Development of a Multi-Drilling Device

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Abstract

Täby Brandskyddsteknik AB is a company that provides a service of fire-proofing tunnels by mounting fire-protection boards to the walls and the ceiling of the tunnel. The installation is done by drilling holes through the board and into the concrete and then hammering bolts into these holes. To reach the ceiling the installers use a scissor-lift. The drilling phase of the installation process is very strenuous work and entails vibrations from the hammer drill and a work posture with the hands raised above the shoulders. To lessen the strain on the installers and to reduce the installation time a multi-drilling device was developed. The device contains six attached hammer drills which are raised to the ceiling by six individual pneumatic cylinders that also provide the required drilling force. It is manoeuvred on an “X”-shaped base with four lockable wheels and contains a winch solution for height adjustment relative to the tunnel ceiling. An economical gain is also made by the company since the multi-drilling device replaces one of the three installers in terms of work. The device is adjustable for only the slimmer boards used by Täby Brandskyddsteknik AB since the larger boards are too heavy for only two persons to lift. The total weight of the device is approximately that of an average male and the device is solely designed after male height measurements since Täby Brandskyddsteknik AB currently does not have any female installers employed. The drilling depth is set with a simple manual adjustment and the upper part with the drill units can be angled to suit the slope of the ceiling with another manual adjustment. The multi-drilling device will only be used by the company’s installers and will therefore only be produced in a very low scale. Simplicity of the construction solutions and the use of standard components were favoured to provide easy manufacture and repair in-house.

The process of the project consisted of an extensive background research including literature studies and observations of the installation work, idea generation with brainstorming, concept evaluation and development of the final concept. The project was concluded with the manufacture of a prototype of the final concept. Due to the time limitation of this project only parts of the prototype could be tested which means that there are very little basis for an evaluation of the functions and benefits of the multi-drilling device. This report also includes suggestions for further development of the device.
Sammanfattning


This project could not have been made without the help of others. First of all we would like to thank Patrik Ljungmark, CEO at Täby Brandskyddsteknik AB, for this opportunity. Great thanks also go out to Konrad Aurin and Peter Westerberg at Täby Brandskyddsteknik AB for all their help during the project. At KTH we had the great help of our school supervisor Conrad Luttrupp. Tomas Östberg, Staffan Qvarnström and Paolo Kallio were ever so patient and helpful when we needed help with the parts for the prototype. We would never have understood where even to begin with the pneumatics without Pål Hallström, Stefan Svensson and Joakim Jensen at SMC who helped us create a complete solution for the prototype. Thanks go also to Peter Berggren, the electrician who guided us through the tangles of the electronics. And not least, the construction worker Sau Lius who, through many hours, helped us build the prototype.

Sara Gardelin & Madeleine Odebring

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### Abbreviations

<table>
<thead>
<tr>
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<th>Description</th>
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<tbody>
<tr>
<td>CAD</td>
<td>Computer-Aided Design</td>
</tr>
<tr>
<td>KTH</td>
<td>Kungliga Tekniska Högskolan/Royal Institute of Technology</td>
</tr>
<tr>
<td>MSD</td>
<td>Musculoskeletal Disorders</td>
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<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
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<td>RULA</td>
<td>Rapid Upper Limb Assessment</td>
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1. Introduction

This chapter describes the background of the project, the problem that is desired to be solved, the aim and the goal of the project, delimitations and methodology.

1.1 Background

This report presents the master thesis project made within the master track Industrial Design Engineering at the Royal Institute of Technology (Kungliga Tekniska Högskolan, KTH) during the spring of 2015. The project was a collaboration with the company Täby Brandskyddsteknik AB. The company offers solutions for active and passive fire protection of buildings and infrastructures. The head office is located in Täby, Stockholm.

Tunnels are an important part of modern societies’ road networks and allow passageways for pedestrians and vehicles such as cars and trains. Fires in tunnels could cause severe consequences due to the rapid temperature build-up that could cause the concrete structures to spall and collapse. The fire and the collapsing structure present severe danger to human lives and also complicate rescue efforts. The subsequent economic impacts due to rebuilding and redirection of traffic are also of a large concern.

To fireproof tunnels, fire-protection boards are mounted to the ceiling and on the walls of the tunnel. The boards protect the concrete from the intense heat which otherwise could cause it to collapse. To be able to fasten the boards to the ceiling or walls, holes are drilled, one by one, through the board and into the concrete, and anchor bolts are inserted. The boards are sometimes drilled beforehand but the heavy work is to drill in the concrete. The boards, which vary in size, must be attached to the concrete in several attachment points according to technical requirements. This amounts to a great number of holes that needs to be drilled in a long tunnel.

1.2 Problem Description

When the fire-protection boards are to be attached to the ceiling a large amount of holes must be drilled which is very time consuming. The drilling is done by hand using a hammer drill. The fire-protection installers have to reach up and repeatedly work above their heads. Since it is hard to drill into the concrete, the work is very tiring for the installers and the work posture might not be ergonomically suitable.

1.3 Aim and Goal

The aim of this project is to reduce the installation time for the fire-protection boards, as well as the work strain on the installers. These improvements would contribute to a better economy for the company since fewer installers are required for the same work and the efficiency of the process is improved due to reduced installation time and fewer occupational diseases.

The goal with this project is to develop a concept for a device that makes it possible to drill several holes at the same time which reduces the installation time and removes the installers from the strenuous task. The device will be designed based on the wishes of the company Täby Brandskyddsteknik AB and is meant to be used by the company’s own personnel and
therefore only produced in a small scale. A first generation prototype will be built to test the final concept. The project will be presented in a report and a presentation.

1.4 Delimitations
This project was limited time-wise to the equivalence of 20 weeks of full-time studies. Knowledge-wise the project was limited to the basic student level of the project group and the expertise that could be acquired from literature studies, teachers and different experts.

The focus of the project was the improvements of the drilling phase of the installation process of fire-protection boards in tunnels since this is believed by Täby Brandskyddsteknik AB to be the most strenuous part of the work. The project was also limited to only focus on the installation of fire-protection boards in the ceiling of the tunnels and not the walls. An unfortunate limitation was the lack of interaction with the installers since they were constantly occupied with their work and in many cases spoke neither Swedish nor English.

The prototype built within this project is a first generation prototype which needs to be developed before it is ready to be used on a daily basis during the installation work. Due to the time limit of the project only a few functions of the multi-drilling device could be tested.
2. Methodology

In this chapter the methods used in this project are summarised.

An extensive background research was made in the beginning of the project including a literature study and an observational study of the installation work performed by the company Täby Brandskyddsteknik AB. The installation work was documented with photographs, film, notes and time recording and was evaluated with a rapid upper limb assessment (RULA). The RULA survey method presents an easy tool to quickly be able to assess how a work posture puts load on the musculoskeletal system and indicate if the worker might be at risk of developing upper limb disorders (McAtamney & Corlett, 1993). The literature included books, relevant websites, KTH course material, and journals, reports and articles from the academic databases Google Scholar, Science Direct and KTHB Primo. Information was also gained from personal conversations with the contacts at Täby Brandskyddsteknik AB and with teachers at KTH.

For the idea generation and concept development sketching and brainstorming were used both individually and jointly in the project group. To evaluate the concepts two methods were used; the creation of simple construction models to test the spatial properties of the concepts and a decision matrix.

The final concept was developed in detail with the help of the computer-aided design (CAD) program Solid Edge ST6 (Siemens PLM Software, 2013). Simple calculations were used to estimate the total cost and weight of the device and to verify the strength of it.

A full scale prototype was built to test the functions of the chosen concept. Unfortunately there was no time to fully test the prototype within this project.
In the beginning of the project an extensive background research was made to gain an understanding of the subject. The work Täby Brandskyddsteknik AB performs in the tunnels was investigated as well as ergonomics, the market and power systems.

3.1 Fire-Protection of Tunnels
During a tunnel fire the temperature rises very quickly and can reach over a 1000°C in only a few minutes. This poses a great risk for the tunnel occupants. Concrete is an incombustible material with low thermal diffusivity, meaning it will not burn and that the heat will spread slowly in the material. However, exposure to high temperatures, approximately 300° for most concrete mixes, causes a decrease in the mechanical properties of the concrete due to physicochemical changes in the material (Khoury, 2000).

If the mechanical properties of the cement structure are severely affected, a phenomenon called spalling might occur. Spalling is the breaking off of pieces from the surface of a concrete structure due to high temperatures. The spalling could be violent enough to cause an explosion of the material. When pieces of the concrete break off the cross-section of the structure is decreased and the reinforcement bars in the structure might be exposed to the heat. This decreases the strength of the structure and could be severe enough to cause it to collapse. (Jansson, 2013; Connolly, 1995)

The use of fire-protection boards is one of the most common methods for passive fire protection of concrete structures. The boards have good insulation properties and their main task is to protect the concrete from fires, although they also can be seen as decorative. During a fire, moisture is expelled from the concrete in the form of vapour due to the high temperatures. This vapour condenses on the back of the fire-protection boards and helps cool down the boards which further protect the concrete. During the extensive tunnel fire tests made in Norway in 2003, the single heavy-goods fire reached temperatures above 1300°C while the panel system protected the tunnel structure from heating above approximately 200°C (Davidson, Harik & Davis, 2013). The fire-protection boards also insulate the concrete from drastic cooling during the extinguishing work which might also cause the concrete structure to fracture. After a fire, the boards close to the heat source have shrivelled up and are often cracked and need to be replaced. (Aurin & Ljungmark, 2015)

Täby Brandskyddsteknik AB usually uses fire-protection boards from the companies Promat and Aestuver. The type of boards that are used from Promat is named Promat Promatec T and the types of boards from Aestuver are named Aestuver T and Aestuver Tx. The “T” in the names means that the boards are designed for tunnel environment (Aurin & Ljungmark, 2015). The Promat Promatec T (Promat, 2015) boards consist of the material calcium silicate-aluminate and the Aestuver (Fermacell Aestuver, 2015a; 2015b) boards consist of cement-bonded glass-fibre reinforced lightweight concrete. All three types of boards have a maximum width of 1250 mm and a maximum length of 3000 mm and a thickness between 10 and 60 mm. The density of the boards is approximately 900 kg/m³ meaning that the boards are quite

3. Frame of Reference
heavy; for example, a board of the dimensions 625x3000 mm with a thickness of 30 mm weighs 50.6 kg.

