a padlock.
19.5	An appropriate test needs to be performed related to safety.
19.7	As only the disconnector is being changed, only the safety features concerning the disconnector need to be tested.

To clarify, requirements 19.5 and 19.7 in table 1 are interconnected, as indicated by the standard. According to the standard, if safety-related tests have been conducted on previous versions of the design and certain parts of the machine are being updated, only the specific updated part needs to undergo testing. This implies that if modifications are made to a particular component, it is not necessary to retest the entire machine.

3.3 RoHS – Restriction of Hazardous Substances

The RoHS standard pertains to the use of hazardous materials in electrical equipment. As per the standard, it applies only to electrical and electronic equipment (EEE) that falls under specific categories. These categories are defined in Annex I, which states that “Electrical and electronic equipment (EEE) that relies on electric currents or electromagnetic fields to function properly, as well as equipment for the generation, transfer, and measurement of such currents and fields, designed for use with a voltage rating not exceeding 1,000 volts for alternating current and 1,500 volts for direct current”. [11] Since the machine exceeds the 1,000 Volt rating, this standard does not directly apply to it. Nevertheless, the standard will be utilized as a guiding principle.

A selected number of restricted material that is restricted according to article 4 [11] and their maximum allowed concentration values are displayed below in table 2:

Table 2: Restricted materials according to RoHS

Lead (0.1%)	Mercury (0.1%)
Cadmium (0.01%)	Hexavalent Chromium (0.1%)
Polybrominated Biphenyls (PBB) (0.1 %)	Polybrominated Diphenyl Ethers (PBDE) (0.1%)

The materials and substances shown in the table above are generally considered to be hazardous to human health. Even doe the standard falls outside the scope of this project, these materials will be avoided.

3.4 IEC 61010-1

The IEC 61010-1 standard will be structured into distinct chapters, starting with an overview of the general requirements. Thereafter, specific attention will be given to delineating the parameters of creepage and clearance distance.

3.4.1 General Requirements

According to the IEC 61010-1 standard, some equipment is excluded from its scope. Stating that "This standard does not apply to equipment falling within the scope of: b) IEC 60204 (Safety of machinery – Electrical equipment of machines)." [12]

Since the machine falls under the scope of IEC 60204, the standard is not mandatory. However, certain guidelines will be followed, and their interpreted requirements are presented below in table 3:

Table 3: Interpreted requirements from IEC 61010-1

Standard: IEC 61010-1	**Interpreted requirement**
7.2	Sharp edges to exposed parts should be smooth and rounded.
7.3	Moving parts should be protected for the user to avoid crushing any limbs (such as fingers).
6.1.1	Protection against electrical shock should be maintained even if part of the safety feature malfunctions.
9.3.2	Flame retardant material should be used.

3.4.2 EN 61010-1 Requirements for clearance and creepage distance

Clearance distance is the shortest air distance to prevent flashover between conductive parts. Flashover is a spark that travels through the air. The clearance distance is primarily dependent on the voltage and insulation level.

The standard defines four levels of insulation, namely basic insulation, supplementary insulation, double insulation, and reinforced insulation. Each level of insulation provides increased protection against electrical hazards. The selection of the appropriate insulation level depends on the severity of the hazard and the accessibility of the specific part. Opticept, having previously designed a product based on the same standard, has determined the insulation levels for this project.

Another important parameter is altitude above sea level, which is considered in the standard by specifying the rated operating altitude. According to Paschen's law, [15] the flashover in gas is a function of distance, voltage, and pressure. As pressure decreases with altitude, a greater clearance distance is necessary. For Opticept products, the rated operating altitude is up to 2000 m above sea level. Table 6 and table 3 in IEC 61010-1, [12] are used to determine the clearance distance, which requires gathering the peak voltage from Opticepts tests and knowledge about the machine.

Three main distances that concern the disconnector:

1. The connection between the High Voltage cables and the disconnector.
2. The separation required in the disconnector.
3. Distance from the High Voltage cable to the metallic cabinet.

Creepage distance is the shortest distance allowed between conductive parts along the surface of a solid insulating material. Unlike clearance, creepage takes into account the bends and corners of the insulating material, as shown in figure 5 below. The blue line represents the clearance distance, and the green line represents the creepage distance. Creepage distance depends on the insulating material, insulation level, voltage, and pollution degree.

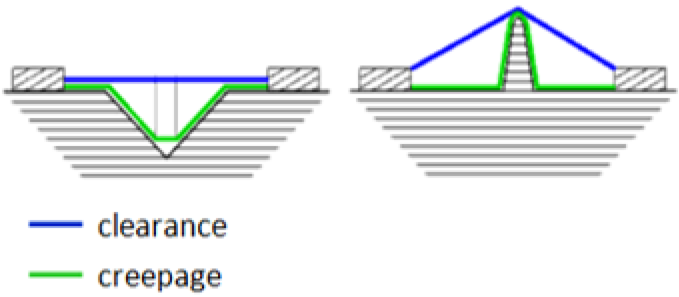


Figure 5: Representation of clearance distance and creepage distance [16]

The materials are divided into four groups based on their Comparative Tracking Index (CTI), which is an index that describes "the maximum voltage at which a material can withstand 50 drops of contaminated water without tracking". [17] Tracking is a path for electricity to travel between conductive parts which can be due to humidity, electrical stress and pollution. The higher the CTI value, the lower the creepage distance required. For materials with unknown CTI values, the lowest CTI value is chosen, and thus the longest creepage distance is necessary. In this project, it is assumed that the CTI test will not be performed, and the material does not have a known CTI value. Therefore, for the creepage distance, the lowest CTI value material group will be chosen.

The pollution degree is a numerical indicator that assesses the potential level of pollution within the machine. Pollution can manifest in various forms such as solids, liquids, or gases, and it has the potential to impact conductivity. The standard establishes four distinct pollution degrees, ranging from one to four, each representing an increasing level of pollution. For instance, pollution degree one indicates no pollution that causes conductivity, whereas pollution degree four denotes conductivity resulting from wet conditions.

Opticept has determined that the pollution degree in the application module is degree 3. Voltages are obtained from Opticept tests and knowledge about the machine. The creepage distance is then obtained using linear interpolation from table 7. [12] The result for the creepage distance and clearance distance is shown in table 4 below.

Table 4: Clearance and Creepage Distance

Position	Peak Voltage [V]	RMS Voltage [V]	Clearance distance [mm]	Creepage distance [mm]
Between HV Cables connections in the disconnector, poll dgr 3, basic insulation, material grp IIIb	12000	2191	28	35
HV Cable to ground, poll dgr 3, reinforced insulation, material grp IIIb	6000	1095	26	36

The separation distance required and the connections between the HV cables are effectively the same distances, as the same voltages, pollution degree, insulation level and material group are the same for the two distances.

3.5 ISO 13849-1/2

The ISO 13849 part 1 and part 2 provide guidance and safety requirements for the design and integration of control systems. This standard provides tools to determine the required performance level by using figure 6 below:

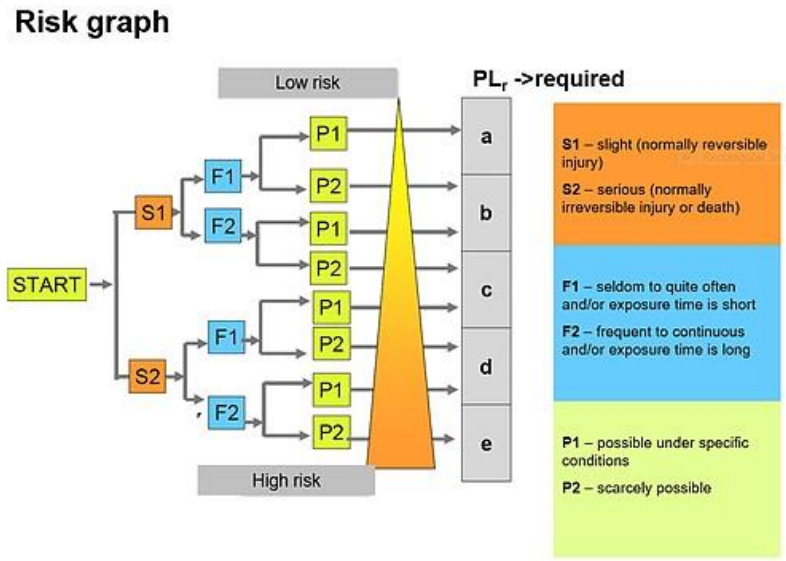


Figure 6: Required Performance Level Risk Parameters [18]

Determining the risk parameters will provide the required Performance Level (PL). For this project, the severity of the injury is considered to be serious (S2), and the frequency and/or exposure to the hazard is considered to be quite long (F2), as the capacitors will store energy for up to 20 minutes after deactivation. The possibility of avoiding this hazard or limiting harm is not considered feasible under specific conditions. To operate the machine, the capacitors need to be charged without exception, leading to a high amount of electricity in the machine. Therefore, the required Performance Level is "e".

The required performance level is connected to an acceptable probability of dangerous failure per hour, which for PLe is between 10^-8 and 10^-7. [14] However, without extended testing, this method is not suitable for determining the Performance Level.

Instead, safety principles from the standard will be utilized during the design process to reduce the probability of failure.

The standard provides some safety principles for the design, for both mechanical and electrical systems. Where some important considerations concerning safety are selected in table 5 below: [13]

Table 5: Important safety principles

Separation Distance	No undefined states
Positive mode actuation	Use of carefully selected materials and manufacturing
Over-dimensioning/safety factor	

These safety principles serve as guidelines and concepts that will be taken into account during the design process, rather than strict rules or requirements. However, adhering to the principle of positive mode actuation is a crucial guideline. This principle prohibits the use of springs for electrical safety purposes due to their elastic nature. Springs are deemed unsafe because they can lose their elasticity over time, resulting in a change in behavior that could compromise safety.

3.6 Requirements and Wishes from Opticept

The requirements and wishes were initially derived from the technical specifications of the existing disconnector. Subsequently, they were further refined to include specific desires and project-specific requirements, drawing upon the experiences gained with the current disconnector. The requirements and wishes proposed by Opticept are outlined in Table 6 below. Moreover, certain requirements and wishes are elaborated upon directly beneath the table.

Table 6: Requirements and Wishes from Opticept

Disconnector should be placed on the back of the Application Module on CEPT7
Should disconnect when the door opens
”Power-part” can be completely removed from the Cabinet *
IP56, be able to poor water in the cabinet where the connector is placed
Should be easy to install in existing machines **
The solution should ensure that the disconnector is in the disconnected state when the door is opened and in the connected state when the door is closed, irrespective of whether the component interacting with the disconnector is removed ***
Should increase the safety compared to the current solution
Should be durable
Aim for good Movement Exchange
Aim for low number of components
Aim for reduction of cost compared to the current solution
Minimize the size of the solution
Manual reset****
Corrosion resistant material
User friendly
Should be able to close the door without connecting the disconnector

*The power-part is where the high-voltage cables connect to the disconnector. **Being easy to install means that welding and similar invasive actions should be avoided.
*** If the feature that is connected between the disconnector and the door is removed (which must be done when the door is open) it should remain in the disconnected state.

**** If the disconnector is in its ON state and the door is closed, opening the door will trigger the disconnector to transition to its OFF state. Once in the OFF state, the disconnector should remain in that position even if the door is closed again. To restore the disconnector to its ON state, the user will need to manually reset it before closing the door.

3.7 Most Crucial Requirements and Wishes

Table 7: Short list of the most crucial requirements and wishes.

Disconnector with visible gap ones in the OFF position and needs to be able to be locked in that position	Should disconnect and remain disconnected while the door is open
IP56 classification necessary	Easy to install in existing machines
Use of springs and/or elastic elements is not allowed	Should be installed in the back of the application module
Avoid using materials according to ROHS	Clearance and creepage distances according to table X1.
Increase safety compared to current solution	Minimize size
Should be able to close the door without connecting the disconnector	Flame retardant material should be used.
Aim for cost reduction	Should be durable

The requirements from the standards and from Opticept can be divided into demands and wishes, according to Pahl and Beitz. Where the demands are non-negotiable conditions, mainly form a safety concern and can be interpreted as Yes or No requirements. While the wishes are more subjective and should be taken into consideration whenever possible. All acquired requirements from the standards are considered as demands. While some of the requirements from Opticept are wishes. The wishes from Opticept are displayed in table 8 below and will be what the different concepts will be evaluated against, in the later chapter “Concept scoring matrix”.

Table 8: Wishes from Opticept

Should be easy to install in existing machines	Aim for low number of components.
Aim for good Movement Exchange	Aim for cost reduction
Increase safety compared to current solution	Minimize size
Should be durable	User Friendly

4 Concept Development

This chapter aims to provide an overview of the concept development structure, as well as clarify the problem at hand and its division.

4.1 Concept Development Structure

The approach to concept generation, as described in the processes and methods chapter, will be followed with some adaptations.

The concept development phase will start by clarifying the problem, and it will be further divided into sub-problems for better understanding and management. The report will then focus on one sub-problem at a time. Completing the concept generation phase for each sub-problem. These sub-problems will then merge into a final design.

4.2 Clarifying the Problem

The fundamental challenge is to design a safe disconnector that satisfies Opticept whishes and demands and meets the relevant standards. Opticept has already conducted extensive research to identify pins and plugs that can handle the required voltage and current without being overly expensive. Therefore, the disconnector must consist of two separate parts that separate when the door opens, as the connectors have already been chosen. This separation needs to be linear and without rotation, as the pins and plugs are quite fragile, also excessive force during linear motion could cause electrical welding or breakage.

To tackle this issue, we can divide it into three sub-problems:

1. Mechanical Solution.
2. Locking mechanism
3. Encasing of the disconnector

Illustrated below in figure 7.

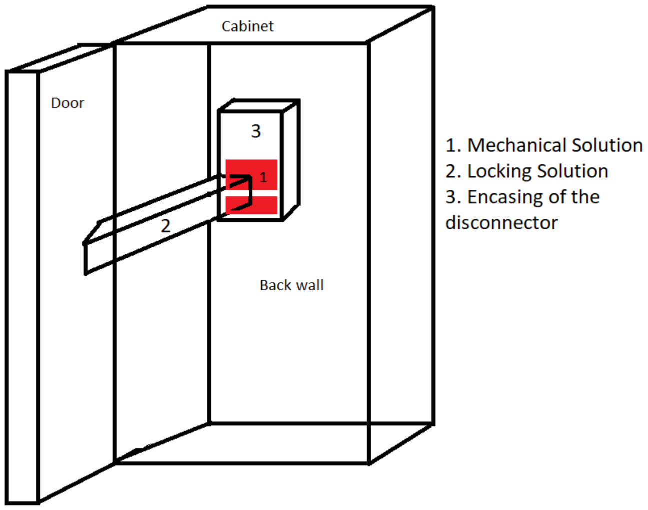


Figure 7: Sub-Problems

The mechanical solution will be responsible for separating the disconnector, it needs to translate the motion of the door into the separation of the disconnector while ensuring that the disconnector remains in the OFF position when the door is open, even if there are malfunctions in the system. The rotational force of the door opening around the vertical axis should be translated into transient force in the disconnector.

Depending on the orientation of the disconnector, it can be implemented either vertically or horizontally. From a perspective of safety and space efficiency, the vertical solution is considered preferable. This approach utilizes both mechanical and gravitational forces as separators, ensuring that the disconnector remains in its OFF state when the door is opened, even in the event of a malfunction.

The locking mechanism should ensure that the disconnector is securely locked in its OFF position. To achieve this, a manual switch should be incorporated, requiring activation for the disconnector to connect when the door closes.

It would be beneficial if the disconnector could separate rapidly upon opening the door. Ideally, only a few degrees of door opening should be sufficient to separate the disconnector. This entails not only losing contact between the pins and plugs but also the additional clearance distance specified by the standards. Any additional movement beyond this point would not impact safety but could potentially increase the size and cost of the solution. Which would result in the locking mechanism limiting the movement to the mechanical solution.

