Capstan-based design

for mechanizing manual well drilling

PRACTICA FOUNDATION

SPEEDKITS

Capstan-based design for mechanizing manual well drilling

By the Practica Foundation

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1 Executive summary

Manually drilled wells can be to 2-5 times cheaper than boreholes drilled with industrial rigs while providing the same quality well. Where applicable, manual well drilling has proven to be an appropriate asset in development and emergency sectors as it increases access to safe and affordable drinking water and stimulates livelihood of local entrepreneurs.

Several principles are available for manual drilling. The techniques 'rota-sludging' and 'rotary jetting' are most effective in unconsolidated soil formations. In soft consolidated formations and highly weathered rock formations, percussion drilling is more applicable. While percussion drilling can penetrate such rock formations, it is considered to be a relatively slow and both mentally and physically exhausting practice. Such difficulties can limit the feasibility of manual drilling.

This paper describes a technical innovation that utilizes a simple and affordable mechanical device to improve the use of manual drilling on consolidated and highly weathered rock formations. Such mechanical device increases the effective drilling time and reduces the labor requirements. The proposed method uses a rotating capstan that provides a lift and relative effective freefall mechanism. This capstan kit is designed as an open source innovation for local fabrication and maintenance in asset-poor areas.

A test case executed in Madagascar indicates that the proposed mechanization offers an efficient and affordable innovation. The mechanization of manual percussion can reduce the cost with a factor of 2,5 compared to manual percussion. This allows (manual) drilling enterprises to overcome the downsides of manual percussion in challenging soil formations while reducing the cost price of a well.

2 Introduction

2.1 Project and design context

The S(P)EEDKITS project (2012-2016) was a 4-year – European Union funded [grant agreement no 284931] - program, that focused on the improvement of various hard- and software solutions of relief organizations used in the first phases of emergency response campaigns. The intended innovations had the dual objective to be quick in deploying (SPEED) and offer a potential use for post-emergency conditions (SEED).

In this project, the applicability of manual drilling techniques in emergency settings was explored. Manual well drilling is a proven borehole construction method in the developmental context. It uses manpower rather than machine-based power to give the drill-bit a percussive or rotational movement. Moreover, it stimulates economic activities of local entrepreneurs and their respective communities[1] (Danert, 2014) thereby increasing local capacity and resilience.

Key characteristics of manual drilling include simplicity, ease of transport, independence of external supplies and cost effectiveness. These characteristics have a significant overlap with the requirements of hardware in emergencies making manual drilling innovations likely to be suitable for emergency settings.

Manual drilling techniques can be divided into 4 main principles[2]: Hand auger, Sludging, Manual Percussion and Jetting. In the project, all principles were examined by means of a SWOT analysis for the emergency setting. Hand augers are readily available on the market and need no adjustment. Jetting was found most suitable for unconsolidated soil formations. A professionalized rotary jetting kit[3] was therefore developed in the S(P)EEDKITS to make it more suitable in emergency settings. The SWOT analysis showed that in case of harder soil formations sludging and/or manual percussion are favored.

Both techniques are characterized by a repetitive manual lifting/freefall movement. This movement loosens the unconsolidated or consolidated formations in the borehole. Yet these techniques can be physical and mentally exhausting, particular in challenging soil formations where the progress can be slow.

As a result of this preliminary study, the conclusion was that mechanizing the lifting & freefall movement with simple and cheap means may provide a significant positive benefit for manual drilling application in emergency settings, especially in developing regions.

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[1] DANERT, K (2014) Chad’s Growing Manual Drilling Industry, Skat Foundation, Switzerland) http://www.rural-water-supply.net/_ressources/documents/default/1-656-34-1425638967.pdf
[2] For futher information: http://practica.org/publications/well-drilling-basic-understanding/
[3] Jetting kits are already available on the market. These kits are limited to 6-7 meters depth and can only serve as a water inlet. The diameter of these kits is 2 inch. Rotary jetting allows wells to be drilled up to 30 meters. A casing up to 5 inch can be installed, which allow the installation of a submersible.

2.2 Mechanisation

A preliminary study was performed on alternatives for mechanizing the manual lifting & freefall movement. The alternatives for mechanization were examined on

- technical simplicity,
- ease of use,
- local relevance (feasibility of local manufacturing and maintenance), and
- affordability (economic feasibility).

The study indicated that the use of a petrol-driven capstan (also referred as cathead) may provide a promising improvement to the conventional method. A capstan is a rotating drum on which a rope is wound. The friction of the rope on the drum – during movement – provides a mechanical advantage that leads to easier lifting of weights. For manual drilling, this weight would consist of either a drill string (in case of sludging) or a drill bit/bailer (in case of percussion). Although multiple sources mention this method for mechanization, limited data[4] with written records of designs and experiences are available.

One of the few existing rigs that was found is called the *Maq Perfor*[5]. It is being used in Nicaragua and uses the capstan to mechanize a particular sludging technique; rota-sludging. Little is known about its performance. Contact with the company that uses this system did not reveal additional hard evidence.

Picture 1: Field example of Maq Perfor drilling in Nicaragua

Based on pictures, the *Maq Perfor* rig[6] was rebuilt at the test location of PRACTICA Foundation in the Netherlands. Performance tests were run using different lifting weights at different rotation speeds of the drum with various ropes.

[4] Examples, apart from the Maq. Perfor, can be found http://phaugh.wordpress.com/tag/well-drilling/ and figure 41 in http://www.fao.org/docrep/x5567e/x5567e05.htm
[5] For further information: http://www.perfor.net/index2.html
[6] Although different pictures show different reductions, the gear reduction for the first test was determined on 1:6. A Honda GX engine has max torque around 2500 rpm resulting in a drum

Rope materials tested included:
- hemp,
- nylon,
- polyester,
- steel cable, and
- manila.