The holes in the board are not allowed to be drilled closer than 35 mm from the edges and not further away than 100 mm. The distance between two holes at the long side is required to be between 550 and 650 mm and the distance between two holes at the short side between 400 and 550 mm. This is to ensure that the anchor points are evenly spaced apart. This project focuses on the slimmer models of fire-protection board; 600 and 625 mm in width with a length between 2500 and 3000 mm. For these boards the hole symmetry will consist of two rows of anchor bolts with five or six bolts on the length depending on the length of the board, see Figure 1. This totals in 10 or 12 anchor bolts and holes to be drilled per board. (Aurin & Ljungmark, 2015)

![Figure 1. The hole symmetry of the slim fire-protection boards with the length 2500 mm and 3000 mm (dashed).](image)

The tunnel client determines which temperature the tunnel must be able to withstand and for how long. Täby Brandskyddsteknik AB makes calculations on what type of boards and what thickness of the boards that should be used based on the type and the structure of the tunnel. The drilling depth into the concrete is usually 35 to 45 mm, depending on the type of anchor bolt or screw, which means that the total drilling depth depends on the thickness of the board. Including the board thickness the drilling depth usually varies between 50 and 90 mm. If the quality of the concrete is especially poor the holes need to be deeper to provide sufficient anchoring depth. The same type of fire-protection board is usually used during large portions of the project and the same drilling depth is thereby also used. The tunnel ceiling can have a slope of up to 6 %, which is equal to 3.43°, in both length and width direction. The boards are usually placed with their long side along the length of the tunnel since it is easier to draw a guide line and move the scissor-lift in that direction. This board orientation is also often more aesthetically pleasing.

If the tunnel walls are very uneven it might be difficult to mount the boards without bending them to fit the rough surface. If the boards are bent too much they might crack. Instead of mounting the boards directly to the wall, strips can be mounted between the wall and the board to create a distance. This distance allows the boards to be mounted without bending. Using strips also creates a deeper seam between the boards which helps prevent the heat from a potential fire to seep through the gap between two boards and reach the concrete underneath. With a deeper seam due to the strips, thinner boards can usually be used without affecting the general fire protection. The seams between the boards are the weak links in the
board system. It is therefore very important to minimize the gaps as much as possible. The maximum allowed gap is 3 mm. (Aurin & Ljungmark, 2015)

3.2 The Equipment used by Täby Brandskyddsteknik AB

To understand what equipment is required for the installation work study visits were made to the construction project Citybanan where Täby Brandskyddsteknik AB is involved in fire proofing the train tunnels. Additional information was obtained through discussions during the meetings with the company.

When the installation of the fire protection boards is performed the installers need equipment such as hammer drills, scissor-lifts, dry wall jacks, pneumatic hammers, compressors, and other typical tools for craftsmen.

The Hammer Drills
The hammer drills are used to drill the holes into the concrete for the anchor bolts that attach the boards to the ceiling. This tool both drills and performs a hammering motion which enables perforation of concrete. Täby Brandskyddsteknik AB prefers hammer drills from brands such as Hilti and Festool since the machines, according to them, have good durability, though the company’s subcontractors bring their own tools which might be of a different brand (Aurin & Ljungmark, 2015). The hammer drills that Täby Brandskyddsteknik AB uses are electrical and powered by an electrical cord since batteries need to be charged periodically which is inconvenient. There exists pneumatic hammer drills on the market, but according to Täby Brandskyddsteknik AB they are very expensive and since they are not a standard the performance is uncertain. A pneumatic drill would probably be advantageous since it should be lighter compared to its electrical equivalent due to its lack of an incorporated motor.

The type of hammer drill used in this project is Hilti TE 2, see Figure 2. The drill weighs 2.7 kg and has a vibrations value of 13.5m/s² for drilling into concrete (Hilti, 2015). A drill bit with a length of 100 mm is commonly used for the installation work.

![Figure 2. The Hilti TE 2 hammer drill (Hilti, 2015).](image)

The project group was allowed to try one of the company’s hammer drills. The model was not the model TE 2 from Hilti (2015) but the weight was approximately the same. When drilling downwards into a concrete floor no force was required by the operator; the tool’s own weight was enough to perform the drilling of a 6 mm hole.
The Scissor-lifts
To be able to reach the ceiling the installers need a scissor-lift. The model of scissor-lift often used by Täby Brandskyddsteknik AB is Haulotte H 15 SXL, see Figure 3. The platform of the scissor-lift is 1890 mm wide and 5300 mm long but it can be extended to a length of 7300 mm. The maximum lifting capacity is 500 kg. (Haulotte Group, 2015)

![Figure 3. The Haulotte H 15 SXL scissor-lift (Haulotte Group, 2015).](image)

The Dry Wall Jacks
Dry wall jacks, also called ceiling supports, are used to hold the fire protection board in position against the ceiling while the installers drill holes and fasten the anchor bolts. One model used by Täby Brandskyddsteknik AB is QS60 from the company Glück, see Figure 4. The model QS60 can be set to lengths between 1450 and 2900 mm and the swivels incorporated into the design enables the dry wall jack to be used for sloping ceilings (Glück Support & Equipment, 2015).

![Figure 4. The Glück QS60 dry wall jack (Glück Support & Equipment, 2015).](image)

Other Equipment
The pneumatic hammer is used to hit the anchor bolts into place after the holes have been drilled. In order to provide the pneumatic hammers with air, a compressor is needed. The
compressors used by Täby Brandskyddsteknik AB usually have a capacity of 8 bar and 80 litres and are powered electrically.

Other equipment that the installers use during their work are for example plunge saws, vacuum cleaners and spotlights. The plunge saws are used when the fire protection boards need to be cut in other dimensions than the standardized and the vacuum cleaners are used to remove the dust that is generated from drilling in the concrete. The spotlights are often used due to the insufficient lighting in the tunnels. The installers often carry ordinary carpenter tools as well, such as hammers and staple machines. The staple machine is used to staple strips, see chapter 3.1, to the back of the fire-protection boards.

3.3 The Installation Process used by Täby Brandskyddsteknik AB
During the study visit at project Citybanan the installation work was observed. Further information about the installation work was gained through discussions during the meetings with the company.

As a rule there are three fire-protection board installers working on every scissor-lift. Limiting factors are the space and weight limit of the scissor-lift. With the three installers and their equipment, only three to four of the slimmer boards can usually be loaded onto the scissor-lift without exceeding the weight limit of 500 kg depending on the size and thickness of the boards. The scissor-lift is raised to the ceiling to a height just above the installers’ heads. If the tunnel is large the installers are raised to a very high working height, see Figure 5.

Figure 5. Large tunnels cause very high working heights for the installers.

Two installers are needed to lift the fire-protection boards that are in focus in this project; 600 or 625 mm wide and 2500 to 3000 mm long. Larger boards are heavier and usually require three persons to lift them. The board has to be precisely positioned against the ceiling as to
not exceed the allowed gap of 3 mm between the boards. Lines are drawn in the ceiling to be able to place the first row of boards correctly; if the first row is crooked it will be difficult to keep the gaps as small as they must be between the rest of the boards. The positioning of the first board is seen in Figure 6.

![Figure 6. Positioning of the first fire-protection board on this section of the tunnel ceiling.](image)

Two dry wall jacks are then placed between the scissor lift and the fire-protection board to hold it in place. The dry wall jacks are placed approximately in the middle of the four outer holes on each side of the board.

The installers use the hammer drills to drill holes through the board and into the concrete. The holes are marked out with a pen or pre-drilled before the boards are lifted onto the scissor-lift. The drilling depth is set with the existing measuring rod on the hammer drill or is estimated by eye sight since the drill bit often has a length close to the depth of the holes that are being drilled. When the holes have been drilled, anchor bolts are inserted into the holes and hammered into place with a pneumatic hammer which is powered by a compressor. When drilling in the concrete it is rather common to hit the reinforcement bars meaning that the hole could not be drilled deep enough. A new hole is drilled close to the first hole with the same dimensional requirements as before. The incorrect hole is filled with fire sealant.

The three installers divide the work between themselves. As seen during the study visits one of the installers handled the hammer drill and another the pneumatic hammer, but sometimes they would switch tasks with each other. At certain tunnel areas the clients of the Citybanan project has decided that the fire-protection boards should be removable. This is done by using special nail-anchors with nuts. To tighten these nuts a screwdriver with a hexagon bit is used which is operated by the third installer. Due to the tight space on top of the scissor-lift the three installers work closely and around each other with their respective tool as seen in Figure 7.
Figure 7. The three installers work around each other to drill, hammer in the nail-anchors and to tighten the nuts on the nail-anchors.

The total installation time of one fire-protection board with 10 holes is approximately seven minutes. The positioning time is approximately 2 to 3 minutes, the drilling time of one hole is approximately 9 to 14 seconds, and the time between the drilling of the first and the finishing of the last hole is approximately 3 to 4 minutes.

A fork lift is often used to load more fire-protection boards onto the scissor-lift. In this way time is saved since the scissor lift does not have to be lowered down to the ground to resupply boards. The scissor-lift has a safety height where it has to stop for a while before it can continue to be lowered. If the work is performed above this height the use of the lifting crane is especially advantageous. If the ground is flat the scissor-lift can be moved without being lowered. The electrical power required for some of the equipment is supplied through extension cords drawn in the tunnel since the power outlet on the scissor-lift is not powerful enough.

3.4 Ergonomics

The fire-protection installers are exposed to ergonomic injuries due to their work position when drilling above their head. Ergonomic injuries develop gradually over time and result in musculoskeletal disorders (MSD). MSD can be seen as injuries and disorders of the soft tissue and the nervous system that can affect almost the whole body but most commonly areas such as the arms and the back. Some of the main causes to MSD are awkward postures, static postures, compression from sharp edges, inadequate recovery time, vibrations and working in cold temperatures. The symptoms can often be seen as numbness, tingling, stiff joints, muscle loss and pain which in many cases mean lost time from work in order to be able to recover. (U.S. Department of Labor, 2000)

The fire-protection installers have no own occupational group and were therefore chosen to be compared to construction workers. Sporrong et al. (1999) states that construction workers are more often affected by work related shoulder pain compared to other professions. During the
year 2013 in Sweden, 56% of the 445 reported cases of occupational diseases for companies active in construction were credited to musculoskeletal disorders (Samuelsson, 2014).

It is recommended to keep the upper arms close to the body and to only work shorter periods of time with the hands above shoulder height (Bohgard et al., 2010). A twisted and/or bent neck is also an unsuitable work posture (Arbetsmiljöverket, 2011). Anton et al. (2001) performed a study where the results showed that keeping the arms close to the body may decrease the risk of shoulder injury when performing overhead drilling. In a study performed by Sporrong et al. (1999) construction workers undertaking ceiling fittings were questioned and studied while performing their usual work. The results were that the workers often suffered from musculoskeletal pain, mostly in the neck, and spent much of their time with their upper arms at levels that are considered harmful in view of shoulder load.

The hammer drills used by the installers at Täby Brandskyddsteknik AB weigh approximately 2.7 kg. The recommendation is a maximum weight of 2.3 kg for carried tools (Bohgard et al., 2010). When drilling downwards the weight of the machine reduces the force required by the operator during drilling, but when drilling upwards the weight of the tool contributes to the work strain on the operator.

The vibration of the hammer drill might also be a source for ergonomic injuries. Vibrations are divided into full body and hand and arm vibrations. Full body vibrations caused by machines could result in tiredness, decreased performance, and have a negative effect on joints and muscular attachments (Arbetsmiljöverket, 2005). Vibrations from handheld tools and machines can cause numbness, reduced sensibility and even pain in the fingers (Bohgard et al., 2010). These injuries could arise from a combination with an unsuitable work posture and not solely from the exposure to vibrations (Arbetsmiljöverket, 2005). In this project the focus lies on the hand and arm vibrations caused by the hammer drills that are used during the work.