The encasing of the disconnector should facilitate the connection of the plugs and pins while ensuring that the alignment is secured. The encasing must also have an IP56-classification without limiting the visible gap created by the disconnector's separation.

5 Mechanical Solution Concept Development

This Chapter covers the concept development phase for mechanical solutions.

The first sub-problem that was to undergo a concept development phase was the mechanical solution. The most crucial demands for this mechanism are:

- Should increase safety compared to the current solution
- Should disconnect when the door opens
- The solution should ensure that the disconnector is in the disconnected state when the door is opened and in the connected state when the door is closed, irrespective of whether the component interacting with the disconnector is removed
- Corrosion resistant material
- Flame retardant material
- No springs

The most relevant wishes are:

- Easy to install
- Minimize the size
- Low number of components
- Aim for good movement Exchange
- Durable
- Cost

5.1 Mechanical Solutions Concept Generation

The basic approach for creating different concepts follows a similar methodology. Firstly, simple ideas of motion translation are drawn to convey the mechanical principles. Figure 8 shows an example of this, demonstrating a gear solution to translate the horizontal motion of the door into the vertical motion of the disconnector. After creating several ideas on how the separation could work, mainly focusing on converting horizontal movement into vertical movement, a selected number of concepts with potential were created in CAD, using Inventor as the CAD software. An example of the gear solution in CAD is shown in Figure 9. A concise description of the mechanical properties will be provided following the presentation of each concept.

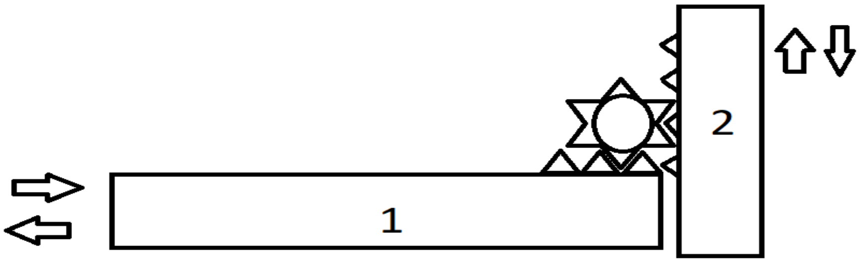


Figure 8: Gear Solution first drawing

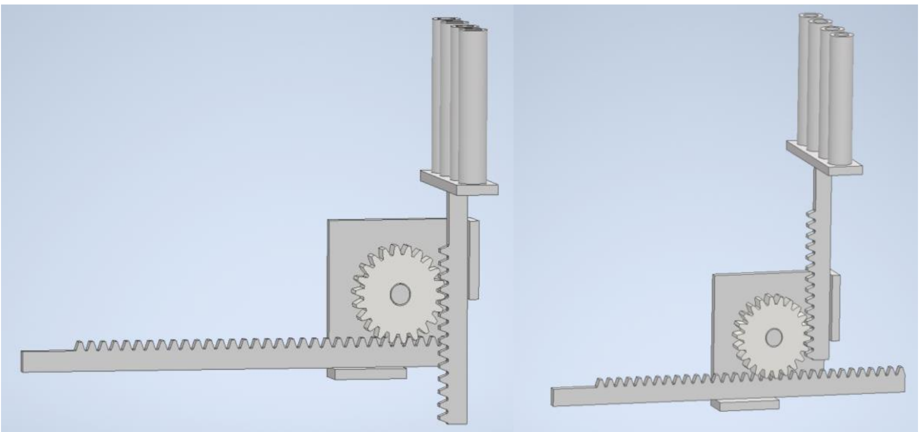


Figure 9: Gear Solution CAD Model

The gear solution utilizes two gear rails and a gear. The first gear rail translates the horizontal movement to the gear, which transfers the movement to the second gear rail vertically. The gear is thick enough to be in contact with both gear rails without interference. Dimensions and aesthetics were not taken into consideration during this phase, rather focusing on the motion is accurately displayed in the CAD model.

Other drawing examples that became CAD models are displayed below.

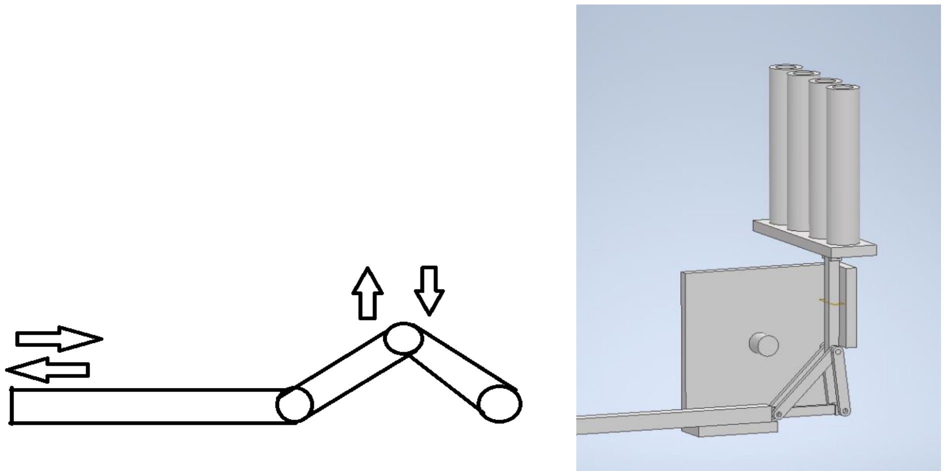


Figure 10: Scissor solution

The scissor solution, seen in figure 10 uses a couple of flat profile parts that can pivot, with the lower parts moving together as the horizontal movement drives them closer, which facilitates the lower part of the disconnector to move upwards.

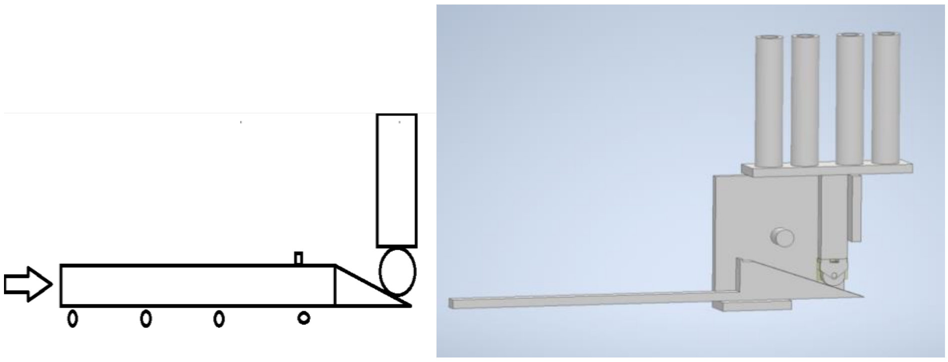


Figure 11: Ramp Solution

The ramp solution, seen in figure 11 utilizes a ramp and a wheel to transfer to motion. As the rail connected to the ramp moves the wheel will travel up the ramp, making the lower part of the disconnector move upwards.

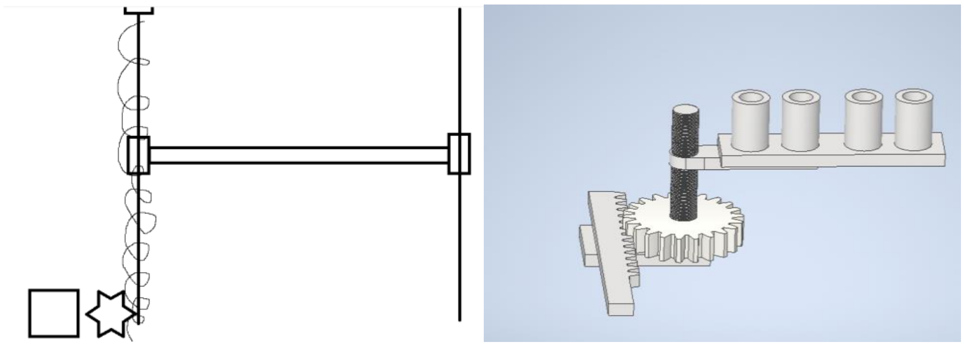


Figure 12: Threaded Rod Solution

The threaded rod solution, seen in figure 12 uses a gear rail, a gear, and a threaded rod that connects to the lower part of the disconnector. The threaded connection to the disconnector rises and lowers as the gear rail and gear rotate the threaded rod.

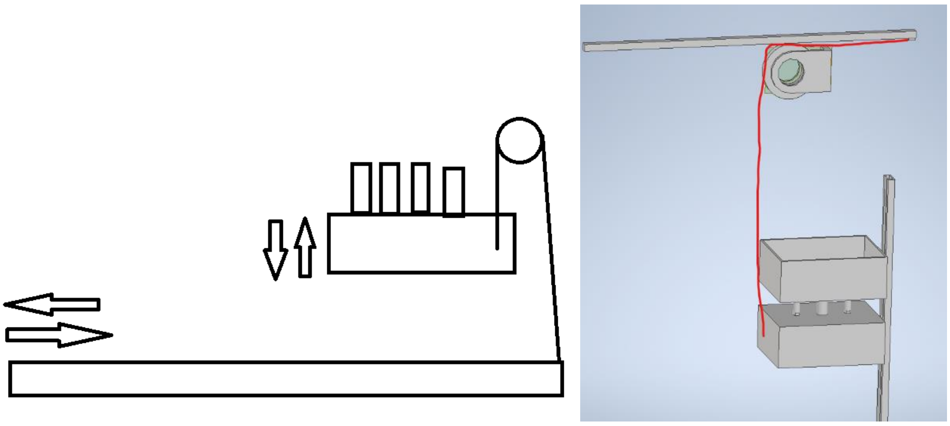


Figure 13: Wire Solution

The wire solution, seen in figure 13, is similar to the original design, utilizing a steel wire and a pulley with an additional rail. The rail transfers the horizontal movement to the wire, which, in turn, pulls the lower part of the disconnector upwards. The initial drawings were created only to display the mechanical principle and the parts that could be utilized. For example, with the wire solution, the basic idea was to utilize a pulley system. After beginning to develop the CAD model, it was realized that the motion exchange in the pulley would benefit from being located above the disconnector. This is why the drawn picture and the CAD models differ.

As mentioned, the CAD models were not made with the purpose of being 100% correct but rather displaying the mechanical solution and showing the motion. This prevented wasting time on developing a correct model that would not be used later in the project while still showcasing the concept in a better way than the initial drawings. Additionally, it allowed for a better understanding of the advantages and disadvantages, which can be difficult when only looking at a crude 2D image of the solution.

Other solutions required more time and refinement to convey a working mechanical solution. The pivot point solution is one of these examples, shown in figure 14 below.

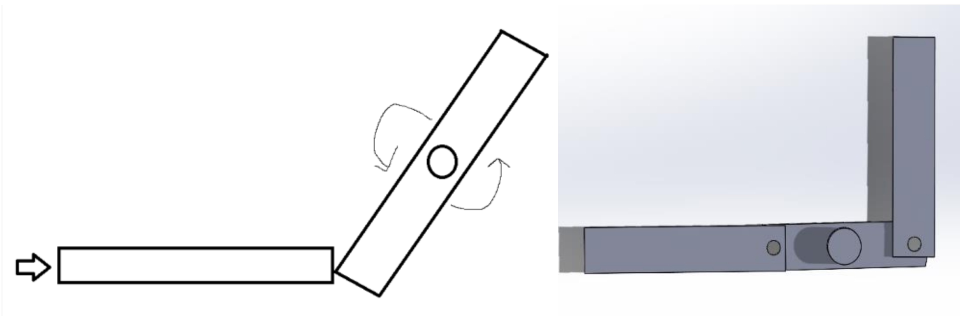


Figure 14: Pivot Point Solution

This solution proved to be problematic because it did not showcase the entire exchange of movement. The horizontal rail would need to move both horizontally and vertically to follow the circular path created by the pivot point. The translation from the door to the vertical rail proved to be more complex than initially anticipated. The other solutions would only need a single connection to the door, which could pivot to translate the rotation of the door to a horizontal motion, shown as an example in figure 15 below:

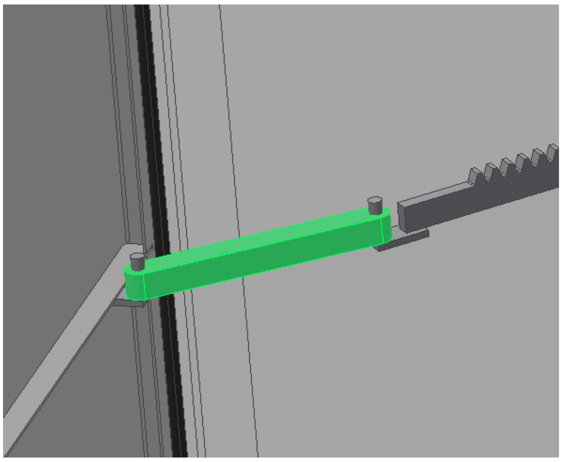


Figure 15: Example of Pivot Connection to the Door

As the pivot solution would need movement in one more direction, another pivot point was necessary, as shown in figure 16 below:

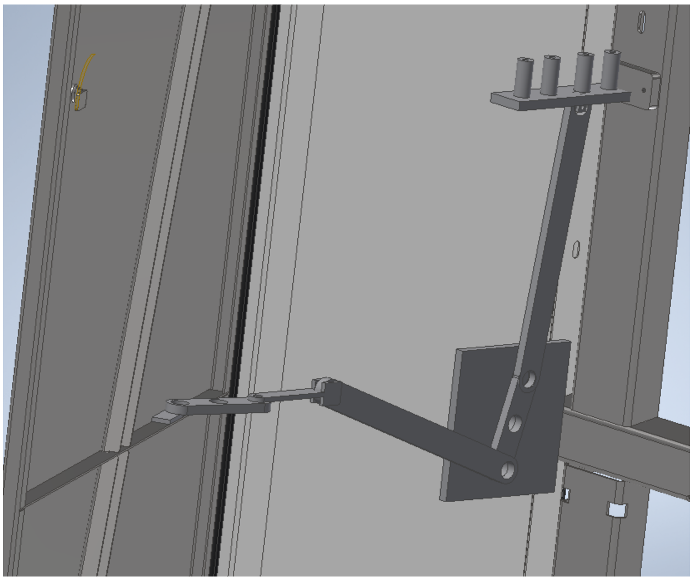


Figure 16: Pivot Solution Connected to the Door

Despite not being a huge negative aspect, further development of this concept was done to avoid having an extra step of translating the movement. This led to a similar contraption that removed the extra transfer step, shown in figure 17 below:

Figure 17: Pivot Solution Version 2

Removing the fastened connection between the pivot point and door removed this second translating step. The vertical pins located on the horizontal rail would make the pivot point rotate as they would come into contact with it. Not satisfied with the force exchange of the vertical pins, another model was created:

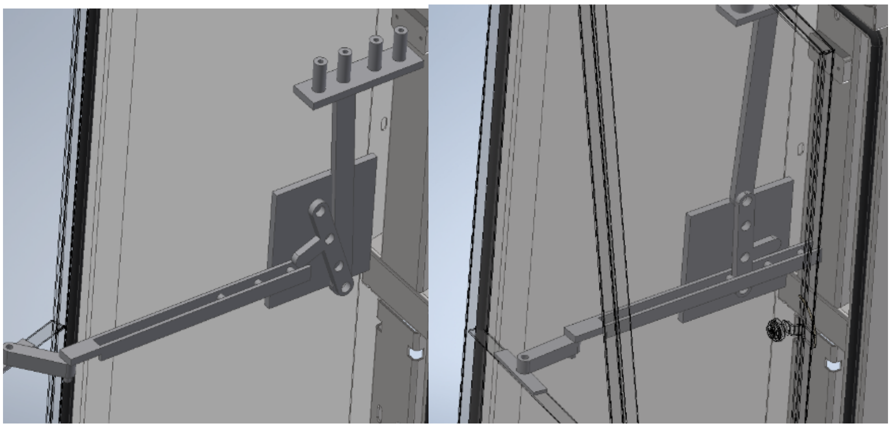


Figure 18: Three-Pronged Pivot Solution

This model removed the vertical pins needed and placed them horizontally instead, shown in figure 18. An extra pin was also added to make a quarter more rotation of the pivot point.