In brief: this testing revealed that friction between drum and rope left all ropes with wearing marks (particular burning). This quick deterioration of rope quality implied that significant improvements were needed prior to practical application of the capstan addition.

2.3 Preliminary, desktop research

As a first step to overcome the problem of rope deterioration, a desktop research was performed. This research was to determine

1. the main theoretical factors that are responsible for rope degradation, especially with particular excessive heating, and
2. whether there exist field experiences with capstans for drilling outside the developmental sector.

The most extensive theoretical research on capstan heating was found to be performed by the Naval Undersea Centre in San Diego[7]. In their paper, they noted that the heat rise from rope friction depends on (i) contact length (of the rope on capstan), (ii) friction force and (iii) the relative speed of the capstan to the rope when the line slides on the drum. The friction force is mainly determined by the material and texture/roughness of the capstan and rope as well as the tension on the rope. Yet calculating the heat of the rope is stated to be nearly impossible due to too many assumptions in the parameters. E.g., '*thermal conductivity as affected by the rope's texture and structural non-homogeneity and the occurrence of rope melting the ensuing thermal, structural and frictional* effects' [Brown, 1977] will cause significant imperfections in the equations. It is therefore suggested that it would be 'advantageous' to perform actual direct measurements of temperature while operating the capstan. It should be noted that capstans used in naval practices are applied for hoisting/pulling, rather than the repetitive lifting & freefall movement.

Further literature research revealed that a few rigs are available on the market that use a cathead for a lifting & freefall movement (rather than a hoisting movement only). These rigs are used for 'standard penetration tests'. These standard tests are designed for subsurface soil investigation for foundation designs. During the tests, a standard 63.5 kg donut hammer is lifted for driving down a drill rod. In comparison, the hammer used is considerably lighter than the weight of the rota-sludge equipment which can weigh up to 200 kg. The machine (also named cathead drill rigs) functions with about 40 blows per minute and typically uses manila rope (d=25 mm).

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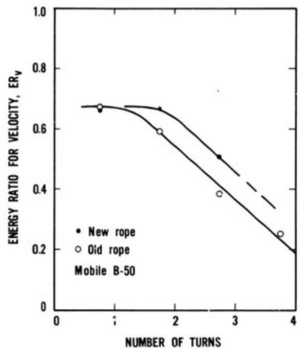
speed of around 415 rpm. This results, assuming a 12 cm (diameter) drum, in a rope speed of about 150 m./min. assuming no slip between rope and drum.

[7] Friction Coefficient of synthetic ropes, by W.E. Brown, Naval Undersea Center in San Diego , 1977



The report *Energy Measurement in the Standard Penetration Test* by Kovacs *et al*[8] suggests, that the fall efficiency can be around 70-80 percent of this system (ratio of potential energy converted into velocity) depending on the age of the rope and the number of turns of the rope on the capstan. This suggests that the system generates a relative efficient freefall of the weight which becomes more efficient with less turns of the rope on the capstan. The fact that the tests were performed with 'old ropes' suggests that ropes last for at least a while.

An off-the-shelf product (*Acker drill*[9]) was used for these tests, which is - in appearance - similar to that of the *Maq Perfor*. It operates with a rope speed of 60 m/min. This is considerable less than rope speed of the *Maq Perfor*. Contact with the equipment's supplier revealed that rope deterioration was not measured, but it was considered an unavoidable factor of the capstan use. A price indication for the *Acker drill* was given at around USD 2.500 dollar (machine only, excluding tripod and shipping).

2.4 Objective of the main R&D research

The preliminary, desk study revealed that capstans are used to lift and drop weights of about 63.5 kg effectively and that off-the-shelf products are available for this type of use. Yet no record could be found related to the degradation of the rope or on the effect of using heavier weights (needed for certain manual drilling equipment). The main design parameters that affect the rope degradation are (i) the speed of the drum, (ii) the type of rope that is used and (iii) the weight to be lifted. It is not known whether the currently available, off-the-shelf products are optimized for these parameters and whether the current designs fit the requirements for manual drilling. Nor is there an open source design that could be used for the introduction of a system that is suitable for local production.

The first objective of the research therefore was to determine optimal design parameters in the context of manual well drilling. Based on these findings it could be determined whether existing rigs need to be improved. Once the optimal design is determined, the effect of wearing of the rope with heavier weights (compared to the weights used for the SPT) could be defined.

[8] Kovacs, William D.; Salomone, Lawrence A. & Yokel, Felix Y. Energy Measurement in the Standard Penetration Test. Washington D.C.. UNT Digital Library. http://digital.library.unt.edu/ark:/67531/metadc38318/. Accessed March 13, 2014.
[9] http://www.ackerdrill.com/files/pdfs/motorized_cathead_kit_bulletin.pdf

3 Design of prototype

3.1 Defining the optimal drum speed

The first design step was to determine the optimal drum speed for manual drilling. The optimal drum speed was defined as the lowest possible drum speed for effective drilling. Below this speed, the slow drilling would compromise applicability for drilling purposes. A higher drum speed would result either in extra, unnecessary wearing of the rope or in a compromise in the weight to lift in order to mitigate rope degradation.

The optimal drum speed was determined empirically by experts after simulating the drilling movement. The prototype built by Practica was based on the *Mac Perfor* design with a speed of 150 m/min. The test caused heavy wearing on the rope while it was clear that the drum span faster than needed. A second explorative test was performed with a product called 'portable winch[10]'. The model tested had a speed of 18 m/min. The tests revealed that the speed was insufficient for an effective drilling action.