In Sweden there exists a regulation for the amount of exposure to vibrations that is allowed during one work day; the action value states the threshold for when intervention from the employer is required and the limit value states the maximum allowed vibration exposure (Arbetsmiljöverket, 2005). The action value for hand and arm vibrations is 2.5 m/s² and the limit value is 5.0 m/s².

The fire-protection installers at Täby Brandskyddsteknik AB drill up to 300 holes each during an eight hour day. According to the CEO of the company each hole takes approximately 30 seconds which means that each installer drills with the hammer drill for a maximum of 151 minutes, or 2.5 hours, per work day. (Ljungmark, 2015)

During one visit to the work place, the drilling time for a hole was estimated to be between 9 and 14 seconds. With 300 holes per day this would amount to a maximum drilling time of 70 minutes, or 1.17 hours, per work day. The difference between the CEO’s time estimation and the one estimated by the project group might be due to different hole depths or the definition of the drilling process.
The daily vibration exposure is calculated with the equation:

\[ A(T) = A(8) \ast \sqrt[8]{T} \]  

(1)

where \( A(8) \) is the vibration value for the tool and \( T \) is the use time of the tool during the work day (Arbetsmiljöverket, 2005).

By inserting the time each installer uses the drill and the vibration value for the hammer drill into equation (1), the daily vibration exposure can be calculated. The vibration value that was used is the value for the hammer drill \( TE2 \) from Hilti (2015) which is 13.5 m/s\(^2\). The daily vibrations exposure when using the hammer drill during 2.5 hours each day is 7.55 m/s\(^2\) and 5.16 m/s\(^2\) when using the hammer drill for 1.17 hours each day. Both exposure values are above both the action value and the limit value.

The amount of time that the hammer drill is allowed to be used without exceeding the action value was calculated by inserting the action value for hand and arm vibrations as the daily vibration value. The allowed time without exceeding the action value is 0.28 hours or 16.5 minutes.

### 3.5 The Human Anthropometry

The dimensions of the human body vary greatly which puts demands on the design of products to ensure good usability for a great number of individuals. One common limitation is to design for the 5\(^{th}\) and the 95\(^{th}\) percentile of a population. This excludes 10% of the population but simplifies the design with practical or economical benefits. (Bohgard et al., 2010)

The multi-drilling device should be comfortable to use for the installers. Three body measurements were selected as to be important for this project; the total body height, the eye height and the elbow height since the operator should be able to stand comfortably beside the device, have a good view of the work and have the controls within a comfortable reach. The body weight is also of importance due to the weight limit on the scissor-lift. The anthropometric measurements and the body weight can be seen in Table 1. Although Täby Brandskyddsteknik AB only has male installers employed the measurements for women were also included for comparison.
Table 1. Anthropometric measurements and body weight for men and women (Bohgard et al., 2010).

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Men 5%</th>
<th>Men 50%</th>
<th>Men 95%</th>
<th>Women 5%</th>
<th>Women 50%</th>
<th>Women 95%</th>
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<tr>
<td>Body height [mm]</td>
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<td>1779</td>
<td>1902</td>
<td>1562</td>
<td>1673</td>
<td>1789</td>
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<tr>
<td>Eye height [mm]</td>
<td>1562</td>
<td>1657</td>
<td>1778</td>
<td>1446</td>
<td>1553</td>
<td>1668</td>
</tr>
<tr>
<td>Elbow height [mm]</td>
<td>1020</td>
<td>1108</td>
<td>1181</td>
<td>957</td>
<td>1044</td>
<td>1130</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>57</td>
<td>75</td>
<td>103</td>
<td>50</td>
<td>64</td>
<td>80</td>
</tr>
</tbody>
</table>

3.6 The RULA Survey Method

During a visit to a worksite of project Citybanan the work of the fire-protection board installers was observed and recorded. These recordings were used to evaluate the work postures during the drilling in the concrete ceiling with the RULA (Rapid Upper Limb Assessment) method.

The RULA method focuses on six body areas which are graded with individual scores; the upper arm, lower arm, wrist, neck, trunk and legs. Further additional scores are included if the work is excessively static, repetitive, or involves loads above 2 kg. These scores are then combined which results in the grand score. The grand score gives a guide to what action is needed to prevent ergonomic injury due to musculoskeletal loads.

The fire-protection board installers often lean backwards and tilt their head upwards to be able to see their work, see Figure 8. This extension of the neck especially, is very strenuous on the body. The elevation of the upper arms, with addition of often lifted shoulders, also contribute to the strain. During the study visits the installers where sometimes seen to be side-bending to be able to reach the drill marks, but since this was not the norm side-bending was not included in the analysis.
The work is not excessively static since the workers constantly move about and is not repetitive since McAtamney and Corlett (1993) define this as a minimum of four repetitions per minute. Since the hammer drills weigh more than the given limit of 2 kg this adds to the evaluation.

From the instructions of the RULA method the grand score was found to be 7. This grand score falls under Action level 4 which is the most severe level; “A score of 7 indicates that investigation and changes are required immediately.” (McAtamney & Corlett, 1993, p 96).

3.7 Benchmark
The industry of fire-protection installation was examined for existing solutions, as was the general construction industry for similar products that could provide inspiration.

Competitors
Täby Brandskyddsteknik AB would describe the fire-protection installation industry in Europe as containing four large actors, including themselves, and smaller local ones. Only one device to assist the drilling during the fire-protection board installation process exists with their competitors according to Täby Brandskyddsteknik AB. This device is a large machine called Fischer Red Mix, produced by the company Fischer and owned by the company Kaefer. The machine is fully automated and performs the whole installation process of fire-protection boards which makes it very large, complicated and slow. Täby Brandskyddsteknik AB claims that the machine has not even been used during Kaefers last two projects. (Aurin & Ljungmark, 2015)

Drilling Devices
Rempel et al. (2007; 2009; 2010) have performed a study with the aim to reduce the strain on construction workers who perform the task of drilling in concrete ceilings. Two devices for drilling a single hole in the ceiling were developed and evaluated in the field. These two
devices were compared to the usual working method of standing on a ladder or lift to reach the ceiling to drill by hand. The two developed devices were an inverted drill press and a foot lever drill press. Both designs used a regular drill mounted into a specially designed L-shaped attachment that was mechanically lifted to the ceiling by turning a handle on the inverted drill press or by pressing down on a lever with the foot on the foot lever drill press. These two devices were tested by construction workers doing their regular work of overhead drilling. The results showed that the two devices caused less fatigue for the workers than the usual method, though the foot lever drill press was reported by a few to cause lower back aches. The two devices were decidedly more difficult to set up, move around and adjust than the usual method which led to further development by the research team. The inverted drill press design was chosen as the superior design and was modified to reduce setup and movement times, as well as to further reduce the strain on the workers. The participants of the sequent study reported that the new design provided less vibration exposure, lower fatigue and better handling and stability than with the usual method. The design was commercialized by the company Telpro Inc. under the name DrillRite™ Overhead Concrete Drill Press (Telpro Inc., 2012). The two designs of the study and the commercialized design can be seen in Figure 9.

![Figure 9. The inverted drill press (left), the foot lever drill press (middle) (Rempel et al., 2009) and the improved and commercialized design of the inverted drill press; DrillRite™ (Telpro Inc., 2012) (right).](image)

Rempel and Barr (2015) have also performed a study to develop a jig for heavy hammer and rock drills which are used for drilling in concrete. Prototypes were made and tested by construction workers through seven iterative steps. When comparing the final model with the usual method of drilling by hand, the jig was found to require less hand force by the operator, reduced the level of perceived fatigue of all evaluated body parts and reduced the exposure to vibrations from the tool. The device was commercialized by the company ErgoMek, LLC under the name DrillBoss™ (ErgoMek, 2015), see Figure 10.
Height Adjustable Devices
To gain inspiration for the idea generation phase, devices that can be raised and lowered were studied. Devices of special interest were drywall lifts and drill stands, see Figure 11. Drywall lifts are three-legged constructions made to lift drywall panels to the ceiling. The hoist mechanism consists of a cable and a hand crank. The drill stand is a system to support drills that is raised and lowered into position with a gear and rack mechanism.

3.8 Power Systems
The most common power systems for height adjustable devices are mechanical, electromechanical, pneumatic and hydraulic.

Mechanical Systems
Mechanical systems, as generally seen, are built with components such as gears, levers, belt drives, and pulleys. These components utilise gear ratio, leverage effect, potential energy, etc.,
to gain a mechanical advantage. The operator provides the energy needed for the system to create a motion.

**Electromechanical Systems**
The electromechanical system is a mechanical system driven by an electrical motor. The system is easier to accurately position than pneumatic or hydraulic systems (Hagelberg, 2015), but the power-to-weight ratio is lesser (Sellgren, 2015). Pneumatic systems often reach higher velocities as well (Hagelberg, 2015). The drive of the electric motor needs to be immediately shut off after completed motion or the motor will overload (Hagelberg, 2015). An electromechanical system has good stiffness and very good relative cost (Sellgren, 2015).

**Pneumatic Systems**
A pneumatic system utilizes compressed gas and mainly consists of a cylinder with a piston and pipes to transport the gas. A compressor is needed to compress the gas. Regular air is commonly used which is freely available and excess air can be emitted back to the environment (Sellgren, 2015). If a high pressure is built, for example when the drive signal continues to feed (Hagelberg, 2015), it can easily be released by a safety valve (Sellgren, 2015). Since gases are compressible, a pneumatic system has quite low stiffness and it can be difficult to control the movement speed and to position correctly between the end positions (Hagelberg, 2015; Sellgren, 2015). Pneumatic systems have a very good power-to-weight ratio and are a cheap way to generate linear motion (Hagelberg, 2015; Sellgren, 2015).

**Hydraulic Systems**
Hydraulic systems are similar to pneumatic systems but utilize liquid instead of gas. Since the hydraulic liquids are incompressible, the system has good stiffness and control (Sellgren, 2015). Oil is a frequently used hydraulic fluid and is often pressurized (Hagelberg, 2015). A risk with using oil is the potential leakage (Hagelberg, 2015). Hydraulic systems have a greater power potential than pneumatic systems and has a very good power-to-weight ratio (Hagelberg, 2015; Sellgren, 2015). The fixture and the components need to be thicker than with pneumatic systems which increase the installation cost and the hydraulic liquid needs to be collected in contrast to the air used for pneumatics which further increases the costs (Hagelberg, 2015).
4. The Implemented work

The project was continued with a specification of requirements, idea generation, evaluation and decision of concepts, and development of the chosen concept.

4.1 Specification of Requirements

Based on the information gathered in the Frame of Reference and the requests from Täby Brandskyddsteknik AB a specification of requirements and wishes for the multi-drilling device was compiled. The list was continually updated throughout the whole project as new facts and insights arose.