5.2 Design Review Meeting

The next step in developing the mechanical solution was to have a design review meeting. The concepts that met the set requirements were presented to Opticept and discussed with members from the research and development department, as well as the director of product development at Opticept. The meeting provided new solutions, either new concepts that were raised during the discussion or concepts that could be improved.

A new concept that was talked about was utilizing chains to convert the horizontal movement to vertical movement. Chains are quite robust but do not handle compression very well. This can be circumvented by encasing the chain in a narrow path, shown in figure 19 below. The solution created had a 90-degree bent pipe into which the chain was to be inserted. Two rails or pipes would be connected to the door and the disconnector would then be linked by the chain. The compression from closing the door would make the chain want to fold, but the walls of the pipe would not allow this, translating the motion to the vertical pipe.

Figure 19: Chain Solution

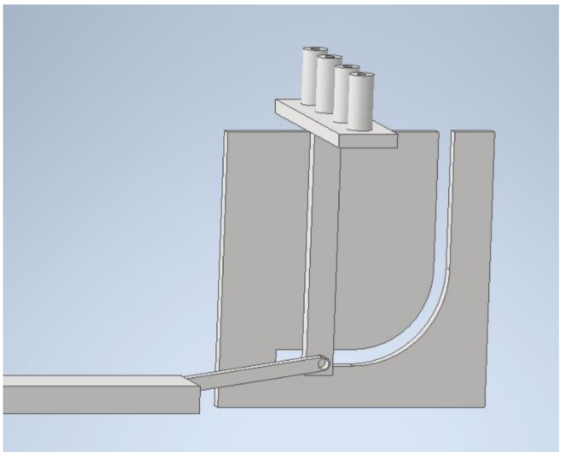


Figure 20: Path Solution

Improvements were made to the ramp solution in response to a negative aspect of the design, which relied on gravity for the separation of the disconnector. If the disconnector were to become stuck, a user would not detect this immediately upon opening the door. Instead, they would need to visually inspect the disconnector to determine if it was stuck. This is not the case with the alternative solutions, where opening the door would require more than the normal amount of force if the disconnector were to become stuck. Introducing a path that a pin could follow would eliminate this problem, and adding a steeper slope to the ramp would enable the disconnector to reach the required clearance distance more efficiently than a consistent 45-degree slope, shown in figure 20 above.

5.3 Internal feedback

To gain more internal feedback, Opticept personnel who were familiar with the disconnector were given pictures and short explanations of each mechanical concept, with no input regarding advantages or disadvantages. Personnel were asked to select their top three preferred concepts and their three least preferred concepts, with a brief explanation for each selection. This approach proved beneficial for concept development and selection. The solutions the personnel at Opticept were given were the 7 concepts shown earlier.

1. Gear solution
2. Scissor Solution
3. Wire solution
4. Threaded Rod solution
5. Path Solution
6. Chain solution
7. Three-Pronged Pivot solution

5.4 Reflection on the concept generation

Upon reflection of the concept generation phase, discussion with Opticept indicates that the mechanical solutions yielded improvements in safety, albeit with variations in their respective strengths and weaknesses. It was observed that these solutions shared a common approach, involving the movement of the lower disconnector. While the concepts displayed notable differences in their methods of achieving this movement, the exploration of a sufficient number of solutions was deemed satisfactory for concept selection.

5.5 Concept Scoring Matrix

To choose a concept based on Opticept's wishes, a concept scoring matrix was created. Non-negotiable demands, either from standards or functional requirements, were identified and kept in mind throughout the development process. Concepts that did not meet these requirements were not further developed and were not included in the concept scoring matrix. As the non-negotiable requirements are Yes or No requirements, including them in the concept scoring matrix would not have yielded any different results.

For instance, the requirement that the disconnector should disconnect when the door opens is critical, and all concepts were expected to meet it, which means concepts that did not meet this requirement did not make it to the concept scoring matrix.

Requirements that were not applicable to the mechanical solution were excluded from the concept scoring matrix, as the problem was divided into subproblems.

The concepts will get a score of 1 to 5, according to figure 21 below, being compared to the current solution as reference.

Relative Performance	Rating
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

Figure 21: Concept Rating [6]

The concept scoring matrix will be divided into two sections, table 9 and 10 to enhance its readability and comprehensibility.

Table 9: Concept Scoring Matrix - Mechanical Solutions - Part 1

Wishes	Current solution (Reference)	Wire solution	Gear solution	Scissor solution	Weight
Easy to install	3	3	2	2	0.20
Increase the safety	3	5	5	5	0.30
Should be durable	3	3	5	4	0.20
Minimize the size	3	3	2	3	0.05
*Number of components	3	3	2	1	0.05
Cost reduction	3	3	2	3	0.10
Movement Exchange	3	3	4	2	0.10
Total weighted Points	3	3.6	3.7	3.4	

Table 10: Concept Scoring Matrix - Mechanical Solutions - Part 2

Wishes	Threaded rod solution	Path solution	Three-pronged Pivot Solution	Chain solution	Weight
Easy to install	1	2	1	1	0.20
Increase the safety	5	5	5	5	0.30
Should be durable	4	4	3	3	0.20
Minimize the size	2	2	2	3	0.05
*Number of components	1	2	1	2	0.05
Cost reduction	2	3	1	3	0.10
Movement Exchange	2	4	4	2	0.10
Total weighted Points	3.05	3.4	2.95	3.05	

5.5.1 Explanation of the scoring matrix

The safety criteria hold the utmost significance in determining the optimal solution, thus carrying the greatest weight in the evaluation process. The criteria of durability and ease of installation are assigned equal importance. Durability is pivotal in ensuring the longevity of the solution and minimizing potential failures. Simultaneously, easy installation considerations take into account existing operational machines where Opticept seeks to enhance safety measures, necessitating non-invasive implementation. These criteria are deemed equally significant and thus carry equal weight in the assessment.

The movement exchange aspect centers on friction and the relationship between the extent of the door opening and the corresponding disconnector separation. Cost, is always an important factor in solution selection, is also weighed on par with the movement exchange criteria. Minimizing solution size and component count impact assembly considerations.

Additionally, the number of components influences durability, as a larger number implies an increased potential for complications. Given the presence of a separate durability criterion, its weight is relatively low in this context. Size is assigned equal importance, as long as the solution can be accommodated within the cabinet it is not a crucial criterion.

Wire solution:

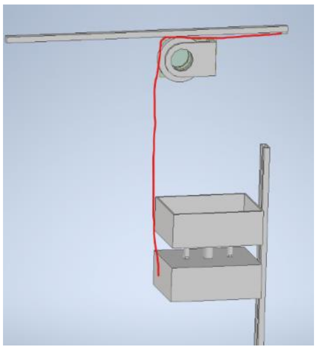


Figure 22: Wire Solution

The wire solution is similar to the current design as it uses the same parts and fastening points. It is expected to receive a similar score to the current solution, except for an increase in safety. The wire solution is designed to remain closed when open, which is essential because a malfunction will reconnect the disconnector in the current design but not in the wire solution.

Gear solution:

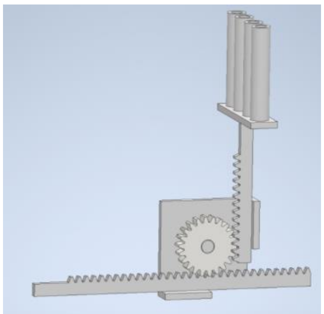
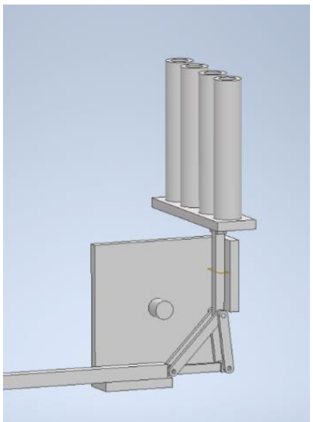


Figure 23: Gear Solution

The gear solution compared to the current design is safer, as gravity prevents the disconnector from connecting when the door is open even due to a malfunction. The gear solution is also much more durable than the current solution, as wires break more easily. Depending on the gear utilized, it can be more expensive than the current solution. It is considered worse than the reference for installing the solution in existing machines as the fastening point would need to be changed. Still, the assembly is not overly complicated. The gear solution also uses more components and takes up more space. The movement exchange is low friction, and the movement transfers smoothly. However, the gear solution has a constant movement exchange throughout the separation, Scissor solution:



The scissor solution is safer than the current solution as it ensures the disconnector is in its OFF position when the door is open. However, it requires another fastening point compared to the current solution, resulting in a lower score in the installation category. The scissor solution has the most components, and many of these components move, leading to low scores in both the component and durable categories. It is worth noting that the friction between these parts could cause wear, and the movement exchange is scored relatively low.

Figure 24: Threaded Rod Solution

Threaded rod solution:

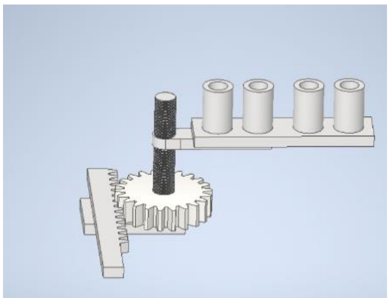
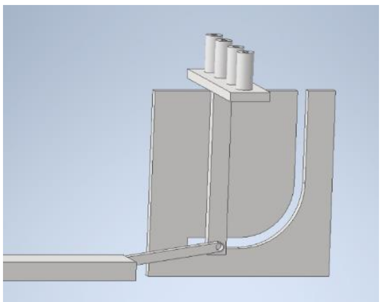


Figure 25: Threaded Rod Solution

The threaded rod solution is complex to install as the components necessary for mounting it in the cabinet are complex and need to interlock with each other. However, it is a more durable solution than the current solution. Two threaded rods would be needed to facilitate a smooth transfer of movement, making it a relatively large solution. The price of this solution is assumed to be similar to the gear solution, as both have similar components, with the threaded rod solution using threaded rods instead of a gear rail.

Path solution:



The path solution requires more parts and is more extensive than the current solution, resulting in low scores in these areas. However, it is durable, and the movement exchange is beneficial as it provides a lot of separation when the door opens. As a result, the path solution scores highly in these areas.

Figure 26: Path Solution

Three-Pronged Pivot Solution:

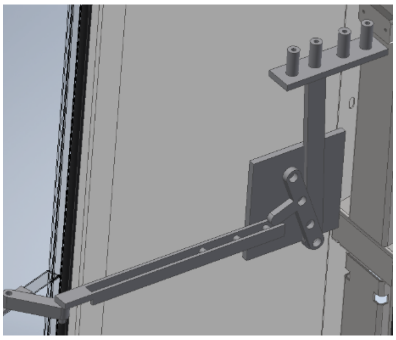


Figure 27: Three-Pronged Pivot Solution

The three-pronged pivot solution requires many components and needs to be relatively large to function, making the solution expensive. The movement transfer is good; however, the solution is could get stuck, resulting in its durability being on par with the current solution.

Chain solution:

Figure 28: Chain Solution

The chain solution can be challenging to assemble and install as the relationship between the chain and the bent pipe needs to be within a tight tolerance. The friction from the chain could cause wear on the pipe and chain, which means it receives the same score as the current solution in the durable category. It is worse than reference in the regard to number of components and movement exchange. It is considered to be the same as the reference in size and cost.

The gear solution scored the highest in the concept scoring matrix and has been chosen for further development and refinement.

5.6 Further Development of the Gear Solution

The gear solution entails a straightforward concept, yet certain key geometries necessitate careful consideration. Establishing a harmonious relationship between the gear and gear rack is vital to ensure smooth movement transfer. Specifically, the gear should possess sufficient width to engage both gear racks effectively. Initially, the plan involved procuring standard gears and gear rails to fulfill this requirement. However, the requirement imposed by Opticept, mandating the use of stainless steel for all steel components, presented unexpected challenges. Although finding stainless steel gear was not a major issue, gear rails made of stainless steel were limited.

When selecting gears and gear rails, an essential characteristic to consider is their module. The module of a gear is a measurement of tooth size. [19] In order for the gear and gear rack to synchronize movement, they must possess matching module sizes. A higher module corresponds to greater tooth strength, enabling the gear to withstand higher loads. In the context of this project, the forces exerted during door opening are not substantial, thus favoring a lower module. However, lower module gears often exhibit narrower dimensions, necessitating a similarly narrow gear rail.

Given the difficulties encountered in sourcing standard stainless steel gear racks, a decision was made to fabricate them by folding and cutting sheet metal. The gear backplate, designed to facilitate attachment to the rear cabinet and alignment rod plate, is also crafted through the folding and cutting of sheet metal.

6 Concept Development Locking Solution

This chapter covers the concept development phase for the locking solutions.

The next sub-problem that was to undergo a concept development phase was the locking mechanism. The most crucial demands for this mechanism are:

- Should increase safety compared to the current solution
- Should disconnect when the door opens
- Manual reset
- Should be able to close the door without connecting the disconnector
- Corrosion resistant material
- Flame retardant material
- No springs

The most relevant wishes are:

- Easy to install
- Minimize the size
- Low number of components
- User friendly
- Durable

6.1 Locking Solution Concept Generation

The process of conceptualizing the locking solution followed a methodology similar to that of the mechanical solutions. Initially, a preliminary sketch was created, and promising concepts were developed in CAD. However, the goals of the locking solution differed depending on the concept under consideration. Consequently, two intentions emerged that appeared to be conflicting. The first intention was for the locking mechanism to require manual resetting after each use, while the second was to limit the movement of the mechanical solution to facilitate fast release and minimize the size. Which lead to different locking mechanisms explained below.

One of the initial concepts utilized two rails with different dimensions and a pin, as shown in Figure 29. The rails could slide within each other, and the inner rail had a slotted connection that could only move freely vertically. As the door would open, the pin would follow the path of the outer rail, coming to a stop when falling into the groove of the outer rail. This would stop the inner rail from moving and disable the movement to the mechanical solution. The user would have to manually reset the pin in order to close the door and transfer the movement to the mechanical solution.

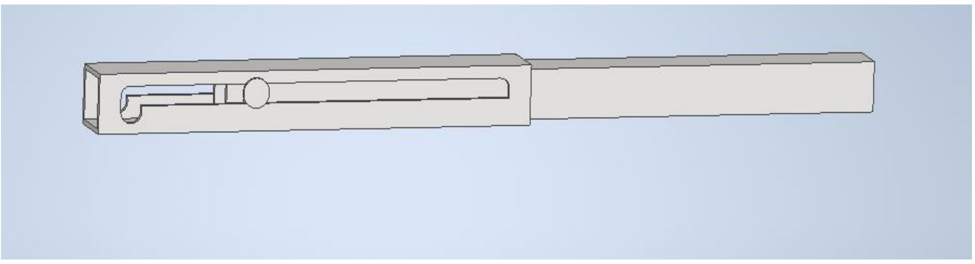


Figure 29: Pin Solution Version 1

However, this solution had some limitations. For instance, it made it impossible to close the door when the disconnector was in its OFF state, and it did not limit the movement of the door to the mechanical solution.

The next solution, depicted in Figure 30, aimed to address the aforementioned limitations by limiting the movement of the door to the mechanical solution.