With multiple gear ratios tested on an in-house prototype it was concluded that the optimal speed is about 30 m/min. The speed of a lift/drop cycle is about the same of that when the action is performed manually. This figure is not absolute and has a high 'tolerance'. But the test revealed that a significantly lower speed would reduce the applicability for drilling. A higher drum speed is possible (see the *Acker drill* as an example) but would cause the rope to degrade unnecessary particular when the drilling equipment is very heavy. Using a drum of 85 mm diameter, this equals a shaft speed of about 110 rpm. This speed it about half the speed of the *Acker drill*, suggesting that a redesign of the hardware could result in improved hardware for mechanizing manual drilling techniques.

3.2 Selection of rope

After the determination of the optimal drum speed, a prototype was built and tests were performed with different ropes. Various ropes were selected for the tests. The selected rope diameter was based on the needed rope strength. In order to determine the best rope, variable weights (ranging from 30 to 200 kg) were lifted and dropped in a constant movement. Tests were performed at different drum speeds (by adjusting the speed of the engine) and at different number of turns on the drum. The temperature of the capstan was monitored in intervals. The temperature reading proved challenging because the aluminum spinning drum made infrared measurements difficult. Yet, clear trends could be established from the readings.

The following type of ropes and cables were tested:

- **Standard synthetic ropes**: Nylon and polyester ropes (10-15 mm).
- **High Tech ropes**: The Samson validator 12 mm rope[11]
- **Steel cables**: standard 5mm flexible steel cable
- **Natural fibre ropes**: hemp and manila (14-18 mm)

[10] http://www.portablewinch.com/

[11] Heat resistant Construction - 100% Vectran® fiber single-braid with Samthane coating. Melting/degradation temperature: 330 oC11. Selected based on expert advice

The temperature readings combined with visual observation shows that the degradation of the different ropes is distinctly different. Synthetic ropes and the steel cable proved least suitable. Whereas the synthetic ropes tended to ravel and melt with high loads, the steel cable caused significant damage as it 'carved' away the metal from the drum. Nor did it provide a satisfactory grip on the drum, making it difficult to use.

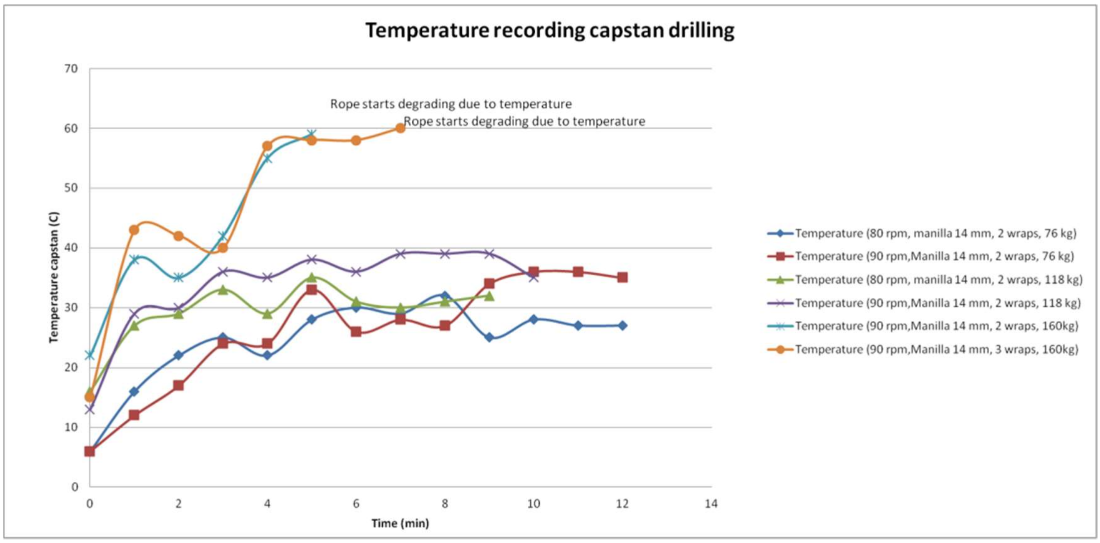
The high-tech rope could handle the temperature increase better when compared to the 'standard synthetic' ropes. Yet, they both appeared to give less grip than the natural fibered ropes. This resulted in a higher relative speed of the rope on the drum due to the slip. As a result, a faster rope degradation occurred. The recorded temperatures when using this high tech rope proved to be high(er) during drilling compared to the natural fiber ropes. The hemp rope tended to suffer less as a result of high temperatures. Yet it tended to break before significant degradation due to temperature. Manilla however, proved to work best. It blackens over time, yet didn't tend to unravel as much as the other ropes tested, nor did it break.

Picture 2: left to right; Damage to Samson validator, hemp, manila with same testing conditions

Given the findings combined with the fact that natural fiber ropes are more likely to be found on local markets it was concluded natural fiber ropes should be the preferred choice for use with the capstan. When available ropes of manila should be preferred to hemp-based ropes.

3.3 Determining maximum lifting weight

With the positive results of Manilla rope, this type was further explored with lifting multiple weights and using multiple wraps around the drum. The aim was to determine the maximum weight in order to get to an acceptable wearing of the ropes. The following graphs show the (indicative) temperature recordings on the side of the (aluminum) capstan.