Requirements

The multi-drilling device shall:

- Drill multiple holes at the same time to reduce the installation time.
- Reduce the work strain on the installers.
- Replace one installer on the scissor-lift in terms of both work and weight; a weight limit was set to 75 kg, see Table 1.
- Be small enough so that the installers are able to walk and work around the device on the scissor-lift, but still accommodate for the hole symmetry, an area limit was set to 1500x800 mm.
- Endure the dust from drilling in concrete.
- Endure the moisture on the installation site in the tunnel.
- Be easy and fast to position correctly against the tunnel ceiling.
- Be able to be raised and lowered into correct position relative to the tunnel ceiling.
- Be able to be angled into correct position relative to the tunnel ceiling; only angling in one direction is required.
- Be adjustable for the different sizes of the slim fire-protection boards; 600 or 625 mm in width and between 2500 and 3000 mm in length with an interval of 100 mm.
- Enable to easily replace the drill bits on the hammer drills when needed.
- Be able to set the drilling depth.
- Be safe for the users.
- Be able to be transported in a container to a different work site.

Wishes

The multi-drilling device should:

- Signal when the drilling is performed correctly.
- Signal when a drill hits the reinforcement in the concrete and is prevented from continued drilling.
- Count the number of holes each drill has made.
- Consist only of simple constructions and standard components to allow easy manufacture and repair.
4.2 Idea Generation

The idea generation phase began with brainstorming and discussions concerning the general structure of the multi-drilling device and how the requirements and wishes could be satisfied. It was decided that a smaller, light-weight structure would be the optimal choice. A large machine like the Fischer Red Mix, see chapter 3.7, has been proven to be cumbersome and a tool support for the operator to wear would only reduce the strain on the installers but not the installation time.

For simplicity and due to the time limitation it was decided to use existing hammer drills for the drilling and not to incorporate the function into the device.

The Number of Hammer Drills for the Device
Since the device replaces one of the three installers on the scissor-lift and the wider boards are too heavy to lift for only two persons, the multi-drilling device will only be used for the slimmer types of fire-protection boards. These slimmer boards are held in place by 10 or 12 bolts depending on the length of the board.

Considering the two types of hole symmetries of the fire-protection boards the multi-drilling device would optimally be designed to drill four or six holes at the same time. Fewer holes drilled simultaneously would probably not be more efficient than the existing method of drilling by hand since the set-up and adjustment time of the device would be longer. A larger amount of holes would probably make the machine too big and difficult to move around on the scissor-lift. Since the fire-protection boards in question need two rows of either five or six holes for bolts it was decided to use six hammer drills for the device with the option to only use four drills when needed. This way the long boards with 12 holes can be drilled in two steps and the shorter boards with 10 holes in two steps with an intermediate step of disconnecting the two redundant drills for the last four holes.

The Support of the Fire-Protection Boards
To hold the fire-protection boards in the same position against the ceiling during the drilling and insertion of the bolts there are two possible options: the current method of using dry wall jacks or to incorporate the function into the device. Since it is very important that the distances between the fire-protection boards are small and precise it was chosen to continue the use of dry wall jacks and let the installers position the boards by hand as they do today. It would also probably take longer time to lift the board into the correct position against ceiling by using the device than to do it by hand.

Concepts of the General Structure
The device must be light-weight, robust, and easy to manoeuvre on the limited space on top of the scissor-lift. During the brainstorming numerous designs of the device were sketched. All the structure designs were given four legs to provide enough support without claiming too much space and used wheels as an easy way to move the device. The structure designs were also all made to allow six hammer drills to be positioned on top. The sketches were discussed and five favourite concepts were chosen to be further evaluated. The five concepts are shown in Figure 12.
4.3 Concept Evaluation and Decision

To be able to evaluate the structure concepts against each other full scale models were constructed with PVC pipes and tape. The models were moved around to give an idea of how easy the structures are to manoeuvre and how easily they can be moved around the dry wall jacks. The concepts that were tested were Concept A, B, D, and E since it was assumed that Concept C could be evaluated through Concept B due to their very similar structures.

The results from the tests were that Concept A, B (and C), and D were easy to move between the two dry wall jacks, while Concept E must be turned 180 degrees to be able to drill on both sides since the dry wall jack on the farther end would be in the way. For all of the concepts it is required that the dry wall jacks are placed in the centre of the four holes at the far end of both sides of the board. Concept B (and C) was easier to move and felt more stable than Concept D and E since the structure is more centred, though Concept A felt the most unstable with its single centred PVC pipe. These structures were however only held together by tape and therefore not as stable as they might have been with proper joining. It is probably easier to walk around the device on the scissor lift when it is centred, but the protruding legs of Concept A might present a tripping hazard.

The feasibility of the five different concepts was also discussed in the project group and with the school supervisor. The results from the test and the discussions gave the foundation to a decision matrix (Ullman, 2010) which can be seen in Table 3. The requirements that were evaluated in the matrix are compact size, manoeuvrability, positioning and angling. A compact size is important due to the limited space on the scissor-lift. Manoeuvrability was defined as how easy it is to manoeuvre the device in general and positioning was defined as how easy the device is to position against the drilling points by moving between the two dry wall jacks. Angling was defined as the simplicity to incorporating angling into the construction.

In the decision matrix each requirement was ranked from 4 to 1 based on its estimated importance. Each concept was then evaluated based on how well they fulfil each requirement in relation to each other and given appropriate scores between 1 and 3, where 1 is the lowest score. The total score for each concept was calculated by multiplying the ranking value for each of the requirements with the given score and adding them together.
Table 3. Evaluation of the five structure concepts with a decision matrix.

<table>
<thead>
<tr>
<th>Evaluation of the Structure of the Device</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirements</td>
<td>Weight</td>
</tr>
<tr>
<td>Compact size</td>
<td>4</td>
</tr>
<tr>
<td>Manoeuvrability</td>
<td>1</td>
</tr>
<tr>
<td>Positioning</td>
<td>3</td>
</tr>
<tr>
<td>Angling</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total score:</strong></td>
<td><strong>29</strong></td>
</tr>
</tbody>
</table>

In Table 3 it can be seen that the concepts with the highest scores are Concept A and B. These two concepts were therefore chosen for further investigation. Concept C received a high score as well but was excluded due to the need for more material and the consequently higher total weight of the device. The development of the two concepts can be seen in Figure 13. Both solutions were designed with the centre-rod as the source for the lifting and lowering mechanism. Concept B incorporates rods for linear steering to prevent the upper part from rotating.

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**Figure 13. The development of concept A (left) and B (right).**

In consultation with Täby Brandskyddsteknik AB it was chosen to continue developing concept A since it is more centred than concept B, and will therefore be easier to work and walk around on the scissor-lift. The tripping hazard is still more present with Concept A but this was considered inferior to the benefits with a more centred solution. With only one contact point with the upper part the angling mechanism could probably be made simpler. Without the linear steering rods it is also lighter. This presents the need of a solution to make the upper part stable with the angling and prevent it from rotating.
4.4 Development of the Chosen Concept

An important development of the chosen concept was to decide the function of the raising and lowering of the device and the hammer drills. It was discussed to place the hammer drills directly on the structure which means that the hammer drills and the structure can be raised and lowered in the same motion. This solution was rejected due to the inability of the drills to work independently of each other since all drills had to be lowered when one drill hits the reinforcement bars. Therefore it was decided to divide the raising and lowering of the structure and the hammer drills into two functions. It was discussed, based on chapter 3.8, which sort of power system that was preferred to use for the two functions.

The Motion of the Hammer Drills

Since the drills have to be raised and lowered separately it would not be time efficient to do it mechanically. Täby Brandskyddsteknik AB already handles electricity and pneumatics for their equipment and since the device does not require large forces there are no benefits in introducing another power system in the form of hydraulics. A pneumatic system was chosen, rather than an electromechanical, since there might be a problem of overloading of the electrical motor for the instances when a drill hits the reinforcement bars and the drive signal continuous to feed. It was decided to use six pneumatic cylinders, one for each hammer drill on the multi-drilling device, to make it possible for the hammer drills to work independently of each other. According to chapter 3.8 a pneumatic system can be difficult to position correctly between the end positions which is needed for the hammer drills since different drilling depths are required. The pneumatic cylinders were therefore designed to only move between their end positions and the drilling depth set through another construction which needed a solution.

The Motion of the Structure

For raising and lowering the structure it was decided to use a fully mechanical solution. Pneumatics is difficult to position correctly which is needed since the device must be able to be placed accurately against the ceiling and there are no benefits in using hydraulics since the forces are relatively small. A fully mechanical system was chosen over an electromechanical since electronics makes the device more complicated and therefore more difficult to repair. The electric motor adds unwanted weight to the construction as well. During the first phase of the project similar products that are adjustable in height were studied to get inspiration. The most interesting products were the drywall lifts; which uses a cable and a hand crank to raise and lower the device, and the drill stands; which uses a gear and a rack mechanism. Two possible solutions were developed; one with a wire and a winch, and one with a gear and a rack. The gear solution would probably be more stable than the winch solution but in consultation with the school supervisor the winch solution was chosen. This decision was based on the very high precision that is needed to get the gear and the rack to move in a smooth motion which can be difficult to achieve for non-experts while building a prototype.
5. The Final Concept

This chapter describes the final concept in detail.

The literature study confirms the statement that the installation of fire-protection boards for tunnel ceilings is very strenuous work. Each installer uses the hammer drill between 1.17 and 2.5 hours per work day when it is recommended to only work shorter periods of time with the hands above the shoulders. It is also recommended that carried tools should have a maximum weight of 2.3 kg which is not met since the hammer drills have a weight of 2.7 kg, see chapter 3.2. The result of the RULA survey method indicates that the installers lead a high risk of developing upper limb disorders regarding their work posture while drilling in the ceiling and that changes are required immediately. The vibrations from the hammer drills during a full work day add to the strain by accumulating to a level above the maximum allowed vibration exposure according to Arbetsmiljöverket (2005).

The final concept was designed using CAD to help validate ideas and to properly dimension the solution. An overview of the final concept can be seen in Figure 14. The multi-drilling device is divided into four parts; the lower part, the middle part, the upper part and the hammer drill units.

![Figure 14. The final concept of the multi-drilling device.](image)

The total width of the device is 710 mm and the total length is 1390 mm. The height is adjustable between approximately 1640 mm and 2100 mm which is suitable for men from the 5th percentile to the 95th according to Table 1 in chapter 3.5. For transport to another work site the device can be lowered to its lowest height and easily fit in a container.
When the hammer drills require maintenance, for example when the drill bits need to be replaced, the multi-drilling device can be lowered to place the hammer drills in eye height. The device can be adjusted to place the tips of the hammer drills’ drill bits at a height between approximately 1540 and 2000 mm. The eye height for men is 1562 mm for the 5th percentile, 1657 mm for the 50th percentile and 1778 mm for the 95th percentile which means that the multi-drilling device is suited for all of the male eye heights. Since only male installers are employed at Täby Brandskyddsteknik AB it was decided to only focus on male anthropometric measurements. The chosen measurements for the multi-drilling device also suits women with the exception of the eye height for the 5th percentile of women which is lower than the lowest height of 1540 mm of the device, see Table 1. The maximum and minimum height of the device relative a male installer with the average body height of 1779 mm, according to Table 1, can be seen in Figure 15.