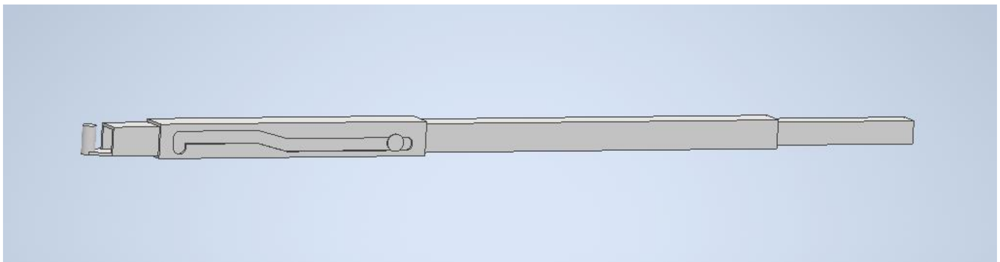


Figure 30: Pin Solution Version 2

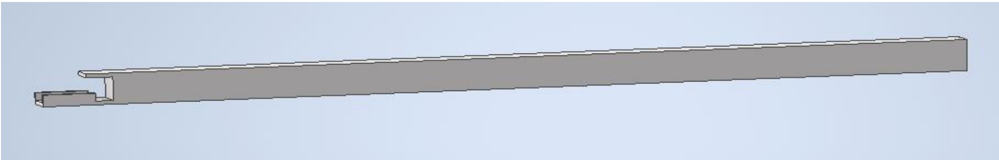


Figure 31: Pin solution Version 2, inner rail

Locking solution 2 involved three rails and a pin. The outer rail was stationary, the middle rail was connected to the door, and the inner rail was connected to the mechanical solution. The inner rail had a hooking mechanism, as shown in Figure 31. When the door opened, the middle rail would pull the pin, which would, in turn, pull the inner rail. At a certain distance, the outer rail would push the pin upwards as it followed the outlined path. The pin would then disconnect from the inner rail, and no further movement would be applied to the mechanical solution. Fully opening the door would lock it in place, and the user would need to manually move the pin to close the door and connect the disconnector.

This solution did not meet the demand that the door should be able to close without connecting the disconnector, and other solutions were generated.

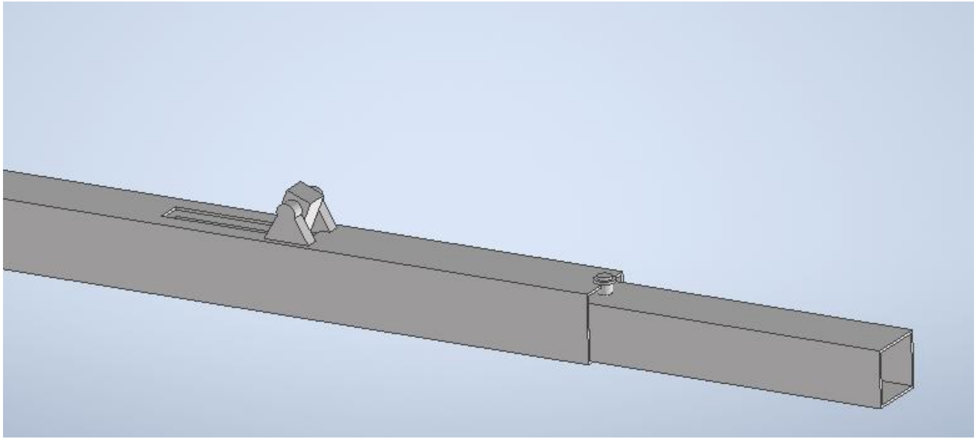


Figure 32: Pivot-Pin solution

Pivot-pin solution utilized two rails that could slide within each other, a pin, and a "Pivot pin." The pin located at the right side of Figure 32 would slide under the outer rail and not translating any movement to the mechanical solution as the door closes. The pivot pin would only transfer motion when the door was opening, falling into the groove and transferring the movement between the rails. Closing the door, the pivot pin would simply rotate above the inner rail. The user would have to manually pull up the pin and close the door, in order to translate any movement to the mechanical solution.

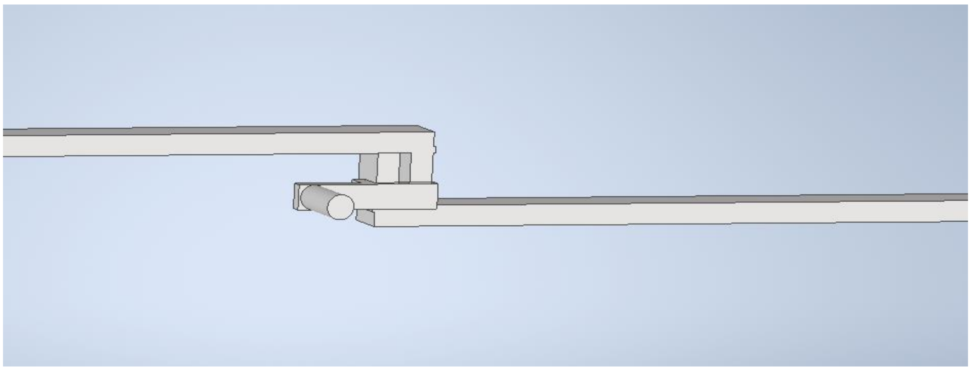


Figure 33: L-Shape Solution

The next solution worked similarly without having a small pin that needed to be manually lifted each time the disconnector needed to be connected. Instead, the L-shape solution has two L-shaped rails with a lever connected to one of the rails, as shown in Figure 33. Opening the door, the shape of the rails would enable movement from one rail to the next, while the lever would fall down, not connecting the two rails. As the lever would be positioned downwards, closing the door would not transfer motion between the rails. The user would have to manually lift the lever and begin to close the door to transfer movement to the mechanical solution.

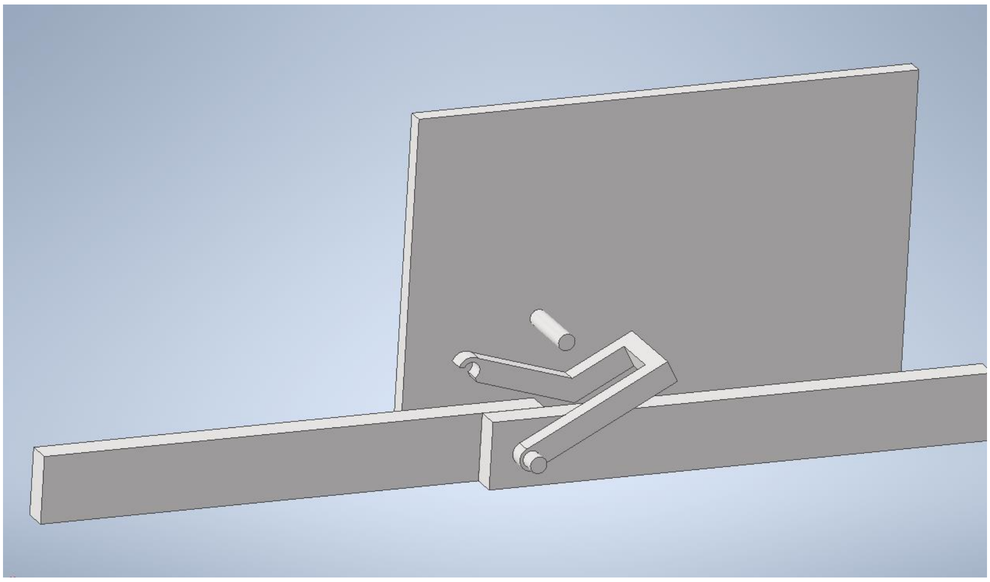


Figure 34: Handle Solution

Having a lever instead of a pin was considered to be a more user-friendly option. Thus, a new solution was devised, utilizing a handle. The handle solution, as depicted in figure 34, had two parallel rails, each with a pin protruding from opposite sides. When the lever connected to one of the rails was in its upright position, it could transfer the movement between the rails. Upon opening the door, the movement would be transferred until the "handle" encountered the pin on the back wall, causing it to fold downwards and release one of the rails. To transfer the movement to the mechanical solution, the user would have to manually fold the handle upwards and reconnect the two rails.

6.2 First Design Review Meeting Locking Solutions

Similarly, to the process of mechanical solutions, a design review meeting was held with Opticept. The locking solution plays a pivotal role in determining the overall user-friendliness and safety of the machine. Therefore, a conclusion was made with Opticept to further develop other locking solutions with the known mechanical solution, to expand the range of alternative locking solutions. Given the versatility of the previously mentioned locking solutions, which can be adapted to various mechanical applications, exploring alternative approaches that capitalize on the mechanical properties of the chosen solution may yield superior outcomes.

6.3 Locking Solution Concept Generation with Known Mechanical Solution

Choosing the Gear solution based on the concept scoring matrix provided different methods in installing a locking mechanism. The new concepts looked at what transfers movement in the Gear solution.

This results in there being several other approaches that were not considered during the initial concept development phase. For the transmission of motion to occur, the horizontal gear rail, the vertical gear rail, and the gear must all come into contact with each other. Moving any of these components out of position would prevent the transfer of motion. There are three alternative methods to achieve this:

1. Relocating the horizontal rail by moving it downwards or to the side to avoid interaction with the gear.
2. Moving the gear out of position.
3. Relocation of the vertical rail.

These three new approaches will be brought up in the following subsections.

6.3.1 **Relocate the horizontal rail**

There are several ways to modify the mechanism to allow for disconnection of the door without the use of the disconnector. One option is to relocate the horizontal gear rail, either by moving it downwards or to the side to prevent contact with the gear. Moving the rail downwards is the preferable solution as moving it orthogonally could cause issues with the gear teeth.

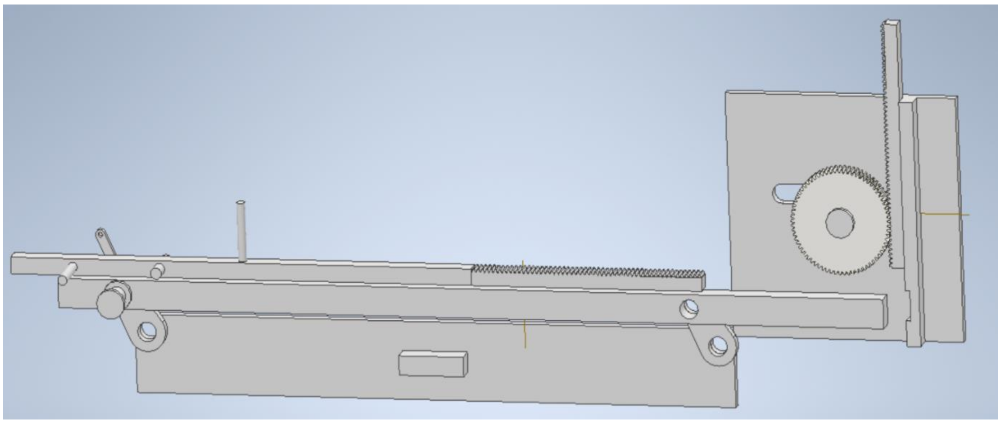


Figure 35: Locking Pivot solution

To achieve this, a solution with two pivot points has been developed, which would rotate the gear rail downwards. A pin connected to the gear rail would interact with a pin connected to the rotational part of the solution, folding the pin and the "pivot rail" downwards, shown in figure 35. Closing the door would not transfer movement to the disconnector, as the gear rail would slide below the gear. To transfer movement to the disconnector, the user would manually have to pull up the "pivot rail" to its upright position. However, this solution would require an additional pivot direction from the door.

6.3.2 **Moving the gear out of position.**

Another option is to move the gear out of position, which could be done with a slotted rail solution, as seen in figure 36. This approach would require a path for the gear to sit in and a connection to another rail to the gear would be necessary. A pin would travel with the rail connected to the door, and after the horizontal gear rail lost contact with the gear, the pin would hit the back wall of the slotted rail, pulling the rail while the door opens. If the door closes, no movement would be transferred, and the user would have to manually put the gear back into place for movement to be transferred.

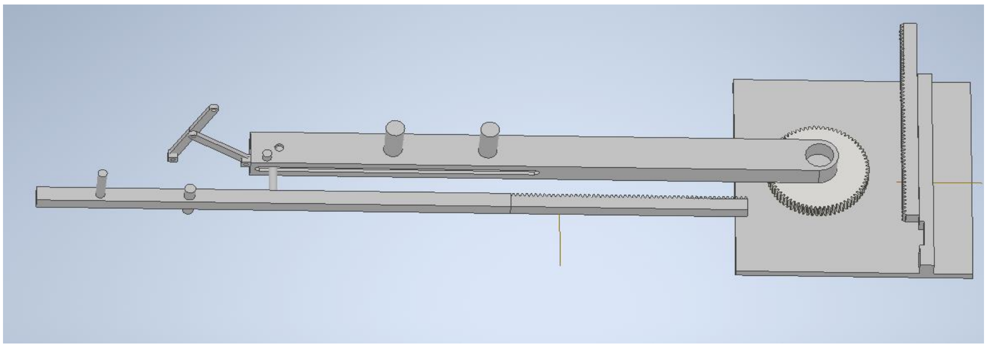


Figure 36: Locking Slot Solution

6.3.3 **Relocation of the vertical rail**

Due to the lower rail being encased and fastened to the lower part of the disconnector, this option was found to be unfeasible. Relocating the lower part of the disconnector could interfere with the alignment of the pins and plugs, making the alignment process more complex. The delicate pins and plugs require a high level of precision to avoid breakage. Consequently, no solutions were developed using this approach.

The locking solution is of utmost importance for both safety and usability of the solution. A second review meeting was held with Opticept to discuss and evaluate each concept.

6.4 Second Design Review Meeting Locking Solution

A second design review meeting was held with Opticept to discuss the locking mechanism created during the concept generation phases. Positive and negative aspects of each design were deliberated upon. A modified version of Pin Solution Version 2, called the Hooking Locking Solution, was also proposed during this meeting.

The basic idea behind the modified version was utilizing slopes and paths to guide the pin.

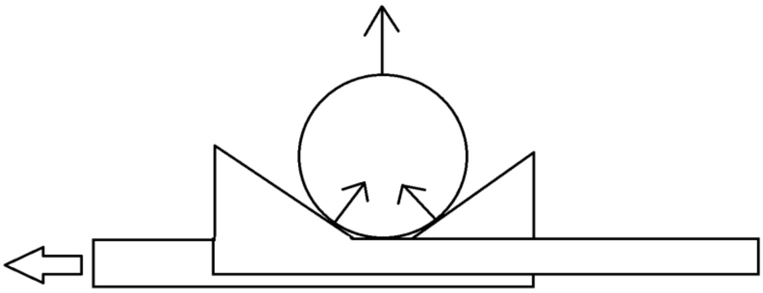


Figure 37: Sketch of basic concept for the hooking Locking Solution

The Locking Hooking Solution utilizes two square-shaped rails that slide against each other, with each rail featuring slots for pin placement. These rails incorporate slopes with angles below 45 degrees, causing the pin to move upward when the door is in motion, as illustrated in Figure 37.

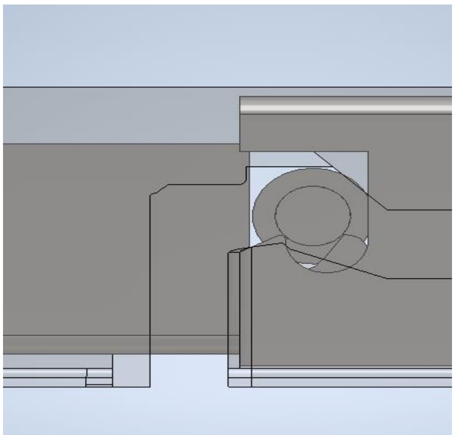


Figure 38: Hooking Locking Solution

Another rail with a cutout path encapsulating the pin restricts this upward movement and instead transfers the motion between the rails. Once the desired distance is achieved, the path allows the pin to move upward, disengaging the rails, depicted in figure 38. The pin will follow the rail connected to the door until the center of the pin gravity is positioned to the left of a downward slope, causing it to fall down beneath the rails. The user would have to put the pin into position for the disconnector to connect.

6.5 Concept Scoring Matrix Locking Solutions

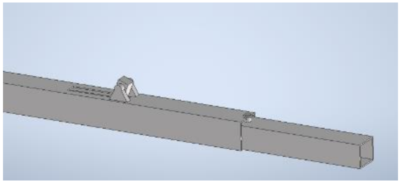


Figure 39: Pivot-Pin Solution

The Pivot-Pin solution is chosen as reference, as the current solution would not work with the chosen mechanical solution.