Graph 1: temperature recording of drum

Picture 3: Manilla rope; *left:* 2 wraps, 76 kg, 80 rpm, *middle*: 2 wraps, 118 kg, 80 rpm *right*: 2 wraps, 160 kg, 80 rpm

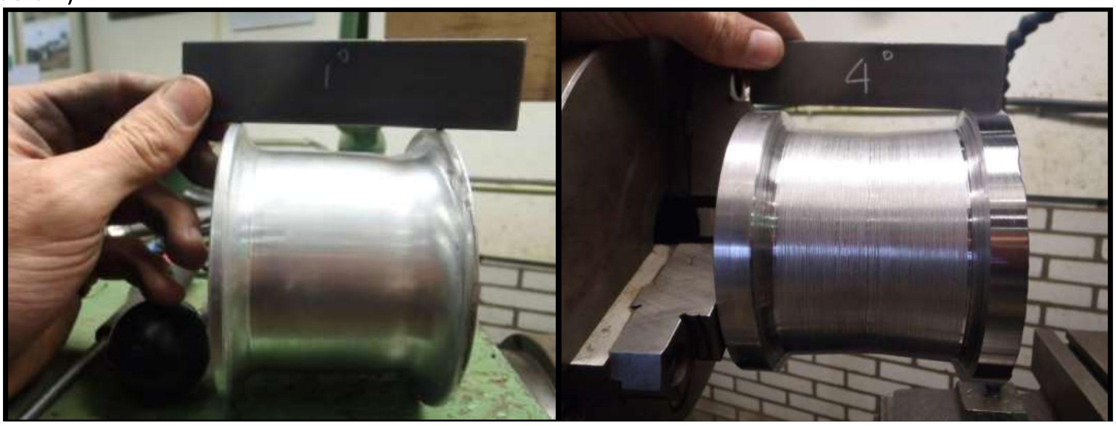
Although it should be noted that the temperature readings on a rotating aluminum drum had limited accuracy, the temperature readings combined with the rope inspection clearly demonstrate the temperature increase with the increase in weight. When the weight increase was as small as 76 to 118 kg, limited damage appeared on the ropes. But when the weight was further increased to 160 kg, the temperature increased significantly. At that point, the rope starts to degrade rapidly.

There are no norms related to rope degradation, so no exact figure can be given on what is acceptable or not. Nevertheless, the readings indicate that using a manila rope, the weight of the drilling equipment should preferably around 100-120 kg or less. Examples of these drilling methods are simple percussion, the *Emas* method and the *Baptist* method and multiple variations of these techniques such as the *Shipo*. Also, rotary jetting and rota sluding can be used when de drill depth is limited. Yet heavier equipment is possible depending on the degradation rate of the rope that one is willing to accept. Mechanization of sludging using equipment up to 200 kg is considered to be unfavorable given the degradation rate. Long-term tests should be performed with natural fibered ropes available on local markets as quality of the ropes will differ from location to location.

3.4 Shape and material of capstan

Although not part of the initial design parameters defined in the desktop research, it was noted that the shape of the capstan would affect the speed of the rope degradation. The initial shape of the capstan was tapered to one side (see picture below left). When the weight was lifted, this resulted that the 'incoming' rope on the capstan was forced in between the rope on the capstan and the side of the capstan. This caused damage on the rope.

By means of experimenting combined with the ease of local production in mind it was concluded that a slight slope towards the middle in the drum has the most satisfactory result (see picture below).

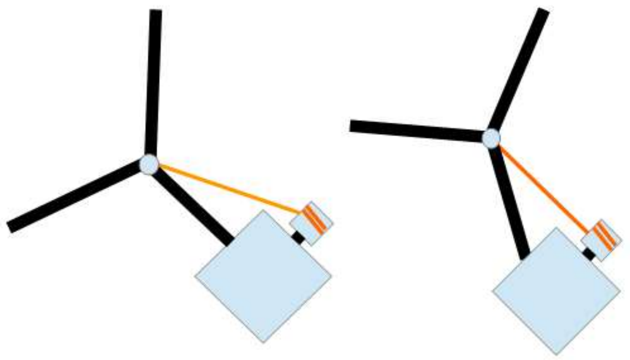


Picture 4: Different capstan designs. Picture on left: Aluminum capstan tapered to the right; Picture on right: Steel capstan tapered to the middle.

During the tests an aluminum capstan was used. A groove on the capstan (also visible on picture 4 (left), on the right of the drum) after one well could be clearly observed. A steel capstan proved to suffer significantly less damage.

3.5 Alignment of Capstan

The alignment of the capstan related to the center of the tripod will affect the degradation of the rope. If improperly aligned, the rope on the drum is pushed to the side of the drum. Incoming rope is pushed between the rope and the side of the drum resulting in wearing. An optimal alignment is when the incoming rope on the capstan is nearly perpendicular to the axis of the capstan. A design where the capstan could be rotated on the pole of the tripod was favored so adjustments in the alignment can be made.



Drawing 1: Top view alignment of the rope with drum.

3.6 Safety

Safety issues related to the use of capstans were found neither in literature nor in product manuals. Yet, safety is a major concern with capstans. The key point of risk is where the incoming rope on the drum is being pushed over the rope on the drum. This makes a knot on the drum. The rope can't be loosened and the weight is lifted upwards once the rope is knotted. If this process continues for too long, the drill rods/bits are pushed to the top of the tripod resulting in a safety hazard. (Especially, if a leg or arm is caught in the rope.) For this situation a safety stops should be added to the machine. The machine operator as well as the driller located close to the borehole should be able to stop the machine. It was noted that when the machine operator was using the machine more often, the frequency of the knotting of the rope on de drum decreased significantly. Also proper alignment of the capstan and a reduction in the drum speed was shown to significantly reduce the frequency of knotting.

Picture 5: Knot of rope on capstan

3.7 Design

Given these findings and the adjustment of starting parameters, an improved design was made. Multiple variations for a design were explored:

- A worm-wheel speed reducer,
- a hydraulic option and
- a chain wheel reduction.

The hydraulic option proved too complicated, expensive and lumpy. Nor are all the parts available on local markets, making it difficult for local production and maintenance. The worm wheel reduction and the chain wheel reducer proved similar in cost range (although the chain wheels were slightly cheaper), but the chain wheels are expected to be more suitable for field repairs and local production. It was therefore decided to make the final design on the chain wheel. An impression of the design can be seen on the pictures below. In appendix 1, a complete set of drawings are given.