![Figure 15](image)

**Figure 15.** The maximum and minimum height of the device relative an installer of average male body height.

The height adjustment is made with the help of a winch. When adjusting the height of the multi-drilling device the winch will be moved between the heights of approximately 645 mm and 1106 mm. This is considered to be acceptable since the elbow height measurement for the 50th percentile of men is 1108 mm, see Table 1, and the device will mostly be in a high position when drilling and only slightly lowered when moving between the drilling points.
5.1 The Lower Part
The lower part is constructed with 40x40 mm profiles and designed as a cross to provide open sides. It is important that the base is open on the sides so that the device can easily be moved around and between the dry wall jacks that are holding up the fire-protection board. To make sure that the device will stay in place when the drilling is performed four lockable wheels are used. The lower part is wider and longer than the upper part to prevent the device from tipping over when the load from the hammer drills is unequally divided. The multi-drilling device can be seen from above in Figure 16.

![Image](image)

**Figure 16.** *The multi-drilling device, without the six drill units, seen from above.*

5.2 The Middle Part
The middle part of the multi-drilling device consists of two profiles, 80x50 mm and 30x30 mm which slide into each other, and the height adjustment mechanism. The lower profile, 30x30 mm, is given extra support for the attachment to the lower part by four small triangular plates on each side. The upper profile, 80x50 mm, is connected via an angling mechanism to the upper part.

**The Height Adjustment Mechanism**
The multi-drilling device is raised and lowered with the help of a winch solution. The winch is attached to the side of the upper profile, 80x50 mm, placed as seen in Figure 15. The wire for the winch is drawn downwards, via a pulley, in through a cut hole in the 80x50 mm profile and then upwards in the hollow between the outer profile 80x50 mm and the inner profile 30x30 mm. The wire is attached to the top of the 30x30 mm profile with a duplex wire clamp. A cross view section of the construction is shown in Figure 17.
Figure 17. *Cross section view of the solution for the height adjustment mechanism. The wire is marked in green.*

The lower profile, 30x30 mm, and the upper profile, 80x50 mm, will move relative to each other when the winch handle is turned. When the wire is wound onto the winch drum the wire is shortened and the upper profile, 80x50 mm, is forced upwards and the whole multi-drilling device is raised. When the wire is unwound from the winch drum, gravity will force down the upper profile, 80x50 mm, and the whole multi-drilling device is lowered.

To enforce stability of the middle part and to ensure free passage for the wire, a guide system was constructed. Three sets of guide wheels are attached to the inner profile, 30x30 mm, to provide stability in one direction. On each end of the guide wheel axes there are small plastic pieces attached which slides against the inside of the outer profile, 80x50 mm, to provide stability in the other direction. The construction of the two uppermost sets of guide wheels can be seen in Figure 18.
It was discussed to use guide wheels in both directions but with such a solution the wire would have no room to run between the two profiles. The outer profile, 80x50 mm, would also have had to be larger to allow sets of guide wheels in both directions. It was proven difficult to find steel profiles to purchase for the prototype of such large dimensions but with a thin wall thickness as to keep the weight reasonably low.

**The Winch**

The winch chosen for the prototype is a winch for smoke vents of the model WA100 from the company *Lufta* (2015). The winch is self-locking in both directions but is constructed as to not require any release of a hatch. The winch house is closed which prevents dust from entering and clogging up the gears inside. The inside of the winch is shown in Figure 19.

**Figure 18.** *The guide system of the middle profile in exploded view (top) and assembled (bottom).*

**Figure 19.** *The gears inside the winch.*
According to the specifications for the winch the lifting height per revolution is 38 mm (Lufta, 2015). The crank force was experimentally estimated to be 3.9 kg when testing with the prototype by loading the crank handle with known weights until it turned.

5.3 The Upper Part
The upper part consists of double 30x30 mm profiles to provide stability and support for the drill units which are placed on top. Like the lower part, the upper part is open on the sides so that the device can be moved easily around and between the dry wall jacks that are holding up the fire-protection board.

Stabilisation against the Ceiling
To stabilise the multi-drilling device the upper part contains four ceiling guide rods in addition to the four lockable wheels of the lower part. The device is raised to the ceiling with the winch crank so that the rods are pressed against the ceiling to create a friction force which prevents movement of the structure when drilling. The rods are attached with bolts for easy replacement since there is a risk of buckling when the ceiling is uneven and one of the four rods connects with the ceiling before the others and the device is continued to be forcibly cranked upwards.

The Angling Mechanism
The tunnel ceilings are not always horizontal which puts a requirement on the multi-drilling device to be adaptable to the angle of the ceiling. As mentioned in chapter 3.1, the maximum slope of the ceiling is 6% or 3.43° and can be in both length and width direction. By discussing the problem with Täby Branskyddsteknik AB it was decided to only allow angling in the length direction of the device since it would provide a more stable and easily repaired solution.

The angling of the device is done between the middle part and the upper part. Two angling attachments are mounted on the bottom of the upper part which are connected to the top of the 80x50 mm profile of the middle part with a bolt. A rod is inserted on the bolt between the two angling attachments to prevent the attachments from being pushed together. An exploded view of the angling can be seen in Figure 20.
Figure 20. An exploded view of the angling mechanism.

Since the maximum slope is very small the distance between the top of the middle profile and the angling attachments only needs to be a few mm to allow a slope of 3.43°. The length of the upper profiles is 1400 mm which means, with the maximum slope, that the end of the profiles will move vertically a total distance of 84 mm relative to each other; 42 mm up or 42 mm down.

To stabilise the upper part, since it is only attached in one point, two wires are used on either side of the middle profile, see Figure 21. One turnbuckle is attached to each wire to make it possible to adjust the length of the wire when the upper part is angled. A swivel is also included to prevent the wire from twisting when turning the turnbuckle to adjust its length. The wires are attached with duplex wire clamps to the upper profile and to the swivels. The wires run diagonally from each other from opposite ends of the upper profiles, see Figure 16. It was decided that only two wires would give sufficient support since fewer wires with turnbuckles are easier to handle.
Figure 21. The maximum angling of the multi-drilling device with the wire solution in detail.

The angling is somewhat time consuming since the bolt has to be loosened, the opposite wire slackened by turning the turnbuckle, the upper part tilted into the desired angle, the bolt retightened, and the wires retightened by turning the turnbuckles. The angle of the upper part will however not be changed very often since the angle of the ceiling often is the same over large areas in the tunnels.

Adjustment to Different Board Sizes
The multi-drilling device will be used for fire-protection boards that are 600 or 625 mm wide and between 2500 and 3000 mm long in intervals of 100 mm. In consultation with Täby Brandskyddsteknik AB it was decided that the same width of 520 mm between the hammer drills could be used for the two widths of the boards without placing the holes too far from the board edges. The distance to the edge of the board is 40 mm when using boards that are 600 mm and 52.5 mm when using boards that are 625 mm. It was also discovered that an interval of 20 mm between 517 and 617 mm, which is in the allowed interval of 550 to 650 mm between the holes, accommodates for all the desired lengths of the boards. The four hammer drill units on the edges could therefore be constructed to be adjusted in six steps along the upper profiles to ensure correct distances between the holes, see Figure 22.
Figure 22. *The six holes used to correctly position the four hammer drills on the edges for the different length sizes of fire-protection boards.*

The existing method is to mark out the placement for the holes with a pen or to drill the holes beforehand. With the multi-drilling device there is no need to mark out all holes but the two holes closest to the edge on both sides.

5.4 The Drill Units

The six hammer drill units are mounted on top of the upper part. The drill units consists of one hammer drill, one drill support, one pneumatic cylinder, one cylinder support and different models of bolts and nuts for the attachments, see Figure 23. The pneumatic cylinders lift the hammer drills to the ceiling and provides the force required for the drilling.

Figure 23. *The drill unit for the centre placement (left) and for the edge placement (right).*
Due to space limitations it was decided to place the two middle hammer drills with their handles facing inwards. This led to the necessity of creating two slightly different kinds of drill units; one for the centre placement of the upper part and one for the edges. Since the two middle drills are facing inwards, the drill supports are positioned perpendicularly on the pneumatic cylinders in contrast to the four drill units on the edges. The cylinder supports of the two middle drill units are also shaped a bit differently to accommodate for the transversal profile of the upper part.

**The Attachment of the Hammer Drills**
The hammer drills are attached onto the pneumatic cylinders by L-shaped drill supports. The hammer drills are inserted into these and attached with round metal mountings. The L-shaped attachment is an easy solution that has been proven to work by the research team Rempel et al. (2007; 2009; 2010). The drill bits of the two centre hammer drills are placed exactly above the centre of the cylinders to make sure that the force is distributed evenly on the cylinders when drilling. The drill bits of the four edge hammer drills on the other hand, had to be placed slightly off centre length-wise since the holes in the drill support cannot be placed too close to the back of the drill support.

The cylinder supports hang on the outside of the upper profiles. It was discussed to place the cylinders on top of the upper profiles to avoid the torsional force that is created by the sideway displacement. This solution had to be rejected because the multi-drilling device would have become too high. During the strength calculations, see Appendix A, it was discovered that the torsional force is negligible. The double profiles of the upper part provide enough stability and prevent the cylinder supports from rotating.

**Setting the Drilling Depth**
The ceiling guide rods are, as mentioned in chapter 5.3, used to stabilise the multi-drilling device against the ceiling. Their other important function is to set the drilling depth. The pneumatic cylinders are designed to only move between their end points of fully extended or retracted. Therefore the distance between the tips of the drill bits and the ceiling need to be adjustable to accommodate for the different drilling depths that are required due to the different thicknesses of the fire-protection boards.

The ceiling guide rods consist of 20x20 mm profiles that are attached to the upper profiles. On the top of each of these profiles a nut is welded. In this nut a short length of threaded rod is inserted. A second nut is used to lock the threaded rod into desired extruded length. By adjusting the extruded lengths of the threaded rods the depth the hammer drills can drill is decided. Attached to the top of the ceiling guide rods are rubber pieces to protect the fire-protection boards from scratches. The ceiling guide rod can be seen in Figure 24.
As the shortest the ceiling guide rods are 10 mm higher than the tip of the drill bits when the cylinders are fully retracted. This means that the hammer drills will drill 90 mm deep holes. By increasing the extruded length of the threaded rods up to 40 mm the drills can drill holes that are 50 mm deep. The length of the threaded rods must be set manually but since the depth of the holes often are the same through large portions of a project it does not have to be done regularly. To be sure that all threaded rods have been adjusted to the same length a water level should be used.

The Control Panel
The drill units are controlled with a control panel that is placed on the middle profile, 80x50 mm. The control panel contains seven rocker switches; one for each of the six pneumatic cylinders and one main switch. The desired drill units are activated by switching on the corresponding switches for each unit. When the main switch is switched on the circuit is connected and signals are sent which activates the chosen pneumatic cylinders. With this solution any number of hammer drills can be used to drill different hole symmetries.

When a pneumatic cylinder reaches its end position a sensor on the cylinder is activated and sends a signal which lights a green diode underneath the switch corresponding to the cylinder in question. The cylinders are lowered by switching off the switches. Each cylinder can be switched off individually with their respective switches or all at the same time with the main switch. Consequently, if one of the hammer drills hits the reinforcement bars that drill can be switched off while the other drills can continue. The failed hole is thereafter filled with fire sealant and a new hole is easiest drilled by hand. The control panel can be seen in Figure 25.
Due to time constraints it was decided to delimitate the controls to only the pneumatic cylinders and not include the hammer drills. Since the hammer drills are complex structures it would be difficult to find the right connections to draw wires down to the control panel. For the prototype it was decided to only create a simple solution to keep the triggers on the drills pressed in during the drilling.