Table 11: Concept Scoring Matrix Locking Solution

Wishes	Pivot-Pin Solution (Reference)	L-shape Solution	Handle Solution	Locking Pivot Solution	Locking Slot Solution	Locking Hooking Solution	Weight
Easy to install	3	3	3	1	1	3	0.1
Minimize the size	3	4	4	1	2	3	0.1
Number of components	3	4	2	1	1	3	0.1
User friendly	3	4	3	4	3	5	0.3
Durability	3	3	2	2	2	5	0.4
Total Points	**3**	**3.5**	**2.6**	**1.26**	**2.1**	**4.4**	

6.5.1 Explanations of the Scoring Matrix

The durability of the locking solution is the most critical factor to consider as it directly impacts the safety of the system. This category does not only encompass the expected lifetime of the solution but also accounts for the risk associated with potential malfunctions. The second most important factor is user-friendliness, which should ensure that the disconnector can be easily connected, and that the safety feature does not interfere with maintenance. Additionally, factors such as ease of installation, and minimizing the solution's size and components, which can enhance the manufacturability and assembly process, are weighed equally.

L-shape solution:

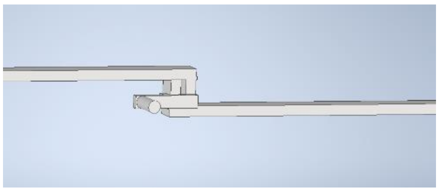


Figure 40: L-Shape Solution

The L-shape solution is as easy to install as the reference and has the potential to be smaller and have fewer parts. It is more user-friendly than the reference as it includes a lever to move, which is easier than moving a small pin. However, the user must pull up the lever and keep constant pressure on the door to keep the lever from falling down. The solution is considered as durable as the reference with regard to this.

The handle solution:

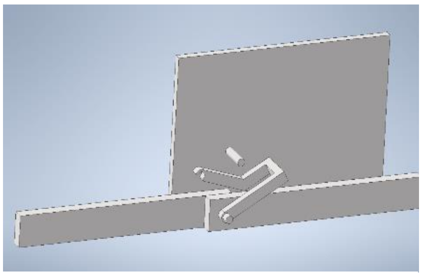


Figure 41: Handle Solution

The handle solution has similar installation properties to the reference, but it can be smaller, although it has more parts. It features a user-friendly handle, but the user must align the handle with the rail connected to the door, making it difficult to connect the two rails. The connection between the two rails depends on the geometry of the handle, and without proper development, it may not guarantee a secure connection. Therefore, it is given a low durability score.

Locking Pivot Solution:

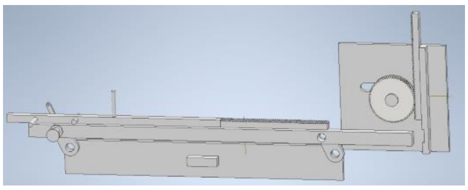


Figure 42: Locking Pivot Solution

The locking pivot solution is challenging to install as it includes several components that interact with each other and require two fastening points to the side wall of the cabinet. Additionally, the rail connection to the door needs another degree of freedom to facilitate downward rotation. Despite this, it is user-friendly as the movement from the downward position to the upper position can be done with a smooth motion. However, the numerous moving parts reduce its durability, making it less durable than the reference.

Locking Slot Solution:

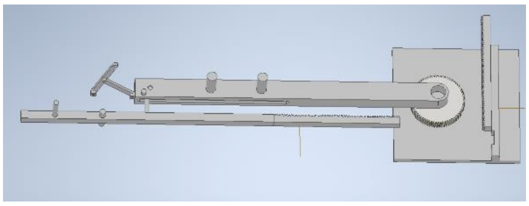


Figure 43: Locking Slot Solution

The locking slot solution utilizes a second rail system that connects to the gear, making installation more challenging as the lever would need a separate fastening point. Additionally, it is larger than the reference and has more components. Although the basic function for the user is straightforward, the door needs to be closed a few degrees for the lever to place the gear in the right position, making it as user friendly as the reference. Ensuring that the gear remains in place during the entire movement when connecting the disconnector can be difficult to guarantee, making it less durable than the reference.

Locking hooking Solution:

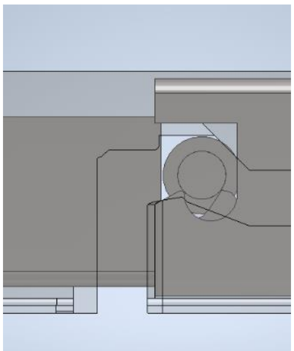


Figure 44: Locking Hooking Solution

The locking hooking solution is as easy to install, roughly the same size, and has the same number of components as the reference. It is much more user-friendly than the reference as the pin to connect the disconnector can be positioned without closing the door. The interlocking between the two rails is secure once the connection has been made, making it very durable, much more so than the reference.

The hooking solution is scored the highest and is further developed and incorporated into the overall solution.

6.6 Further development of Locking Hooking solution

Realizing having stainless steel sliding against each other and on each other would cause friction and noise. Some kind of sliding material between the rails was needed. The initial idea was to fit plastic sheets at the bottom of the contraption, see figure 45.

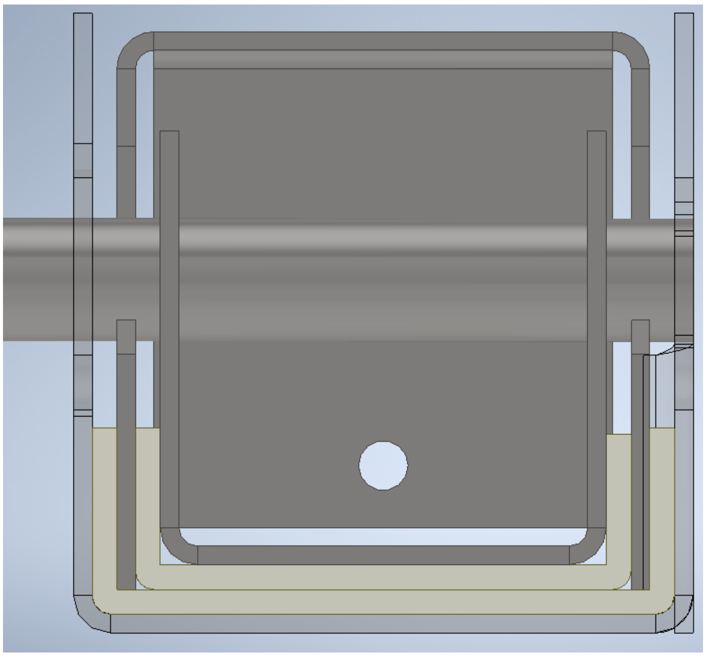


Figure 45: Sliding Material for Locking Solution

Recognizing the challenges associated with manufacturing sliding U-shaped components with precise tolerances, including the influence of bend, additional considerations surfaced. Consequently, an alternative approach was adopted, opting to construct the stationary rail from a plastic material.

6.6.1 **Final Locking Solution Design**

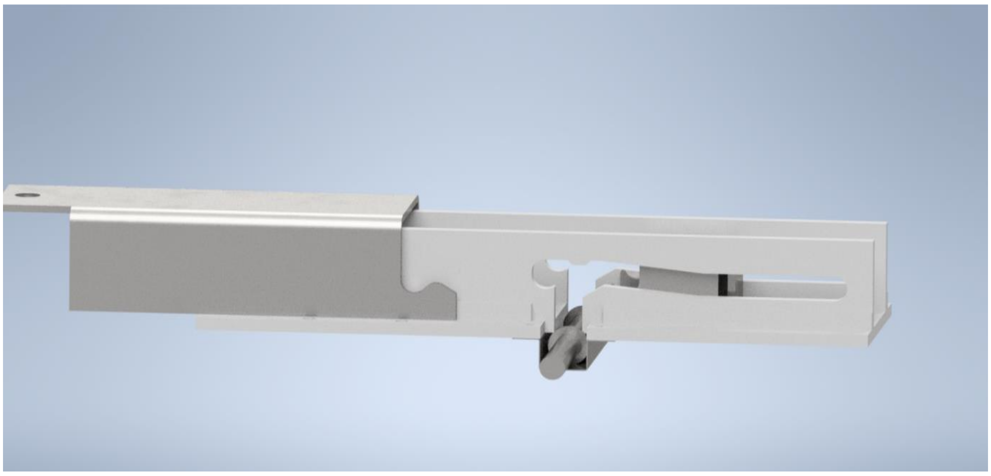


Figure 46: Final Locking Solution Design

The final locking solution design utilizes two U-shaped rails, which can be manufactured by bending and cutting a piece of stainless steel. The path rail is made of POM (polyoxymethylene) to facilitate low friction between the parts. At the left side of the path part, there is a cutout for the pin to be placed, for connecting the two steel rails. When opening the door, the pin will fall down into a “pin-catcher” and no movement from the door will transfer to the mechanical solution.

The movement was examined in Dynamic Simulation in Inventor. Where forces and relationships between parts can be examined. This provided a better insight into how the different parts acted together, and dimensions were worked on in order to get smooth connection and disconnection. The movement is depicted and explained in further detail in Appendix B.

7 Concept development Encasing

This chapter covers the concept development phase of the encasing solutions.

The last step of the concept generation was encapsulating the pins and plugs, making sure that the relevant demands and wishes were met. The relevant demands are:

- IP56
- “Power part” can be easily removed
- Corrosion resistant material
- Fire retardant material
- Smooth edges
- Alignment for pins and plugs
- Visible gap
- Needs to be separated into upper and lower parts
- Fastening of the chosen pins and plugs

The wishes are:

- Easy to install
- Cost reduction
- Low number of components
- Durable

7.1 Method

The approach taken for encasing the pins deviated from the methodology employed for the mechanical and locking concepts. The strict requirements imposed by the project limited the range of feasible solutions, thereby obviating the need for a separate concept selection phase. Instead, reasoning and decision-making occurred iteratively throughout this phase.

7.2 Fastening the pins and plugs

The initial step involved selecting the method of fastening the pins and plugs. The current design incorporates 3D-printed upper and lower parts that serve as connection points for the cables, pins, and plugs. However, in consultation with Opticept, it was determined that alternative solutions should be explored due to the high cost associated with 3D-printed components.

To mitigate cable-related issues, a decision was made to fasten the cables to the stationary upper section of the disconnector, while the lower section solely serves to redirect power to the upper section. Consequently, the lower section can be a singular component, whereas the upper section was initially envisioned to consist of two or more parts to facilitate the removal of the power part.

The pins must be securely affixed to a non-conductive material that meets fire redundancy requirements stipulated by the standards. The clearance and creepage distances from the pins must also be taken into account, as these dimensions affect the encasement's size and attachment points.

Various encasement solutions were evaluated for the mechanical solution's attachment to the lower section of the disconnector, such as plastic sheets, plastic mounting plates, and plastic boxes. Plastic boxes were deemed the most suitable choice, with the option of either custom-manufactured or standard plastic boxes. Opticept has frequently procured products from RS, a reliable company offering a wide range of products. Notably, the Hammond 1591 series comprises fire-retardant black boxes, available in various dimensions that can align with the required specifications, showcased in figure 47.

Figure 47: Hammond 1591 Series Plastic Box [20]

During the initial concept generation for these plastic boxes, the dimensions were determined based on the clearance and creepage distances specified by the standards. Once these dimensions were established, standard plastic fire-retardant boxes meeting the given criteria were identified. The Hammond 1591 series, known for its versatility, encompassed a diverse selection of plastic box dimensions that aligned with the requirements.

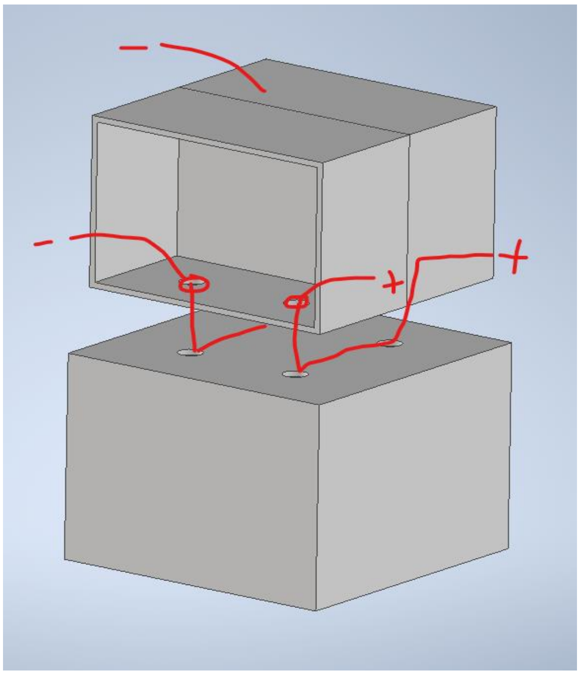


Figure 48: Showcasing how the Electric Connection between the Disconnector could be established.

To accommodate the need for removing the "power part" section of the disconnector, the initial design entailed one box for the lower section and two boxes for the upper section. As seen in figure 48, the upper outer box represents the power part and is responsible for transmitting the electricity to the lower part. The lower part then connects to the upper inner box, which is connected to the chamber. Holes for the pins and plugs would have to be drilled in the boxes, as well as the connection for the cables.

7.2.1 Requirement adaptation

Recognizing the contradiction between the requirements of removing the power part of the disconnector and the requirement for IP classification, a careful examination was conducted. The rationale behind the requirement for power part removal stemmed from facilitating testing of the machine's power module. However, considering that the power module is undergoing development and improvements are expected, the necessity of such tests in the future may diminish. Consequently, after consultation with the development team at Opticept, a decision was made to prioritize the IP-classification requirement.

This reduces the complexity of the design necessary; the upper part of the disconnector could be constructed utilizing the same encasing as the lower part of the disconnector. Packing was taken into account during the design process, making sure that the IP classification could be met.

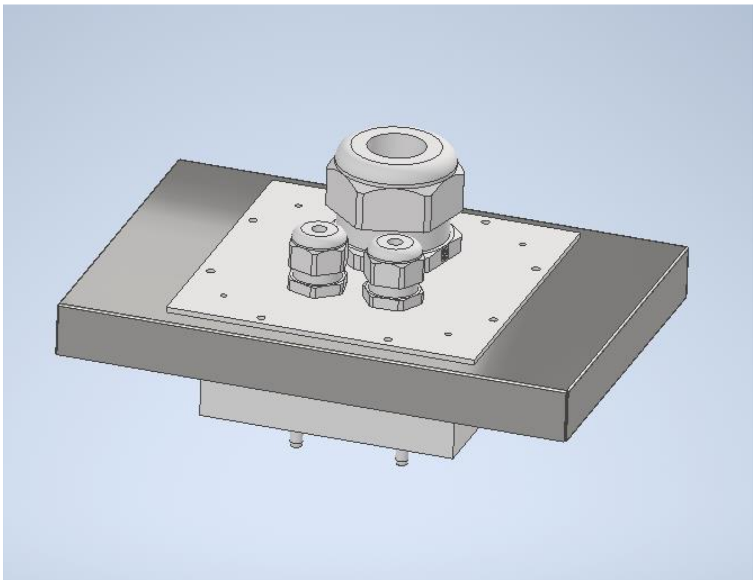


Figure 49: Upper Part of the Disconnector

The upper part could, as mentioned, be one singular component. To facilitate the IP classification the lid of the box is mounted on top of a sheet metal place, with packing between the surfaces, seen in figure 49. The high-voltage cables will connect through cables glands visible at the top of the lid. These cable glands have an IP classification of IP56, which Opticept has used in the past.