These drawing are limited to the machine only. The design of the bailer and the percussion bit can be found on www.practica.org/publications/ in the percussion manual. The tripod described in the manual needs to be adapted. In the manual, a fixed pulley is described. Rather than using the fixed pulley, a separate, rotating pulley is advised. This allows the rope to be aligned with the drum more easily. Furthermore a threaded end needs to be attached to one of the legs of the tripod so it fits in the attachment hole on the machine (drawing 4 in appendix 1). This allows the machine to rotate relative to the leg of the tripod so it can be aligned with the pulley. In addition to this two electric switches should be placed that function as a safety stop.

During action a counterweight is placed on the frame of the machine.

Picture 6: Capstan design

3.0 Field testing

The first field tests were performed in the Netherlands. Two successful wells were completed using the percussion method (combination bailer and percussion bit). A second more extensive, comparative field trial was done in Madagascar. In this trial, the production with locally available hardware and the technical performance in the field was tested with more realistic soil formations.

In order to come to a (financial) comparative analysis the following three options were explored:

1. Manual well drilling with the percussion method. This method completely relies on manual labour for the drilling movement;
2. Well drilling with the percussion method supported by the capstan. The manual labour needed for the percussive movement is reduced because the capstan aids both the lifting movement.
3. Well drilling with rotary jetting and sludging methods[12] with additional support from the capstan. This method was mainly rotary jetting based yet a rotation movement was given to the drill string using the rotary arm of the sludging method. This percussive movement was only used to penetrate the hard formation. For drilling in the soft formation 'un-mechanized' rotary jetting was used.

The drilling was done by an existing well drilling company specialized in rota-sludge and rotary jetting. The technique of percussion was new for the drillers. A test well has been made before the start of the comparative analysis to make the drillers familiar with percussion technique. The difference in experience of the drillers per drilling method will have caused an inevitable imperfection in the results.

Picture 7: Capstan combined with rotary jetting and the rotation arm of rota-sludging

[12] For further explanation of the methods please visit http://practica.org/publications/

During the production, clutch reduction and the chain tensioners proved to be hard to obtain. Therefore, the chain tensioners had to be manufactured locally. These performed well, but lack of 'suspension' rubbers resulted in a noisy operation. Moreover, by not using the clutch reduction, the machine didn't operate at the peak of its performance when the preferred revolutions were achieved. Both downsides were making the machine sub-optimal. However, the setting proved sufficiently effective given the limited depth of the wells drilling and the related limit in equipment weight.

The total cost of the complete capstan system was about 2.200 euro (including a 35% profit margin). 85% of this budget was for fabricating the capstan machine itself. 15% was spent on making the basic manual percussion system (bailer, bit, tripod and rope). A cost breakdown can be found in appendix 2.

The price difference between a locally manufactured capstan and the *Acker drill* mentioned in the literature study is relatively small: about 400 euro although shipping costs should be added to the price of the *Acker drill*.

3.1 Comparative analysis and technical performance

The three wells were drilled close to each other to work in a similar geological profile. The general profile consisted of 2 m of laterite, 6-7 m of clay mixed with sand and mica, 1 m of weathered quartzite below which a clay mixture with sand/mica was encountered. Although the profiles proved relatively similar, there were slight deviations in depth and geology. The full drill logs can be found in appendix 3.

Picture 8: layer of weathered quartzite

To come to a comparative analysis two types of formations were defined:

- *Hard formation*: this is the layer of weathered quartzite. In practice, this layer would be impossible to penetrate with un-mechanized rota-sludging and rotary jetting.
- *Soft formation*: this is the formation of clay and sand/mica mixes in between the first layer of laterite and the weathered quartzite. In general, these layers are penetrable with un-mechanized rota-sludging and rotary jetting.

The following table (table 1) gives an overview of the drill speeds in the two different layers for the different drilling methods and the number of drillers needed to achieve this speed.

Table 1: comparative data field test

Performance			
Drill method	Hard formation	Soft formation	Number of drillers needed
	Average drill speed (m/day)	*Average drill speed (m/day)*	*(minimum)*
Manual percussion	0,25	1,1	6
Percussion with capstan	1	1,6	3
Sludging/jetting with(out) capstan	0,6 (with capstan)	2,8* (without capstan)	4

*Rotary jetting was used without the use of the capstan in order to penetrate the soft layer.

The table shows that the average drill speed increases in hard formations with the use of the capstan. Un-mechanized rotary jetting proved to be the fastest drilling method in soft formations.

Based on this data, the labor cost, cost of consumables and depreciation of hardware per meter drilled could be calculated (Table 2) together with other measured parameters in the field. This was done per type of formation.

The following table (table 2) gives an overview of the cost.

Table 2: Cost overview (Subtotals and assumptions in cost are included in appendix 4).

Drill technique	**Labour cost**		**Consumables**		**Depreciation**	
Formation	Hard formation	Soft formation	Hard formation	Soft formation	Hard formation	Soft formation
Unit	*euro per meter drilled*	*euro per meter drilled*	*euro per meter drilled*	*euro per meter drilled*	*euro per meter drilled*	*euro per meter drilled*
Manual percussion	84,0	19,1	1,2	0,3	3,7	0,7
Percussion with capstan	10,5	6,6	2,5	1,6	22,0	4,4
Sludging/jetting with(out) capstan	23,3	5,0	6,1	0,8	37,5	3,5

The table above suggests that particularly the cost of manual drilling, when compared to the mechanized drilling, is highly influenced by the labor cost. Although labor is relatively cheap, the speed of the drilling is also significantly lower. Although the machine was set up with an equal (initial) frequency of the percussive movement and the manual movement, the difference in speed could be explained by the mental and physical aspects of the methods. The frequency of manual drillers might drop overtime while the machine provides a consistent movement. In this test case, it took the drillers 4 days to penetrate one meter of weathered rock (!).