5.5 Electronic and Pneumatic Systems

The systems for the electronics and pneumatics were constructed in detail with the help from three pneumatic engineers at the company SMC.

As described in chapter 5.4, the electric system includes six switches and six diodes, one for each pneumatic cylinder, one main switch, and sensors for the cylinders to signal when the end position is reached. The six sensors are connected to a so called PRSB sensor unit. The system is powered by a power supply unit which converts the mains voltage of 230 V to the required 24 V for the components.

The electric system is divided into two circuits. When the desired switches are switched on along with the main switch the first circuit is connected which gives power to the valve terminal. The valve terminal contains six valves which are connected to the six switches for the cylinders. Each valve controls the air flow to their respective cylinder. With the circuit connected through the valves, depending on if the corresponding switch is switched on, the air can flow through to activate the cylinders. When the cylinders reach their end positions signals are sent from the sensors to the PRSB sensor unit which connects the second circuit. When the circuit is connected through the PRSB sensor unit the six diodes are lit to indicate that the drilling has been performed correctly and that the drill units should be lowered.

To simplify the connections of all the wires terminal blocks were used. Their only function is to provide secure connections between the different components. The electronic schematic can be seen in Figure 26.
The pneumatic system is powered by a compressor. The air is then led through a pressure relief which acts as an emergency switch. The pressure relief contains a noise silencer to reduce the noise from the flowing air. A filter regulator is then connected with an air tube to the valve terminal. The filter regulator is used to set the air pressure for the system and to clean the air from oil and water that comes with the air from the compressor.

The six valves in the valve terminal contain two air outlets each, A and B, which are connected to the pneumatic cylinders through two speed controllers. The speed controllers prevent the air from backtracking and can be manually set to adjust the air flow in and out of the cylinders. When the switches on the control panel are switched on the valves receive a signal to let the air go through outlet A into the bottom of the cylinder and push the cylinder upwards. The air then exits out through outlet B at the top of the cylinder. The valves go back into their starting position when the circuit is broken when the switches are switched off. In this position the air flows through outlet B and pushes the cylinder down and then exits through outlet A. The pneumatic schematic can be seen in Figure 27.

**Figure 26. The electronic schematic.**
5.6 Strength Calculations
Steel was chosen as the material for the structure of the multi-drilling device. A discussed alternative was aluminium, but the lower density of aluminium compared to steel is equivalent to the also lower stiffness due to a lower Young’s modulus for aluminium (Sundström et al., 1998). It would therefore require more material with an aluminium structure which would result in a less compact solution. Aluminium is also more sensitive to fatigue which might become an issue due to the vibrations that will be transferred from the hammer drills.

A few sections of the structure for the device were selected for strength calculations, see Appendix A. The worst case as discovered was the bending of the inner middle profile 30x30 mm when only four drill units are used which causes a moment from the upper part on the middle part. The inner profile bends approximately 5.93 mm but with a safety factor of 4 compared to the yield strength for steel there should be no risk of collapse of the structure.

5.7 Weight Calculations
It is important that the device is as light as possible due to the weight limit on the scissor-lift. The number of fire-protection boards that can be loaded onto the scissor-lift depends how heavy the rest of the equipment is. As defined in the specification of requirements in chapter 4.1 the device shall replace one installer in terms of weight meaning that it should not weigh more than 75 kg which is the weight for the 50th percentile of men.

The weight of the final concept was calculated with the help of the CAD model and the specifications for the parts ordered for the prototype. The estimated total weight of the multi-drilling device is approximately 73 kg, see Table 4. After the completion of the prototype it was placed on a scale to measure the true total weight. The prototype was showed to weigh approximately 77 kg.
### Table 4. The estimated individual part weights of the multi-drilling device.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Weight [kg]</th>
<th>No.</th>
<th>Total Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lower part with lockable wheels</td>
<td>11.61</td>
<td>1</td>
<td>11.61</td>
</tr>
<tr>
<td></td>
<td>Middle part with guide system incl. pulley</td>
<td>5.30</td>
<td>1</td>
<td>5.30</td>
</tr>
<tr>
<td></td>
<td>Upper part with angling system</td>
<td>14.57</td>
<td>1</td>
<td>14.57</td>
</tr>
<tr>
<td></td>
<td>Drill units excl. hammer drills and pneumatic cylinders</td>
<td>1.93</td>
<td>6</td>
<td>11.55</td>
</tr>
<tr>
<td><strong>Pneumatics</strong></td>
<td>Pneumatic cylinders</td>
<td>1.24</td>
<td>6</td>
<td>7.44</td>
</tr>
<tr>
<td></td>
<td>PRSB sensor unit, valve terminal, pressure relief and filter regulator</td>
<td>1.64</td>
<td>1</td>
<td>1.64</td>
</tr>
<tr>
<td><strong>Electronics</strong></td>
<td>Control panel with components, apparatus casings and power supply unit</td>
<td>2.28</td>
<td>1</td>
<td>2.28</td>
</tr>
<tr>
<td><strong>Winch</strong></td>
<td><em>Lufta WA100</em></td>
<td>2.10</td>
<td>1</td>
<td>2.10</td>
</tr>
<tr>
<td><strong>Hammer drills</strong></td>
<td><em>Hilti TE 2</em></td>
<td>2.70</td>
<td>6</td>
<td>16.20</td>
</tr>
<tr>
<td><strong>Total weight:</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>72.69</strong></td>
</tr>
</tbody>
</table>

### 5.8 Material Cost Calculations

The material and components for the prototype was bought from several different suppliers. The steel profiles were bought from the company *Bromma Stål* with extra lengths in case more material than calculated was needed. The pneumatic components were ordered from the company *SMC* which had assisted with the pneumatic solutions. The three *SMC* engineers also helped with listing the electric components that were required. The electronics, including the apparatus casing for the control panel, were ordered from the companies *Mouser* and *Elfa* since neither had all the required components. After a consultation with an electronics expert it was realized that some of the electric components were superfluous and were therefore not used in the prototype. The costs of these components were therefore excluded from the cost calculations.

The four lockable wheels, the pulley and the six guide wheels were bought from the company *Tellus*. The two swivels for the wire anglings were bought from the retail store *Jula* and the winch was ordered from the company *Lufta*. The six hammer drills were ordered from *Hilti* in Germany since the model *TE 2* is not available in Sweden. From *Ahlsell* the threaded rod, all the bolts and nuts, the turnbuckles, the wire, the duplex wire clamps, two additional apparatus casings for the electronics and pneumatics, and cable glands for fixing the air hoses in the apparatus casings, were acquisitioned.
The costs for each company order are presented in Table 5. Shipping fees were not included in the calculations.

**Table 5. The material costs of the prototype.**

<table>
<thead>
<tr>
<th>Prototype section</th>
<th>Company</th>
<th>Cost [SEK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Bromma Stål</td>
<td>2 321</td>
</tr>
<tr>
<td>Pneumatics</td>
<td>SMC</td>
<td>33 349</td>
</tr>
<tr>
<td>Electronics</td>
<td>Mouser</td>
<td>528</td>
</tr>
<tr>
<td></td>
<td>Elfa</td>
<td>748</td>
</tr>
<tr>
<td>Wheels</td>
<td>Tellus</td>
<td>680</td>
</tr>
<tr>
<td>Swivels</td>
<td>Jula</td>
<td>50</td>
</tr>
<tr>
<td>Winch</td>
<td>Lufta</td>
<td>2 170</td>
</tr>
<tr>
<td>Hammer drills</td>
<td>Hilti</td>
<td>10 000</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Ahlsell</td>
<td>1 779</td>
</tr>
<tr>
<td><strong>Total cost:</strong></td>
<td></td>
<td><strong>51 625</strong></td>
</tr>
</tbody>
</table>

As seen in Table 5 the total material cost of the prototype is 51 625 SEK.
6. The Prototype

In this chapter the manufacture and the testing of the prototype are described.

6.1 Manufacturing of the Prototype
The prototype was built at Täby Branskyddsteknik ABs head office with the help from a construction worker with knowledge in welding. The prototype was built based on detail drawings created from the CAD model, see Appendix B for a selection of the most interesting drawings. During the construction a few adjustments of the device were made to improve the stability. The improvements are not included in the drawings.

The first step when building the prototype was to cut the profiles into the desired lengths and to drill the holes. The profiles were then welded together part by part. When welding the upper part it was discovered that the profiles twisted in the heat which led to the decision to add additional supports between the long profiles to ensure straightness and stability. The supports can be seen in Figure 28.

![Figure 28. The additional supports on the upper part.](image)

The angling attachments on the upper part were redesigned in consultation with the welder to get a more stable solution. The redesigned angling attachment can be seen in Figure 29.
To provide further stability for the upper part it was decided to double the angling wires on each side of the device, see Figure 30. Hooks were also added as new attachment points for the wires since there is a risk of the wires wearing down against the edge of the upper profile.
The cylinder supports, the drill supports and other small pieces were submitted to *Litsby Industrier AB* for cutting and bending. Additional mountings were welded onto the cylinder supports to provide further support from the lower profile as well, see Figure 31.

![Figure 31](image1.jpg)

**Figure 31.** The additional support welded onto the cylinder support to provide support from the lower profile as well.

When the steel structure was finished it was painted with primer and then with a light grey paint to protect it from corrosion. The guide wheel units were manufactured by Tomas Östberg at *KTH* who also helped with drilling the holes in the apparatus casings. The painted lower bottom half of the prototype with the guide wheels is shown in Figure 32.

![Figure 32](image2.jpg)

**Figure 32.** The two uppermost guide wheel units assembled on the bottom half of the painted structure.
Since some of the pneumatic and electronic components were quite large they had to be placed outside of the control panel in two additional apparatus casings. The PRSB sensor unit was placed in a casing which was attached to the upper part since the sensor cords were too short to be drawn any further. The valve terminal, which was the largest component, was placed together with the power supply unit in a casing on the opposite side of the middle profile, 80x50 mm, from the control panel which was placed above the winch. Attachments for the boxes were welded onto the structure which the casings could be screwed onto. The placement of the three apparatus casings and the winch is seen in Figure 33.

*Figure 33. The placement of the control panel, the two apparatus casings and the winch.*
The attachment for the pulley for the wire is seen in Figure 34.

![Figure 34. The pulley attachment.](image1)

The KTH teacher Staffan Qvarnström assisted with his electronics expertise when the electronic components were assembled. The wirings inside the control panel are seen in Figure 35.

![Figure 35. The wiring on the inside of the control panel.](image2)
The hammer drills were attached to the drill supports with metal brackets and stabilized underneath with metal parts as seen in Figure 36.

Figure 36. The attachment of the hammer drills on the drill supports.

One of the ceiling guide rods with its welded nut is shown in Figure 37. The original rubber pieces were replaced with larger ones as to provide better protection and impact dampening for the fire-protection board.