7.2.2 **Alignment**

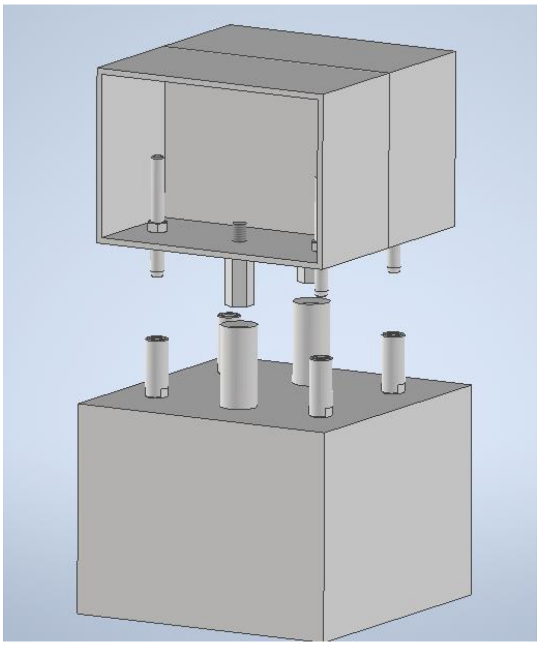


Figure 50: Standoffs Example

Standoffs and hollow standoffs, seen in the middle of figure 50, were thought to be good to utilize to minimize the force on the actual pins and plugs while being used to align them. Opticept wanted a more robust solution for alignment and instead utilizing alignment rods was deemed to be the best choice.

The alignment rod interacts between the lower and upper part of the disconnector and works both as a stopper and an alignment tool to ensure that the pins and plugs connect properly. As the upper part of the disconnector is stationary, the alignment rods do not need to be connected to the upper part. This way the assembly and installation will be easier.

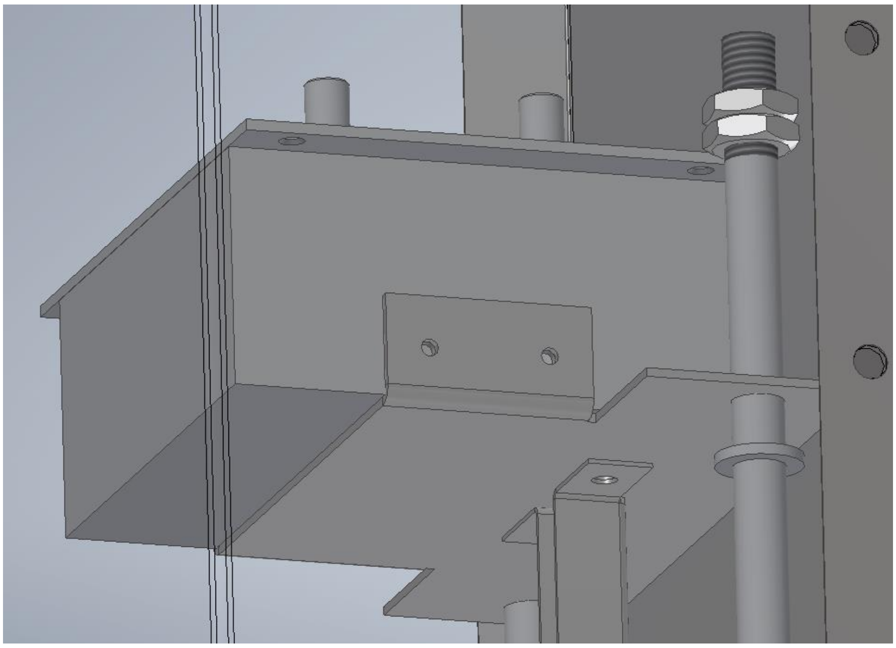


Figure 51: Alignment Rods and Connection to the Lower Part of the Disconnector

The rods are then inserted into a sheet metal plate fastened onto the lower part of the disconnector, making sure that the pins and plugs are connected properly, showcased in figure 51. The vertical rail is connected to this sheet metal plate as well, in order to transfer the movement from the mechanical solution.

The alignment rods are secured to a plate situated below the gear baseplate, by internal threads. The upper "stopper" can be constructed using two nuts that are tightened in opposite directions, utilizing the external threads of the alignment rods.

7.3 Final design choices

In order to meet the requirements that the disconnector in its OFF state provides a visible gap for the user to see, the main body encasing the solution will be made of plexiglass. Connected to the backplate of the solution, similar to the design of the current solution. The presence of a plexiglass cover enclosing the solution necessitates a strategically placed hole to accommodate the interaction between the locking and gear solutions. Failing to consider this aspect adequately could pose challenges in terms of maintaining the desired IP classification.

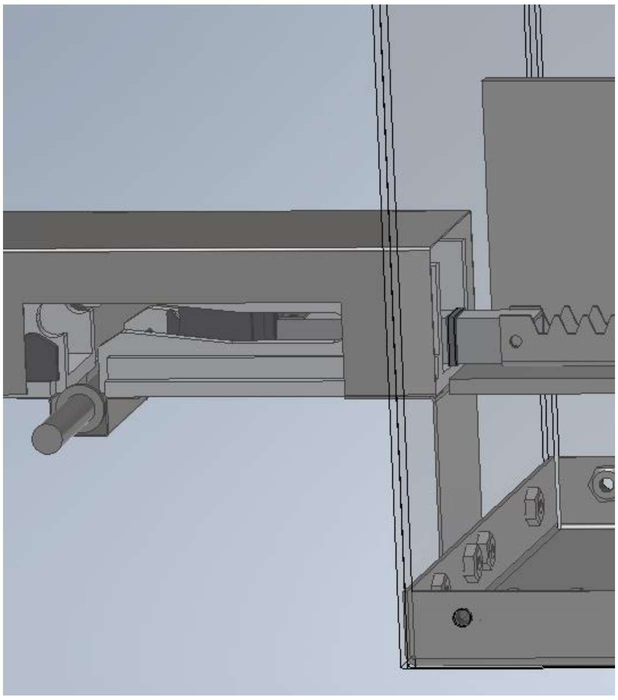


Figure 52: Plexiglass Square Hole

To address this concern, a solution was devised to ensure the smooth integration of the two systems. A square steel bar, capable of being encapsulated by the gear rack, was employed as an extender linking the locking and gear solutions, as seen in figure 54. Consequently, only a small square hole in the plexiglass cover is required. To enhance the seal and reduce friction, a silicone sealing strip can be employed along the periphery of the hole. A standard steel bar is utilized, which governs the dimensions of the gear rack, subsequently determining the size of the gear itself.

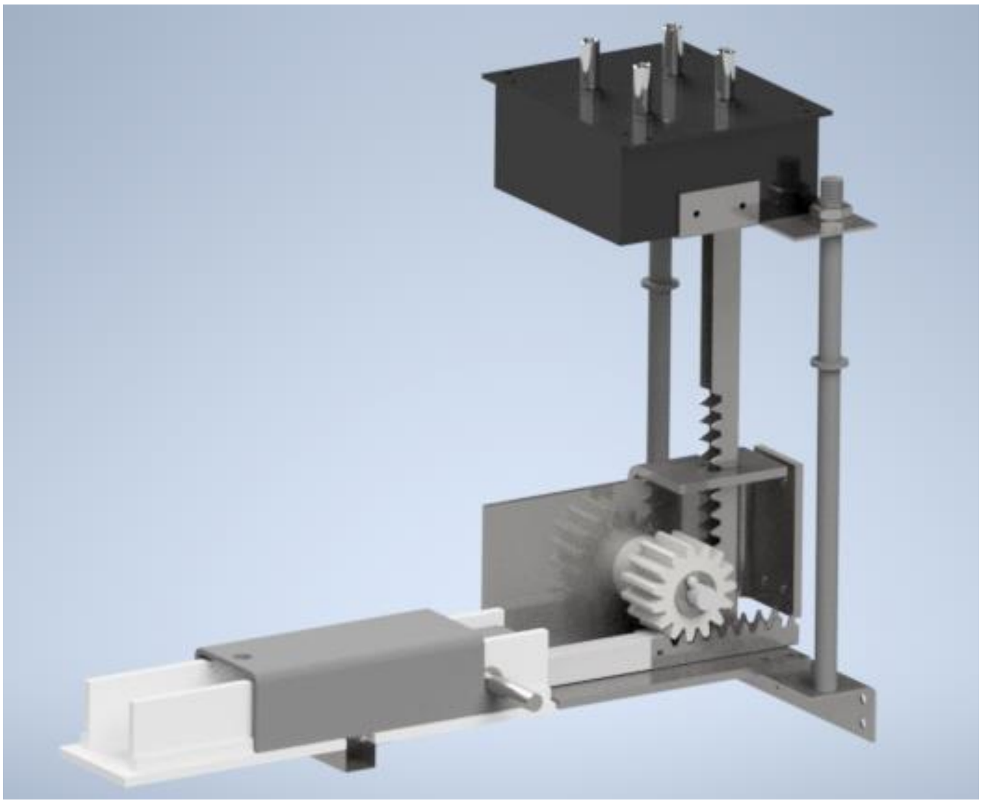


Figure 53: Gear Solution Final Version and its Connections

The next step was finding a gear that would be wide enough to ensure that both gear rails could be in contact with the gear without interfering with each other. As mentioned earlier this meant that a higher module was necessary. A standard spur gear rail with the module 3 was considered the best option that has a width of 30 mm. The gear rail would then also have to have module 3 to ensure that the movement could be transferred between the two gear rails. This final version of the gear solution is showcased in figure 53, with its connection to the lower part of the disconnector and the locking mechanism.

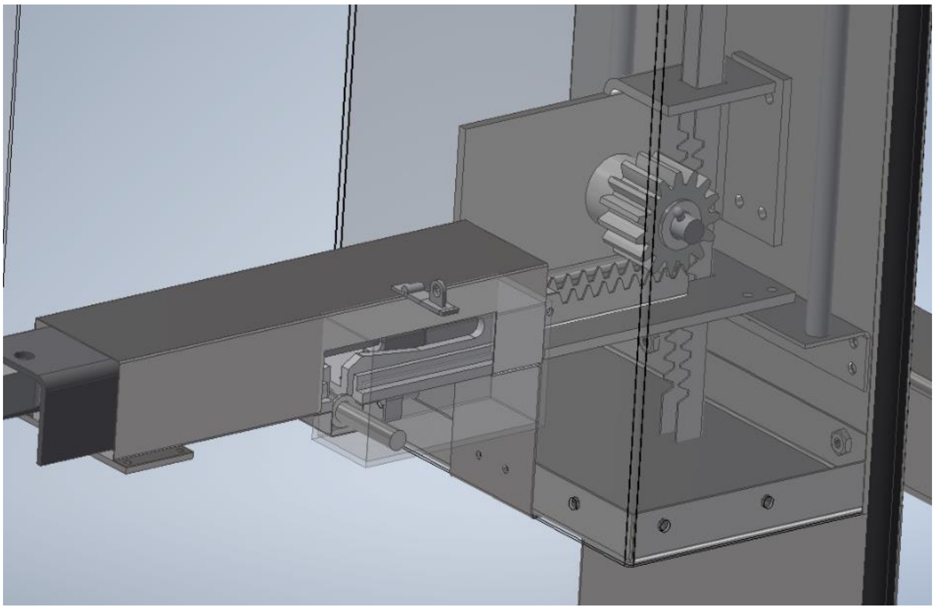


Figure 54: Connection between Locking Mechanism and Gear Mechanism

The final step involves addressing the lock solution by applying a sheet metal cover to minimize the risk of fingers being trapped and crushed. Additionally, a protective box was incorporated to enclose the pin and its corresponding cutout, as seen in figure 54. This box can be securely locked by the user using a padlock, as mandated by the demands.

8 Final Design

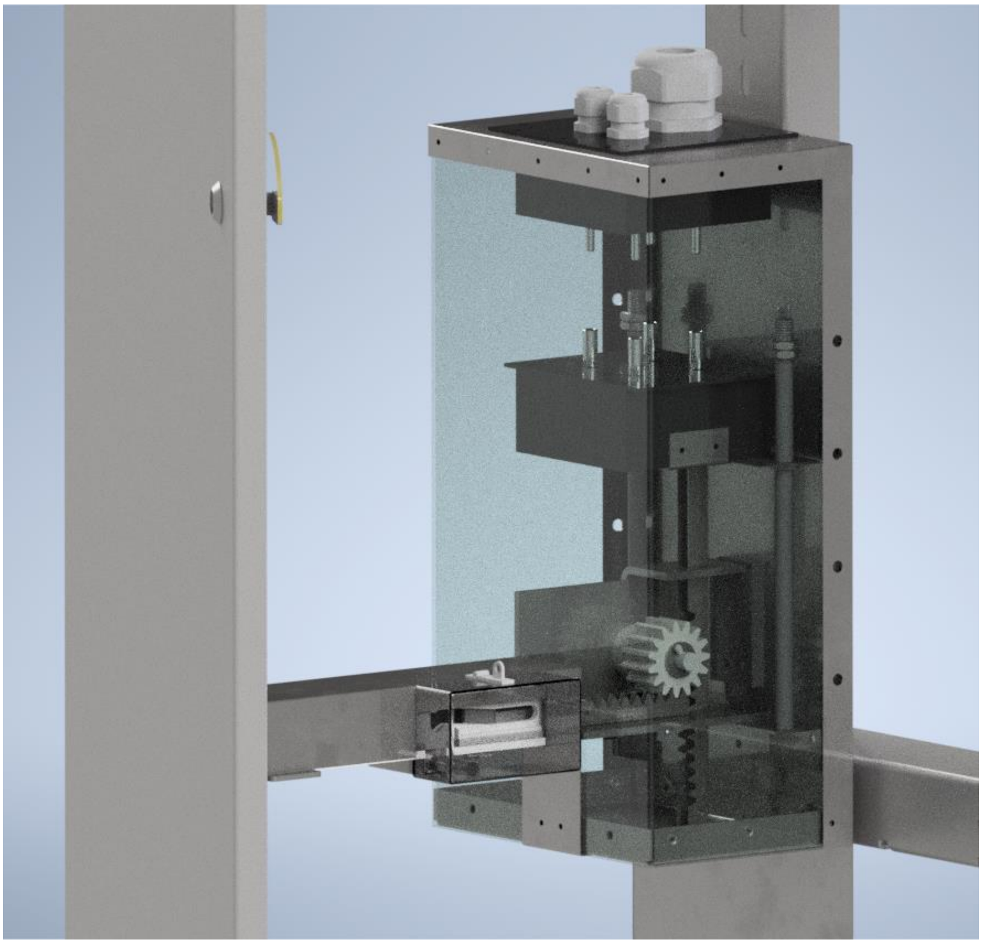


Figure 55: Final Design Rendered Image

The final design consists of the three main chosen concepts discussed in this report and can be seen in figure 55. It consists of 50 parts, not including bolts, washers, and weld nuts. Constituting 3 main assemblies, Gear solution, Locking solution, and Encasing.

Beginning from the top, the upper section of the disconnector features cable glands on its upper part to facilitate the connection of high-voltage cables to the pins. The lid of the upper part of the disconnector is positioned externally, encompassing a larger sheet metal lid with packing material between the two lids. The external sheet metal lid is connected to the backplate and the plexiglass, ensuring that no water can penetrate the design. Consequently, packing material is also placed around the plexiglass.

On the opposite side, a similar sheet metal lid is installed, but this one is assembled within the plexiglass to prevent water from seeping between the lid and the plexiglass. To achieve this, weld nuts are welded on the inside of the lower sheet metal lid, allowing the bolts to be fastened from the outside. Additionally, packing material is used around this section. The spur gear is positioned on a sheet metal gear baseplate which is connected to the main backplate using bolts. The gear backplate is connected to the alignment rod plate, which is situated beneath it. The alignment rod plate supports part of the load while securing the alignment rods. These rods ensure that the lower part of the disconnector remains in its vertical plane, preventing damage to the pins and plugs from unexpected movements. Furthermore, they ensure that as the horizontal gear rail disengages from the gear as the door opens, the lower part does not descend further than necessary.