For the mechanized forms of drilling particular the post 'depreciation' determines the price of a well. Particular when hard formations were encountered. An important assumption is that the hardware in hard formations depreciates 5 times faster than the hardware used in soft formations.

The following table (table 3) gives a complete overview with all the costs accumulated.

Table 3: total cost

Drill technique	**Total cost**	
Formation	Hard formation	Soft formation
Unit	*euro per meter drilled*	*euro per meter drilled*
Manual percussion	89	20
Percussion with capstan	35	13
Sludging/jetting with(out) capstan	67 (with capstan)	9 (without capstan)

Although the sample size of the field data is small (3 wells with a total duration of 30 days drilling), the table above suggests that using the mechanized capstan system can be economically viable compared to manual percussion. The difference in cost is mainly caused by the reduction of drillers needed and the increased speed of drilling. The more 'hard material' in the soil formation, the more viable it gets. A daily rate of 3,50 euro per day per worker has been used for the price calculation, based on the rate in Madagascar. Higher daily rates, which are likely to be found in other parts of Africa, will cause even greater differences between the methods.

Whether percussion with the capstan or sludging/jetting with the capstan is economically more viable depends on the ratio in which hard and soft formations are encountered. A lot of hard formations will favor the economically viability of mechanized percussion. Predominantly soft formations will favor the mechanized sludging/jetting. Using rotary jetting for the soft formations and then change drilling technique to mechanized percussion is suggestively the most efficient method.

Interviews with the drillers and the drilling company owner suggest that the added value of the mechanization lies in the fact that the drill company can now penetrate hard layers. In the past these layers couldn't be penetrated with rotary jetting/rota-sludging due to technical and/or financial reasons. The manual percussion of these layers proved possible but very time consuming (four days for one meter) and very demotivating.

The technical performance of the device was seen as good. Improvements could be made in the chain tensioners and it was reported that the rope occasionally knotted. This happened particular in the beginning of the drilling when the drillers didn't align the capstan properly. The knotting also reduced if the speed of the drum was reduced. A guiding system or further tapering of the drum could be explored to further reduce this problem. The wearing of the rope was seen as acceptable for this depth range.

4 Conclusions and recommendations

Mechanizing the lifting & freefall movement with simple and cheap means may provide a significant, positive benefit for the manual drilling sector. A capstan can be used for lifting heavy weights/equipment while providing a relatively efficient freefall when the rope is loosened. Mechanizing the movement results in more effective drilling time and labor reductions. These characteristics make it a promising option to mechanize manual drilling techniques.

The researched principle is already in use in different applications. Nevertheless no system was found that was technically optimized for the purpose of mechanizing manual drilling techniques. Nor are any open source designs are available.

The mitigation of rope degradation was examined to optimize the design. This will allow heavier drilling equipment to be lifted which makes the design wider applicable (in depth and drilling technique). To mitigate rope degradation, the optimal drum speed and the most favorable rope type were determined with the help of empirical tests. The results were integrated in a tentative *open source* design based on a petrol-driven capstan.

The technical and financial feasibility of the design was determined with a comparative analysis in Madagascar. Three wells were drilled in a similar geological profile and were tested with three different drilling techniques: (i) manual percussion, (ii) mechanized percussion by means of the capstan, (iii) a combination of rotary jetting and rota-sludging (mechanized in the hard formation and un-mechanized in the soft formation).

Admittedly, the small sample size limits the validity of the results, but the obtained data provide a good indication on the likely costs (see table).

Drill technique	**Total cost***	
Formation	Hard formation	Soft formation
Unit	*euro per meter drilled*	*euro per meter drilled*
Manual percussion	89	20
Percussion with capstan	35	13
Sludging/jetting with capstan	67 (withcapstan)	9 (without capstan)

**The cost overview includes labor cost, depreciations costs and the costs of consumables.*

Of particular importance in the mechanization of (manual) percussion is the penetrability of weathered rock formations that would have been impenetrable with conventional rotary jetting and sludging methods. By mechanizing percussion the cost of drilling in weather rock reduced about 2,5 times (compared to manual percussion). The difference in cost is mainly caused by the reduction of drillers needed and the increased speed of drilling.