Figure 37. One of the four ceiling guide rods.
The complete prototype can be seen in Figure 38.

Figure 38. The complete prototype.

6.2 Testing of the Prototype
Due to the time limitation of the project only parts of the multi-drilling device could be tested. The height adjustment mechanism with the winch had been fully constructed and could therefore be successfully tested. A safety hazard was discovered when the device was accidentally raised above the second guide wheel pair and the upper part almost fell off. Due to this it was decided to add a safety wire to prevent the device from being raised too high.

The pneumatics could also be tested and with some finer adjustments of the settings of the components the drill units could be raised and lowered simultaneously or individually and with appropriate speed. The drill units could easily be selected on the control panel and then individually or simultaneously be lowered using the different switches or the main switch.

Further testing of the prototype will be continued by Täby Brandskyddsteknik AB. The current plan is to try to connect the hammer drills to the control panel to enable both the drills and the pneumatics to be controlled by the same individual switches. When the prototype is finalised it can be tested for its full function. The first test will be done in a simulated environment of drilling into a concrete ceiling. The simulated ceiling will probably consist of a fire-protection board screwed onto the underside of a wooden pallet which will be raised up with a fork-lift. The multi-drilling device can then be positioned underneath and its functions be tested. If these simulated tests are successful the next step is to test the device in the intended work environment on a work site in a tunnel.
7. Further Development

This chapter presents the project group’s suggestions for future developments of the multi-drilling device.

7.1 The Stabilisation Solutions
The stabilisation of the multi-drilling device consists of two parts; the lockable wheels and the ceiling guide rods. In the final solution the four wheels have locks that are locked independently. A preferred solution would be the ability to lock all the wheels with one motion by connecting them to the same pedal or handle. Instead of connecting all the wheels, legs could be folded down to lift up the wheels from the ground and in that way prevent motion of the device relative to the ground.

When the device is raised towards the ceiling the guide ceiling rods will be pressed against the fire-protection board and stabilise the device. To prevent the guide ceiling rods from buckling if the device is forcefully raised the ceiling rods should include springs that will compress when the device is continued to be raised. The springs have to be strong enough though to provide sufficient stability.

7.2 The Height Adjustment Solution
The final solution and the prototype of this project included a winch solution to be able to raise and lower the multi-drilling device. The alternative, a gear and rack solution, was deemed too difficult to build a well-functioning prototype of. It is believed a gear and rack solution would provide a more solid construction both in appearance and stability. There is always the risk of the wire of the winch solution wearing down against an edge and snapping off after a while resulting in serious danger for the installers. The gear and rack mechanism is already used in the construction industry as seen with the drill stand in chapter 3.7. Due to the harsh environment in the tunnels the gear house would require proper encasement to prevent drilling dust and dirt from entering.

The manual control of the gear could be either a crank or a handwheel. Further study is required to determine which is the better alternative for the task in question of height adjusting the multi-drilling device. The placement of the manual control should be improved from the existing solution since the winch crank is fastened on the outer middle profile which moves with the upper part of the device. The manual control should be positioned at the same height regardless of the height of the device as to provide a comfortable handling. If the middle profiles had been reversed with the outer profile attached to the lower part and the inner profile attached to the upper part, the outer profile, and thereby the manual control, would be fixed in height. This solution would however not work with the existing wires for the stabilisation of the upper part since these would be attached to the inner profile instead and prevent it from fitting in the outer profile. If the wires would be attached to the fixed outer profile the turnbuckles would have to be readjusted every time the device was lowered or raised. To attach the outer profile on the lower part, and thereby fixing the manual control in height, the wire solution has to be replaced with a less obstructing construction.
7.3 The Angling Solution
The wire solution to stabilise the upper part due to the angling is complicated, unpractical and time consuming since both turnbuckles need to be adjusted at the same time when adjusting the angle of the upper part. The problem with the angling solution is its instability. If the angling mechanism could be made stable the wires would be redundant which would simplify the placement of the manual control of the height adjustment as described in chapter 7.2.

To provide an easily handled angling a solution could be to make the upper part self-adjusting to the slope of the ceiling. If the angling contained springs the upper part would orient itself against the ceiling when forced upwards and pressed against the ceiling. With a ball joint the device could accommodate for slopes in all directions. Further development would be to test this idea for stability and function.

7.4 The Positioning
The positioning of the multi-drilling device against the fire-protection board might need additional assistance than solely using the eye sight and markings on the board for the holes. With an edge guide solution the device is more easily placed straight and correctly to ensure that the holes will be drilled within the allowed distances from the board’s edge. This edge guide could be constructed as seen in Figure 39 and attached to the ceiling guide rods. The edge guide has to be designed to accommodate for the different widths of the boards since the distances between the board’s edge and the holes will vary. It must also accommodate for different board thicknesses and drilling depths, in Figure 39 this is solved with slots on the ceiling guide rod. Furthermore, it only aids in positioning against the long side of the board and not along the short side. The solution must be further developed before it can be incorporated into the device.

Figure 39. An edge guide solution.
7.5 Controlling the Hammer Drills

The controlling of the hammers drills were not considered a prioritisation due to the project’s time limit and the complexity of the hammer drills’ wiring and construction. The suggested solution was a simple idea of using cable ties to hold in the trigger on the hammer drills’ handles.

The preferred solution would be to incorporate the control of the hammer drills into the control panel. Each drill could be connected to the six switches that control their respective pneumatic cylinder and a second main switch added to the control panel which powers the drills when switched on. This could probably be accomplished by an experienced electrician. When using the multi-drilling device the operator simply selects the desired drill units by switching on the individual switches, then switching on the main switch for the hammer drills which powers the selected drills, and lastly switching on the main switch for the pneumatics which activates the selected pneumatic cylinders. A sketch of the control panel including the control of the hammer drills is presented in Figure 40.

![Control Panel Sketch](image)

**Figure 40.** A sketch of the improved control panel including a main switch for the power for the hammer drills.

With this solution it is important to lower the cylinders with the main switch for the air instead of switching off the individual switches. If the hammer drills are powered off while in the concrete it is more difficult to extract them compared to extracting them while they are still rotating. The drill bits might get stuck and the problem has to be manually solved.

Additional functions that probably could be added to the control panel is a drilled hole counter for each hammer drill and a signal system for when a drill hits the reinforcement in the concrete and is prevented from continued drilling. These two functions were requested by Täby Brandskyddsteknik AB, see chapter 4.1, but unfortunately unfulfilled due to the project’s time limitation.

7.6 Adaptation to Installation on Walls

This project was limited to only focus on the drilling in tunnel ceilings and not the walls. A problem that must be solved for a doubly functioning device is foremost the stability. The lower part of the device was made wider than the upper part to prevent the device from tipping over which means that the device cannot reach outside of the scissor-lift. It would be
preferable to modify the base to be smaller but still provide enough stability, especially when tilting the upper part 90 degrees to position the drills for drilling in the wall. Another problem is how to position the multi-drilling device in relation to the safety fence of the scissor-lift. Either the device has to drill above the fence or the drill units have to be positioned on the outside of it.
Discussion

The multi-drilling device was designed using commonly available steel profiles and electronic and pneumatic components from the shelf of different suppliers. The construction solutions were also chosen based on their simplicity to allow easy repair of the device. The multi-drilling device will be a tool used by the installers at Täby Brandskyddsteknik AB and only produced in a very small scale. Therefore, the company need to be able to easily manufacture and repair the device mostly in-house.

During the literature study of ergonomics, and especially after performing the RULA method, it was confirmed that the installation work is very strenuous work for the installers. The RULA verdict even read “investigation and changes are required immediately” which shows how important this attempt to improve the installers’ work situation is.

Due to the time limitation of the project the prototype could unfortunately not be tested. This provides very little basis for any significant evaluation. An extensive study where the device is used for the normal installation work is required to fully discern the benefits of the multi-drilling device. The multi-drilling device was designed to fulfil the requirements and some of the wishes made by the project group from discussions with the company. In theory all the requirements should be fulfilled with some exemptions. For example, the total weight of the prototype was discovered to be slightly above the set limit which is probably due to simplifications done during the estimated weight calculation and the added supports on the prototype. However, two of the requirements were not prioritised for this first generation prototype; that the device should endure the dust from drilling in concrete and the moisture in the tunnel. Since the electronic and pneumatic components are divided between three different casings with multiple holes each, the risk is high for dust to enter the casings which could cause failure. Without proper sealing of the casings, moisture from the tunnel could also enter and cause problems in the long run. This problem of casing the components is therefore important for the future development of the multi-drilling device.

The multi-drilling device drills up to six holes at the same time which is more time efficient than the usual method of drilling each hole by hand. The multi-drilling device also provides a more ergonomic work position than the usual method since the installers do not need to hold a heavy hammer drill and raise their hands above shoulder height to drill the holes. The installers probably still have to tilt back their heads to supervise the work but with the shortened drill time the time spent looking upwards is hopefully somewhat shortened. An important feature of the device is that it is easy and fast to position correctly against the tunnel ceiling. If the device is difficult and time consuming to set-up there is a large risk that the installers will consider it too bothersome and will revert back to drilling by hand.

The multi-drilling device should also replace one of the installers in terms of both work and weight which means that only two installers are needed on the scissor-lift instead of three. This would lead to an economical gain for the company since they can hire fewer persons to do the same work. In terms of absence due to ergonomic injuries this should also slightly improve the company’s economy due to the reduced strain on the installers during the drilling
phase of the installation process. There are probably room for improvements for the other phases of the installation work as well. With only two installers on the scissor-lift it is easier for them to move around, even with the multi-drilling device. Since the prototype has not been tested on a scissor-lift it is unknown how easy it is to walk and work around it. The device was made as compact as possible without compromising function and stability.

As discussed in further development, the project group’s opinion is that a gear and rack solution is preferable to the winch solution used in this project. There is always the risk of the wire snapping off which could injure the operator. With the existing solution with the winch the crank force was estimated to be approximately 3.9 kg. Even if the installer can safely be assumed to be strong males it puts unnecessary strain on them with a somewhat heavy winch crank force. This force is only for the raising of the device, the force for lowering the device is almost negligible. If the winch solution is kept for further developments of the multi-drilling device the crank force could with benefit be lowered slightly by using another winch with a different gear ratio.

If Täby Brandskyddsteknik AB chooses to continue developing the multi-drilling device it is the strong suggestion from the project group to provide real work environment tests and to include the installers in the process. The installers might have inputs and ideas that neither the project group nor the contact persons at Täby Brandskyddsteknik AB have thought about. Further work should include evaluation of the work with the prototype in comparison with the existing method of drilling by hand. This could be made with the RULA method or simply by letting installers test both methods and decide which they prefer.