The locking mechanism is connected to the door, two support arms, one connected to the cabinet wall, and one connected to the lower sheet metal lid. The locking mechanism is covered with a sheet metal cover that prohibits fingers from getting into the mechanism. The arm and the cover have rounded corners per the standard of not having sharp edges.

9 Discussion

This chapter covers a discussion about the project plan, the overall project, further development and how the standards impact the design.

9.1 Project plan evaluation

The original plan for this project, presented as a Gantt chart in Appendix A figure A1 and A2, entailed developing a prototype and conducting tests; however, this plan did not come to fruition. During the project planning phase, the complexity of the design was underestimated, largely due to the standards and requirements of Opticept. This was particularly evident in the development phase. The aim was to create a range of mechanical and locking solutions independently to maximize the number of options available for a comprehensive solution. However, the conflicting requirements of increased safety, resettable locking mechanism, and rapid attainment of the necessary disconnector separation distance posed significant challenges. Significant time was devoted to generating novel concepts and drawing them in CAD, combined with the task of addressing the initial design flaws of each concept. Due to this the timeframe of creating a physical prototype was decided to be too short to accomplish this. As an alternative, dynamic simulations were employed, serving as additional proof of concept.

The actual project progression is shown in Appendix A figures A3 and A4, where the Prototype and testing segments of the project have been removed.

9.2 Project evaluation

The goal of this project was to design a safer disconnector, while still reaching the requirements set by Opticept and the relevant standards. While all demands have been considered during the concept development phase, some can be confirmed in this stage of the project. Such as: no use of springs, flame retardant material, no use of materials according to ROHS, visible gap, being able to lock the disconnector in its OFF state, clearance and creepage distance, no sharp edges, and protection for the user to avoid crushing fingers. Other requirements need to be confirmed with a physical prototype, like the IP56 and the reset mechanism of the disconnector.

The locking mechanism was tested virtually using the dynamic simulation tool the CAD software inventor has to offer. It provided some insight into how the mechanism will work, but as far as safety is concerned, it is not enough to validate the design.

9.3 Further Development

9.3.1 **Locking Mechanism**

The locking mechanism holds significant importance in this design, as it directly affects user safety. Ensuring the correct operation of this aspect is of utmost importance for the success of the entire project. It is essential to acknowledge that the behavior of the solution may differ from the results obtained in dynamic simulations, depending on the force exerted when opening the door. Therefore, physical testing is necessary to validate its performance.

Regarding the plastic cover for the pin on the locking mechanism, it is designed to open downwards to minimize the size of the cover. Users would need to be instructed to close the box after each use. If Opticept considers this process to be inconvenient for users, an alternative approach could be implemented where the cover opens upwards and closes automatically upon release and is only securely locked when needed.

9.3.2 Gear Solution

Implementing a gear mechanism is a commonly employed and standardized approach for resolving such mechanical challenges. It is possible to explore the availability of gears with a smaller module that possesses sufficient width. Custom manufacturing or identifying a company specializing in the production of such gears could provide potential solutions in this regard.

The desired separation distance is achieved around 22 degrees of opening the door. However, should Opticept desire a faster separation, two gears with different dimensions could be employed. The smaller gear would connect to the vertical gear, while the larger gear would connect to the horizontal gear. This arrangement would facilitate a faster separation in the disconnector. This would also result in the ability to utilize gears with smaller modules.

9.3.3 Encasing

To ensure that the design is adequately protected against water ingress, tests for the IP classification must be conducted. Additionally, a decision regarding the type of packaging needs to be determined.

The IP classification primarily applies to the electrical components, indicating their level of protection against the ingress of solid objects and liquids. Consequently, ensuring IP classification for the connection between the locking mechanism and gear mechanism may not be necessary. Instead, a lid similar to the lower sheet metal lid could be installed above the gear back plate to prevent water penetration in that specific area. However, it remains crucial to safeguard the gear solution from dirt and other potential obstructions to maintain safety standards, which is why the design has prioritized making the entire encasing IP56-Classified. But can however be another possibility to reach the desired IP classification.

The upper and lower sections of the disconnector could alternatively be manufactured through 3D printing, presenting the advantage of a more compact solution and the incorporation of vertical pipes to enhance alignment, similar to the current design. The 3D-printed parts for the current disconnector are supplied by AMPrint Service, with an average cost of approximately 10,000 kr per liter.

A preliminary calculation was performed for the upper and lower sections using 3D printing, resulting in an estimated cost of around 2000 kr (excluding alignment pipes). In comparison, the Hammond 1591 boxes are priced at 230 kr. It should be acknowledged that the quoted price for 3D printed parts is a general estimate and may increase if thicker materials are required to ensure rigidity and accommodate printing considerations. Nevertheless, the utilization of 3D printed components may simplify assembly by eliminating the need for hole drilling, while potentially achieving more precise alignment of the pins compared to manually drilled holes.

9.3.4 **Positioning**

The positioning of the door connection was selected to facilitate easy installation. However, if the connection were situated higher up, it could potentially enable a smaller design for the disconnector. Similarly, if alternative connection points to the back of the cabinet were available, it would be possible to reduce the size of the baseplate that connects the disconnector to the cabinet.

Ideally, the lower section of the disconnector would align with the upper part of the gear back plate, aiming to minimize the overall size of the solution. By modifying the connection points, it would be feasible to create a more compact design, potentially resulting in a shorter vertical rail as well.

9.4 Standards with Respect to Education

According to Ullman, [21] the classic design paradox is illustrated in figure 56 below, which states that as the design freedom decreases, the information gained about the design increases at the same rate.

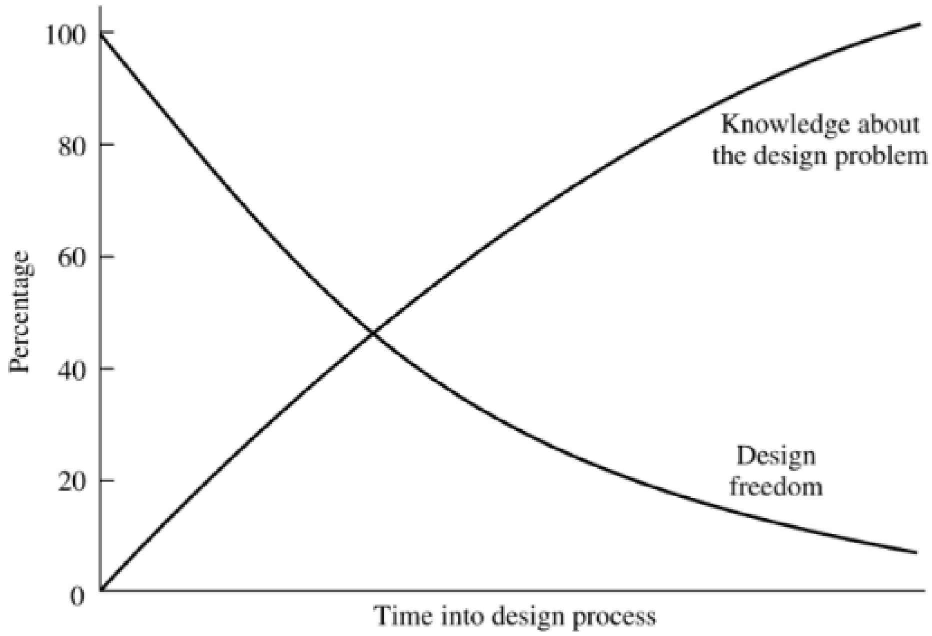


Figure 56: Design Freedom Compared to Knowledge about the Design [21]

This paradox is clearly depicted in the present project, particularly when designing for safety standards. These standards place restrictions on design in critical areas such as the use of springs, clearance and creepage distance, visible gaps, and the need for remaining in the OFF position even in case of malfunction. After selecting a mechanical solution, the design freedom for the locking mechanism became quite limited. Balancing requirements such as durability, reset capability after opening the door, compactness, and user-friendliness resulted in the need for a complex solution. Despite generating multiple solutions, the trade-off between durability and usability dictated the choice of locking mechanism.

Gathering and interpreting requirements from standards is a crucial step in the mechanical engineering design process, but it is often overlooked in education. Complying with standards is essential to ensure the safety of the final product, as changing the design later in the development process becomes exponentially more expensive, as depicted in figure 57 below:

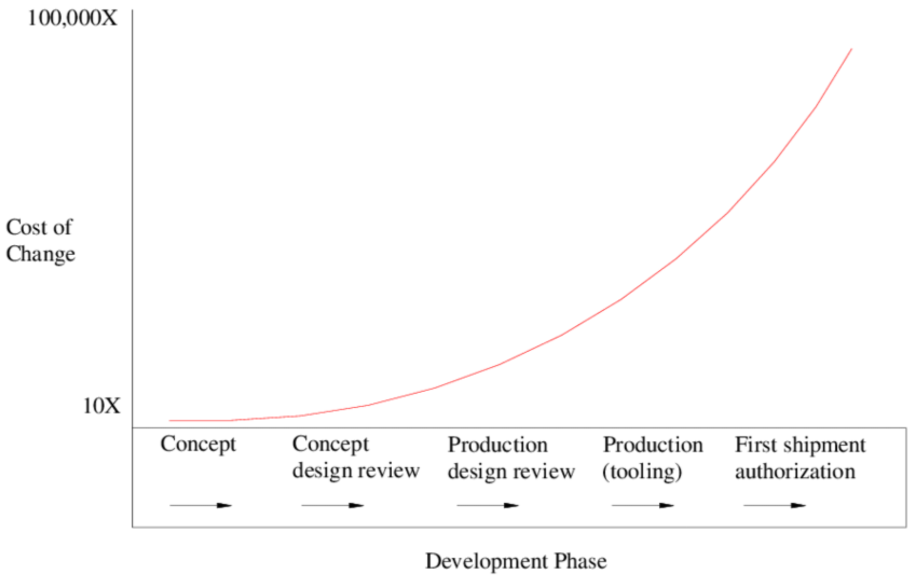


Figure 57: Cost of Change Compared to the Development Phase [22]

Therefore, it is crucial to determine the relevant standards at the outset of the project. However, the current specialization programs "product realization" and “product development” do not adequately address this issue. A course that covers designing products to meet standards could be beneficial, including mechanical standards for designing mechanical components. For example, a “Designing for safety” or “Design for Standards” subject could be included in the "Design for X" course, which could explore relevant information about standards and how they impact different design choices.

10 Conclusion

This master thesis, conducted in collaboration with Opticept Technologies, provides valuable insights into the integration of safety standards throughout the development process of mechanical disconnectors utilized in Pulsed Electric Field (PEF) machines. The thesis examines relevant standards and delves into the associated requirements and guiding principles. These requirements and principles are subsequently translated into design criteria that form the fundamental basis for the development process, highlighting their pivotal role in ensuring safety.

This master thesis provides a comprehensive approach to developing mechanical disconnectors for high-voltage machines used in PEF treatment. The thesis utilizes Ulrich and Eppinger's product development process, which is a widely recognized framework for product development, providing a structured approach to the development process. Additionally, the thesis draws on Pahl and Beitz's method for engineering design, which divides requirements into demands and wishes. While these methods were adapted due to design restrictions specific to the project, they still provide structure to the development process as a whole. The thesis underscores the importance of adhering to specific safety requirements and their profound impact on product development. Overall, this thesis offers valuable insights into integrating safety standards throughout the development process of mechanical disconnectors utilized in Opticept PEF machines.

Overall, this master thesis underscores the significance of adhering to specific safety requirements and their profound impact on product development. It offers a comprehensive development process that encompasses concept generation while considering specific design criteria, through close collaboration with Opticept, resulting in a viable solution accompanied by further development aspects.

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12 Appendix A

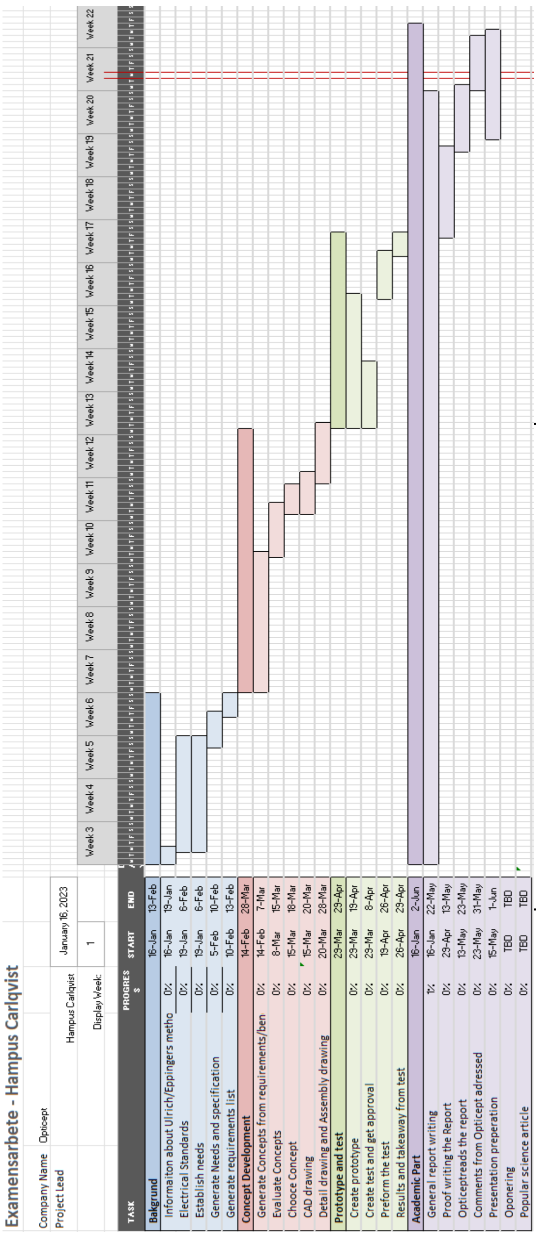

Figure A1: Initial Gantt Chart

TASK	PROGRESS	START	END
Bakgrund		16-Jan	13-Feb
Informaiton about Ulrich/Eppingers meth	0%	16-Jan	19-Jan
Electrical Standards	0%	19-Jan	6-Feb
Establish needs	0%	19-Jan	6-Feb
Generate Needs and specification	0%	5-Feb	10-Feb
Generate requirements list	0%	10-Feb	13-Feb
Concept Development		14-Feb	28-Mar
Generate Concepts from requirements/b	0%	14-Feb	7-Mar
Evaluate Concepts	0%	8-Mar	15-Mar
Chooce Concept	0%	15-Mar	18-Mar
CAD drawing	0%	15-Mar	20-Mar
Detail drawing and Assembly drawing	0%	20-Mar	28-Mar
Prototype and test		29-Mar	29-Apr
Create prototype	0%	29-Mar	19-Apr
Create test and get approval	0%	29-Mar	8-Apr
Preform the test	0%	19-Apr	26-Apr
Results and takeaway from test	0%	26-Apr	29-Apr
Academic Part		16-Jan	2-Jun
General report writing	1%	16-Jan	22-May
Proof writing the Report	0%	29-Apr	13-May
Opticeptreads the report	0%	13-May	23-May
Comments from Opticept adressed	0%	23-May	31-May
Presentation preperation	0%	15-May	1-Jun
Opponering	0%	TBD	TBD
Popular science article	0%	TBD	TBD