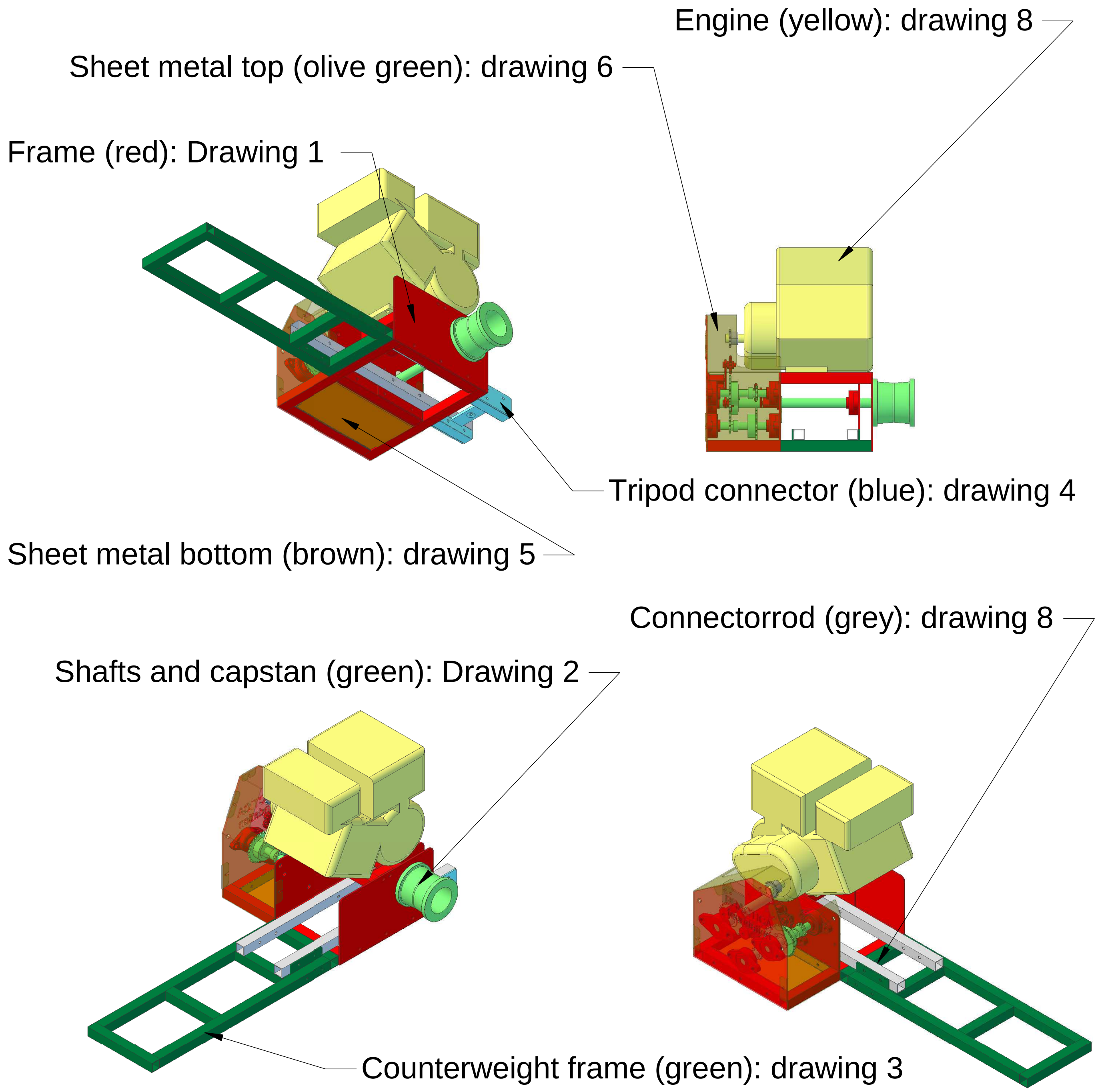
Un-mechanized Rotary jetting was found to be most effective in soft soil conditions. Using rotary jetting for the soft formations and then change drilling technique to mechanized percussion, once a hard formation is encountered, is suggestively the most efficient method.

Based on the findings the following recommendations can be made:

- The open source design of the capstan is made to further strengthen the capacity and resilience of the drilling sector in the developmental setting. It is specially designed to be locally producible and specifically adapted to complement (existing) manual drilling kits. In case of 'short interventions' by relief organisations, more expensive off-the-shelf capstan systems are available (e.g. *Acker drill*). They are likely to function properly, yet due to the higher rotation speed of the capstan the rope will wear quicker and/or will limit the maximum weight to be lifted.
- If the implementation of the system is considered, feasibility of production is to be viewed first. In particular, the engine proved difficult to obtain. The availability of bearing blocks and natural fibre ropes are also crucial. Availability of a quality machine shop is required in order to make the necessary adaptions to adapt the design.
- Likely feasible areas for the introduction of the system are areas where there are hard soil formations that are penetrable by means of (manual) percussion.
- Percussion is a difficult drilling technique. Existence of local drillers with (manual) percussion experience will significantly increase a success rate of a capstan-based tool's introduction.
- Safety is an issue when using this technique as the rope can form a knot around the capstan. Safety stops should be provided, one near the machine operator, one near the person close to the drill pit. The capstan should be aligned properly. Tapering of the drum can be further explored to reduce knotting. A guiding system of the rope might reduce the chance of knotting. Use safety precautions (such as the safety stop) at all times.
- If the system is used in combination with rotary jetting/sludging, it is recommended to study the average depth of wells in the vicinity. The drill string shouldn't become too heavy in order to avoid extreme damage to the rope. As an indication: the maximum weight to the drilling equipment should be around 150 kg depending on the level of acceptable rope deterioration. Long-term field experiments are required in order to determine this value more precisely.
- The tentative design described in this paper should be seen as a basis for further expanding possibilities in the manual drilling sector. Further testing and exploring of the capstan system is highly recommended.