This project experienced several bottlenecks where the work could not be continued without first solving the specific problems at the time. Already at the beginning of the project the background research took much longer than expected and as a consequence the rest of the project was delayed. Some of the indecisiveness concerning the importance and relevance of different subjects might have been avoided if the project group had received a school supervisor at the start of the project and not until a few weeks in. Further time savings could have been done during the development of concepts if meeting with Täby Brandskyddsteknik AB had been held on a more regular basis. Regular meetings had probably helped to detect the problems earlier in the process and backtracking of some of the work could have been avoided. Long delivery times for some of the components for the prototype, although unavoidable for the project group, further delayed the project. Furthermore, the welder who manufactured the structure of the prototype was unavailable during two weeks which contributed to even further delay of the prototype. Aside from the time delays no major problems occurred during the project.
Conclusions

- From the observations of the installation work and the evaluation with the RULA method it can be concluded that the fire-protection installers perform a strenuous work which can lead to ergonomic problems. This project can be seen as a first step to improve the installers working environment.

- Due to the time limitation of this project the prototype could not be tested in its entirety. It is therefore difficult to evaluate if the multi-drilling device fulfills the specified requirements and wishes.

- Tests need to be made with the prototype, first in a simulated environment and if successful, later in the real work environment in a tunnel. Based on the test results appropriate changes and improvements can be made.
References

Literature


**Personal Contact**


**Programs**


**Websites**


Appendix A. Calculations

This appendix presents the strength calculations for selected parts of the structure for the multi-drilling device.

Strength Calculations

The structure of the multi-drilling device is submitted to different forces due to the drilling forces and the weights of the different parts. The sections of the structure believed to be the most exposed were investigated in this appendix. The profiles used for the structure consists of steel beams with the cross view sections hollow and solid square and solid circular. The second moment of area $I$ for each cross view section differs as seen in Table 1.

**Table 1. Second moment of area for different cross view sections (Sundström et al., 1998).**

<table>
<thead>
<tr>
<th>Cross view section</th>
<th>Second moment of area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hollow square</td>
<td>$I = t \cdot b^3$ + $\frac{1}{2} \cdot t \cdot b^2 \cdot h$</td>
</tr>
<tr>
<td>Solid square</td>
<td>$I = \frac{b \cdot h^3}{12}$</td>
</tr>
<tr>
<td>Solid circular</td>
<td>$I = \frac{\pi \cdot d^4}{64}$</td>
</tr>
</tbody>
</table>

The chosen material for the structure was steel. The material properties for steel required for the strength calculations are presented in Table 2.

**Table 2. Material properties for steel (Björk, 2007).**

<table>
<thead>
<tr>
<th>Constant</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>$E$</td>
<td>210</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\nu$</td>
<td>0.31</td>
<td>–</td>
</tr>
<tr>
<td>Yield strength</td>
<td>$\sigma$</td>
<td>210</td>
<td>MPa</td>
</tr>
</tbody>
</table>

The different weights for interesting sections of the multi-drilling device are shown in Table 3.
Table 3. Section weights of the multi-drilling device required for the strength calculations.

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Total Weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill unit</td>
<td>One drill unit with hammer drill, pneumatic cylinder and supports</td>
<td>5.87</td>
</tr>
<tr>
<td>Upper part</td>
<td>Upper profiles with angling system</td>
<td>14.57</td>
</tr>
<tr>
<td>Middle part</td>
<td>Outer profile 80x50 mm with pulley, winch, electronics and pneumatics</td>
<td>9.72</td>
</tr>
<tr>
<td></td>
<td>Inner profile 30x30 mm with guide system</td>
<td>1.60</td>
</tr>
</tbody>
</table>

**Lower Profile**
The lower profile consists of 40x40 mm profiles with a wall thickness of 2 mm. To calculate the tension in the profiles the calculations were simplified to only one of the profiles in the form of a supported beam loaded with a centred force, see Figure 1.

![Figure 1](image)

**Figure 1. The force F acting on a supported beam.**

For the case of a supported beam the deflection $\delta$ is given by the equation

$$\delta = \frac{F \cdot L^3}{48 \cdot E \cdot I}$$  \hspace{1cm} (1)

where $F$ is the load, $L$ is the length of the beam, $E$ is Young’s modulus and $I$ is the second moment of area (Sundström et al., 1998). The force acting upon the lower profile is half the weight of the whole multi-drilling device, see Table 3, since the device is supported by two 40x40 mm profiles in the lower part. Including the drilling force of 30 N for each of the six hammer drills the total force acting on one of the lower profiles is 395.55 N. With the knowledge that the profile is 1500 mm long and with Table 1 and 2 the deflection is calculated from equation (1) to be 1.55 mm.

The resulting maximum tension $\sigma_{\text{max}}$ is calculation with the equation

$$\sigma_{b_{\text{max}}} = \frac{M_{b_{\text{max}}}}{W_b}$$  \hspace{1cm} (2)

ii
where $M_{b\text{max}}$ is the maximum moment due to bending and $W_b$ is the section modulus (Sundström et al., 1998). $W_b$ is calculated as

$$W_b = \frac{I}{h/2}$$

(3)

where $I$ is the second moment of area as seen in Table 1. The maximum moment due to bending occurs in the middle of the beam. This results in a maximum moment of 296.66 Nm and a maximum tension of 69.53 MPa. Compared to the yield strength limit, see Table 2, the safety factor $n$ is 3.02.

**Pulley Rod**

The pulley and its axis carries the whole weight of the upper half of the multi-drilling device including the upper part, the six drill units with a drill force of 30 N each, and the middle profile 80x50 mm with the winch, electronics and pneumatics. Simplified the pulley rod can be seen as a solid round supported beam as seen in Figure 1 with a diameter of 12 mm and a length of 90 mm. The force acting on the pulley and its axis is 775.10 N and through equation (1) the deflection is calculated as 5.51 nm. The chosen pulley for the prototype is dimensioned for 80 kg load (Tellus, 2015).

The maximum moment is calculated as 34.88 Nm and with equation (2) the maximum tension as 0.21 MPa. The safety factor $n$ to the yield strength limit, see Table 2, is 1021.39.

**Inner Middle Profile**

The inner middle profile 30x30 mm has a wall thickness of 2 mm and a length of 850 mm. When only four of the drills units are used a moment of 124.18 Nm, due to the force from the two drill units on the edge, affects the upper part and thereby the middle part. Simplified the profile can be seen as a cantilever beam, see Figure 2.

![Figure 2. The force F and moment M acting on a cantilever beam.](image)

The deflection $\delta$ for a cantilever beam is calculated through the equation

$$\delta = \frac{F \cdot L^3}{3 \cdot E \cdot I}$$

(4)

where $F$ is the load, $L$ is the length of the beam, $E$ is Young’s modulus and $I$ is the second moment of area (Sundström et al., 1998). With equation (4) the deflection is calculated to be 5.93 mm and the maximum tension through equation (2) to be 51.74 MPa. The safety factor $n$ to the yield strength limit, see Table 2, is 4.06.
Long Upper Profile

Each half of the upper profile 30x30 mm is submitted to bending due to the four drill units on the edges. Half of the profile’s length is 700 mm and the wall thickness is 2 mm. One drill unit causes a load of 88.70 N including a drill force of 30 N but since the long profiles are placed double the affecting force is only half; 44.35 N. The profile can be seen as a cantilever beam, see Figure 2. The deflection is calculation through equation (4) to 0.67 mm and the maximum tension due to bending through equation (2) to 25.87 MPa.

The long profile also experience torsion due to the placement of the pneumatic cylinder on the side of the beam. The angle $\phi$ of the torsion for the profile is calculated through the equation

$$\phi = \frac{M_t \cdot L}{G \cdot I_v}$$

(5)

where $M_t$ is the moment due to torsion, $L$ is the length of the beam, $G$ is the shear modulus and $I_v$ is the moment of inertia (Björk, 2007). The value of $I_v$ for a 30x30 mm beam with a wall thickness of 2.5 mm is 5.40 cm$^4$ according to Björk (2007). The shear modulus $G$ is calculated through the equation

$$G = \frac{E}{2 \cdot (1 + \nu)}$$

(6)

where $E$ is Young’s modulus and $\nu$ is Poisson’s ratio (Björk, 2007), see Table 2. With the lever length of 35 mm the resulting torsion angle is calculation with the help of equation (5) and (6) to be 0.00050 radians or 0.029°.

The shear stress $\tau_{max}$ is given by the equation

$$\tau_{max} = \frac{M_t}{W_t}$$

(7)

where $M_t$ is is the moment due to torsion and $W_t$ is the section modulus. The value of $W_t$ for a 30x30 mm beam with a wall thickness of 2.5 mm is 3.22 cm$^3$ according to Björk (2007). The maximum tension due to torsion is calculated through equation (7) to be 0.96 MPa.

The resulting total tension due to bending and torsion is calculated with von Mises equation

$$\sigma_{vomMises} = \sqrt{\sigma_{max}^2 + 3 \cdot \tau_{max}^2}$$

(8)

where the different tension are combined. Through equation (8) the total tension is calculated as 25.93 MPa. The safety factor $n$ to the yield strength limit, see Table 2, is 8.10.

Middle Upper Profile

The middle upper profile 30x30 mm has a wall thickness of 2 mm. The halves of the profile can be seen as a cantilever beam, see Figure 2, with a length of 110 mm. With three drill units on each side of the upper part the bending force on each half of the middle upper profile is 266.1 N including a drill force of 30 N for each hammer drill. The deflection is calculation
through equation (4) to 0.11 mm and the maximum tension through equation (2) to 23.28 MPa. The safety factor $n$ relative to the yield strength limit, see Table 2, is 9.02.

**References**


Appendix B. Drawings

This appendix presents a selection of the drawings made for the manufacturing of the prototype.

The Drawings

The selected drawings are presented in this shown order:

- No. 1 – The Multi-Drilling Device
- No. 2 – Exploded View of the Lower Part with the Middle Profile 30x30 mm
- No. 3 – Exploded View of the Middle Part
- No. 4 – Middle Profile 80x50 mm
- No. 5 – Exploded View of the Upper Part
- No. 6 – Measurements of the Upper Part
- No. 7 – Upper Profile 30x30 mm with Holes for Drill Unit Adjustment
- No. 8 – Exploded View of the Drill Unit for the Edge Placement
- No. 9 – Exploded View of the Drill Unit for the Centre Placement
<table>
<thead>
<tr>
<th>Item Number</th>
<th>Title</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lower Part</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Middle Part</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Upper Part</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Drill Unit Edge</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Drill Unit Centre</td>
<td>2</td>
</tr>
</tbody>
</table>

Part: The Multi-Drilling Device

Material: Scale: 1:13

Created by:
Sara Gardelin
Madeleine Odebring

Date: 16-07-2015
Drawing no. 1
Part: Middle Profile 80x50 mm

Material: Steel EN10305-5

Scale: 1:5

Created by: Sara Gardelin
Madeleine Odebring

Date: 21-05-2015

Drawing no. 4
**DETAIL A**

- Upper Profile 30x30 mm with Holes for Drill Unit Adjustment
- Material: Steel EN10305-5

**DETAIL B**

- Holes for Drill Unit Adjustment
- Material: Steel EN10305-5

Created by:
- Sara Gardelin
- Madeleine Odebring

Date: 21-05-2015

Drawing no. 7
Part: Exploded View of the Drill Unit of the Centre Placement

Material: 

Scale: 1:5

Created by: Sara Gardelin Madeleine Odebring

Date: 16-07-2015

Drawing no. 9