Figure A2: Zoomed-in Picture of the Tasks in the initial Gantt Chart

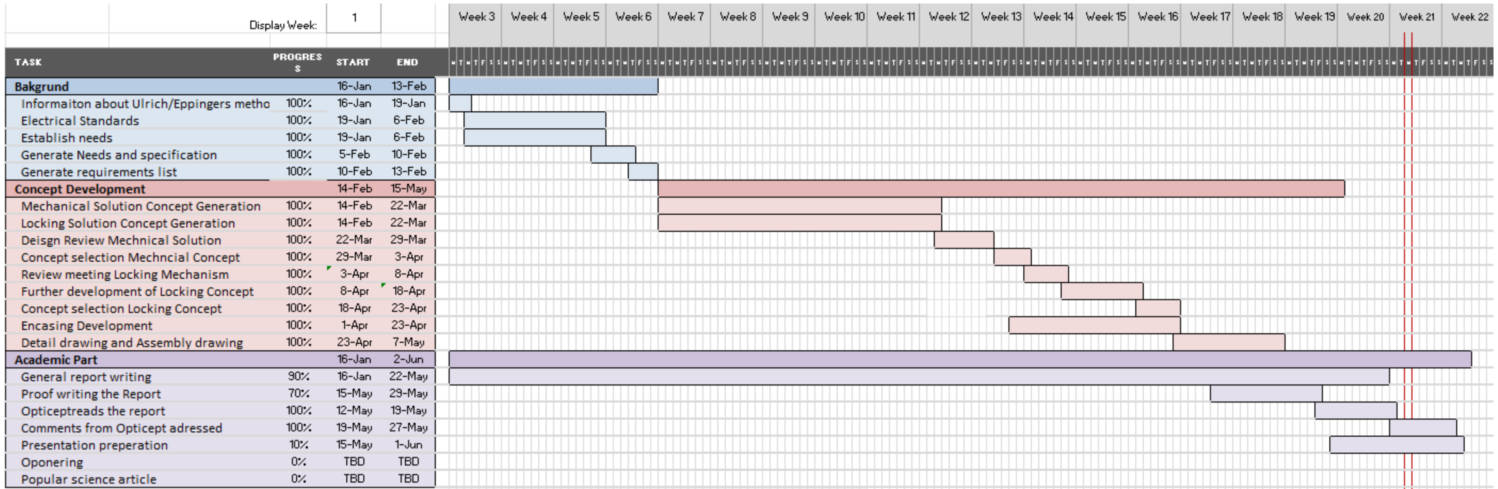

Figure A3: Actual Project Progression

Bakgrund		16-Jan	13-Feb
Informaiton about Ulrich/Eppingers metho	100%	16-Jan	19-Jan
Electrical Standards	100%	19-Jan	6-Feb
Establish needs	100%	19-Jan	6-Feb
Generate Needs and specification	100%	5-Feb	10-Feb
Generate requirements list	100%	10-Feb	13-Feb
Concept Development		14-Feb	15-May
Mechanical Solution Concept Generation	100%	14-Feb	22-Mar
Locking Solution Concept Generation	100%	14-Feb	22-Mar
Deisgn Review Mechnical Solution	100%	22-Mar	29-Mar
Concept selection Mechncial Concept	100%	29-Mar	3-Apr
Review meeting Locking Mechanism	100%	3-Apr	8-Apr
Further development of Locking Concept	100%	8-Apr	18-Apr
Concept selection Locking Concept	100%	18-Apr	23-Apr
Encasing Development	100%	1-Apr	23-Apr
Detail drawing and Assembly drawing	100%	23-Apr	7-May
Academic Part		16-Jan	2-Jun
General report writing	90%	16-Jan	22-May
Proof writing the Report	70%	15-May	29-May
Opticeptreads the report	100%	15-May	25-May
Comments from Opticept adressed	100%	25-May	2-Jun
Presentation preperation	10%	15-May	1-Jun
Opponering	0%	TBD	TBD
Popular science article	0%	TBD	TBD

Figure A4: Zoomed-in Picture of the Tasks in the actual project progression.

13 Appendix B

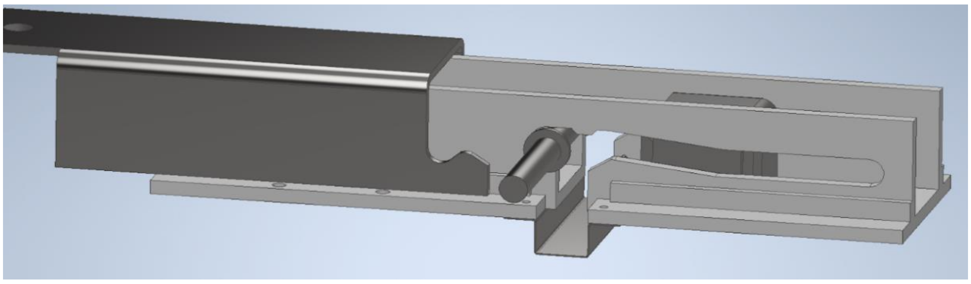

Figure B1: Starting position, pin position for connecting the disconnector.

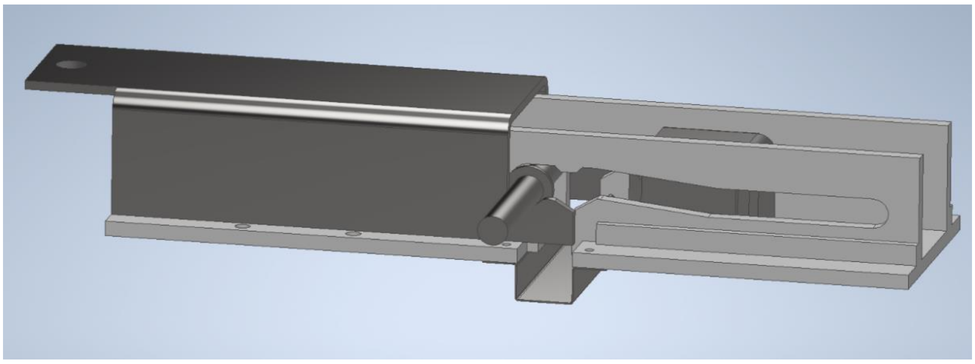

Figure B2: The left rail connected to the door connects to the pin.

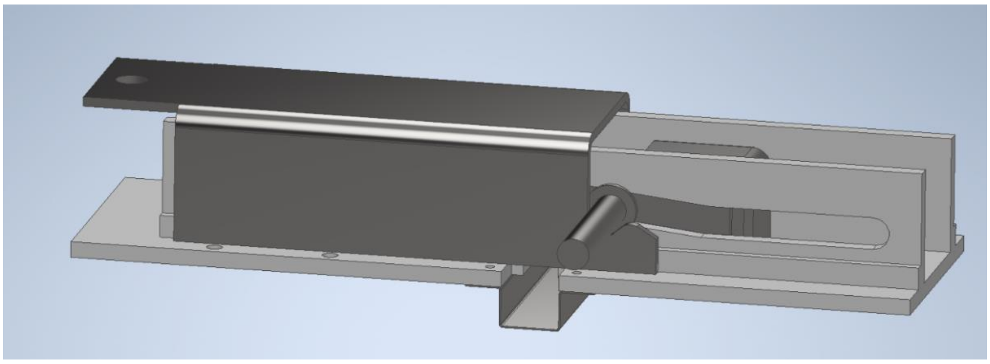

Figure B3: The left rail moves the pin into contact with the second rail connected to the mechanical solution.

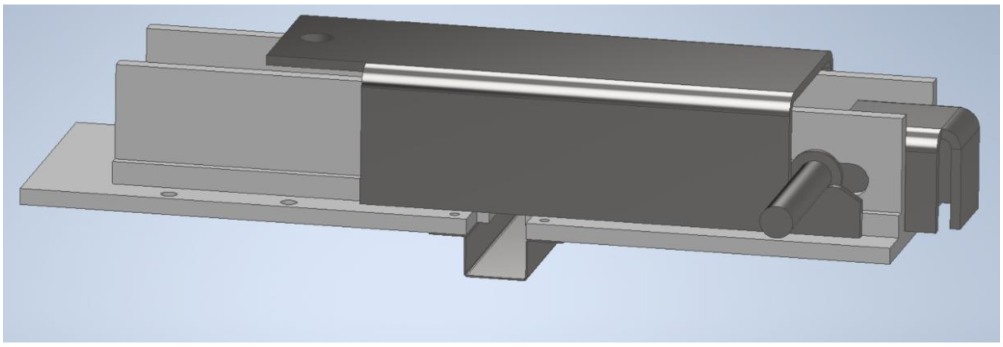

Figure B4: End position. The disconnector is connected.

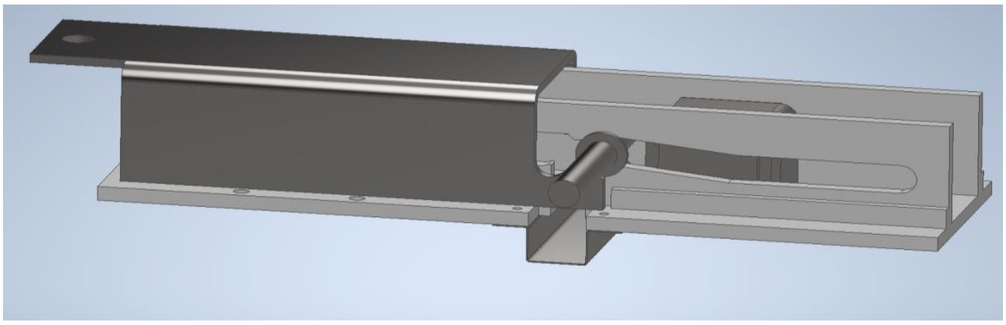

Figure B5: Opening the door both rails will move back towards the starting position, disconnecting the disconnector.

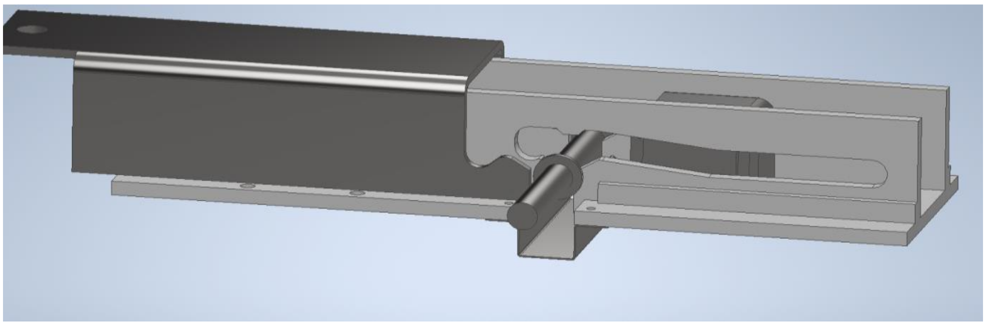

Figure B6: The pin will disconnect from both the rails and fall down towards the pin catcher.

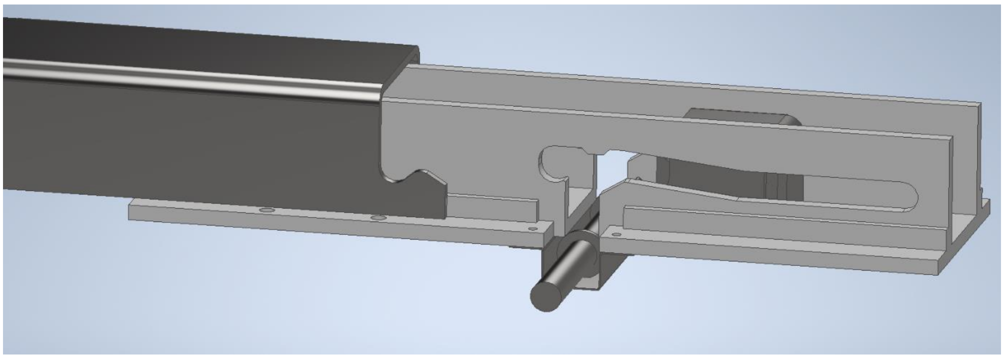

Figure B7: The door is completely open, and the pin needs to be reset in order to connect the disconnector.

Key geometries:

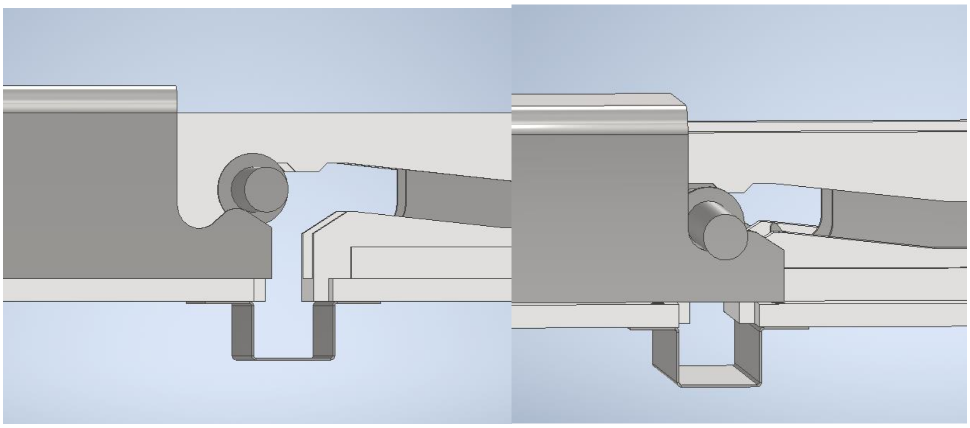

Figure B8: Starting Position

In the pin's starting position, the left rail connected to the door has a slope for the pin to climb, the slot on the top will prohibit the pin from falling down into the pin catcher, instead be placed in the grove of the left rail.

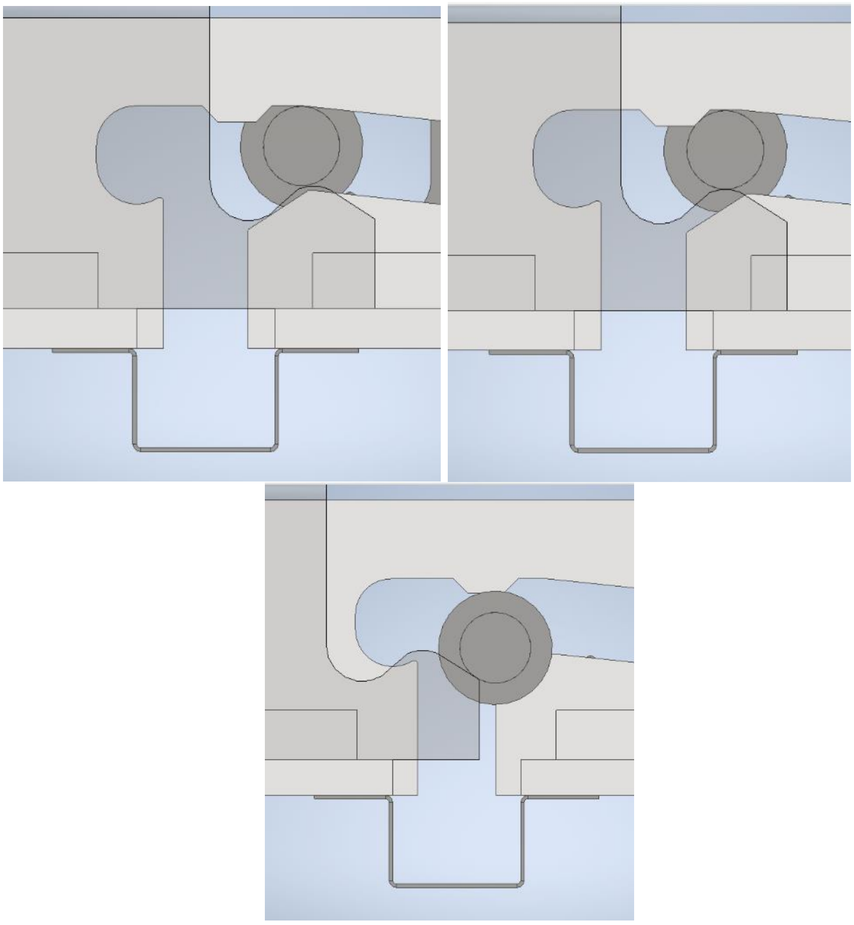

Figure B9: Disconnecting the Pin

After disconnecting from the right rail connected to the mechanical solution, the path and geometry of the left rail will push the pin upwards, the pin will move above the "hill" of the left rail and disconnect from the rail, at this point the pins center of gravity will be on the left side of the ramp on the path rail, making sure that the pin falls down towards the pin catcher. The slot on the top will act like an extra safety step, prohibiting the pin from falling down the left rail groove again.