Appendix 1

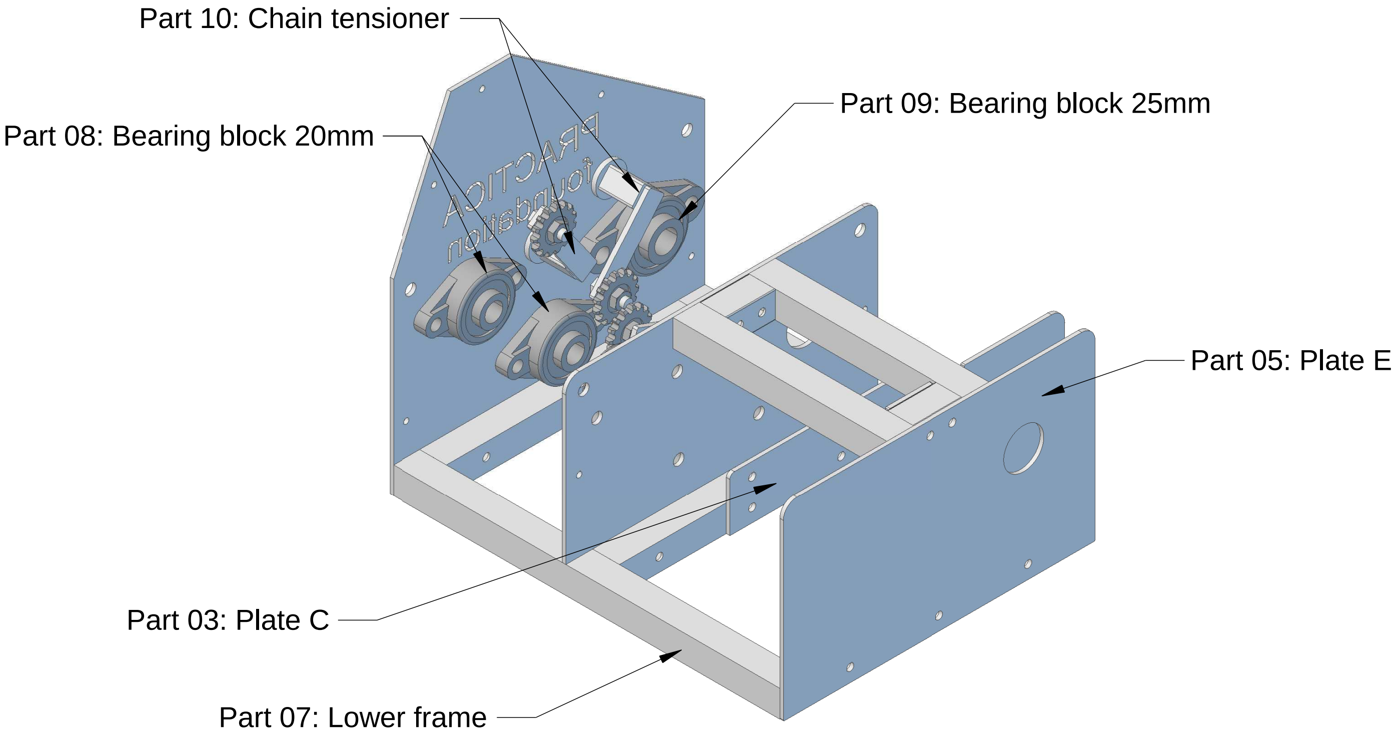
Technical drawings

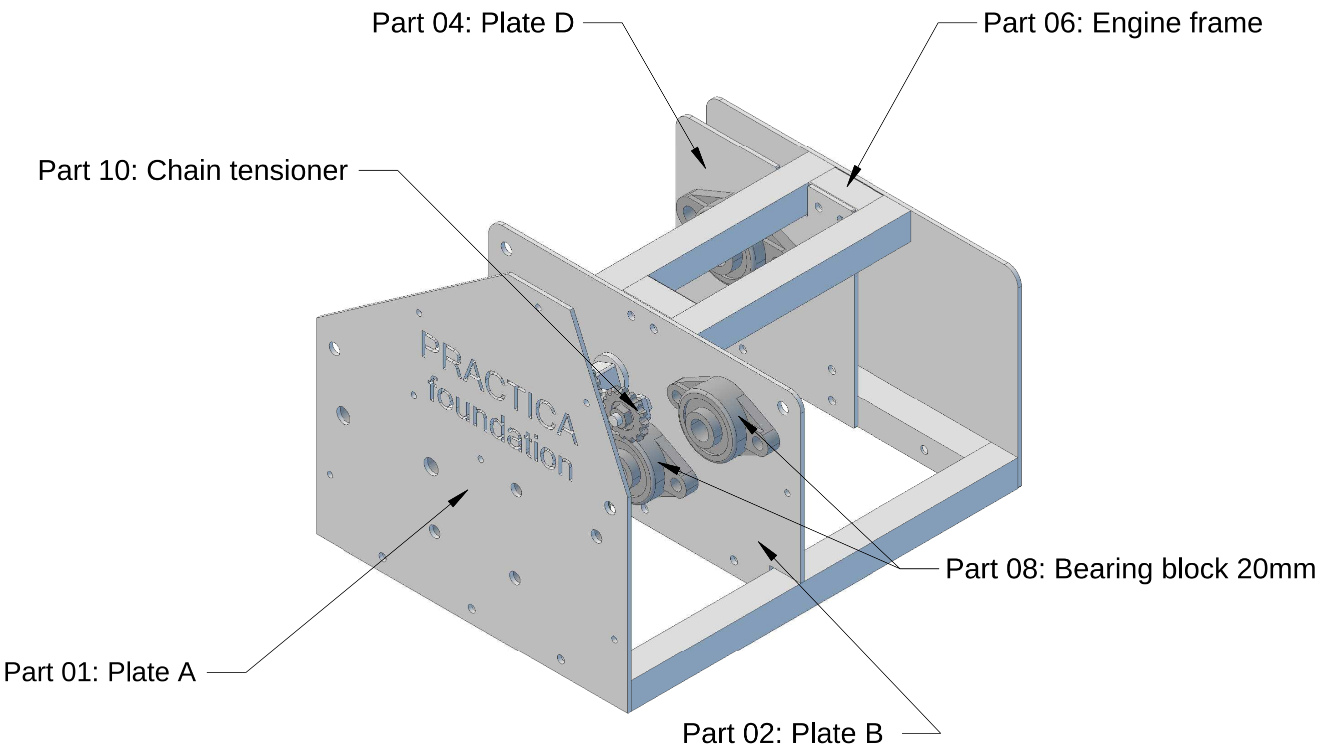


Colours are only used as indication of assembly of parts.
Each assembly is specified in the drawings.
A complete assembly guide is presented at the end of this document.

PRACTICA FOUNDATION

Drawn by:	Date:	Version:	Dwg no.	Scale	A4
Ilja van Kinderen	Sept 2014	Draft 1.0			





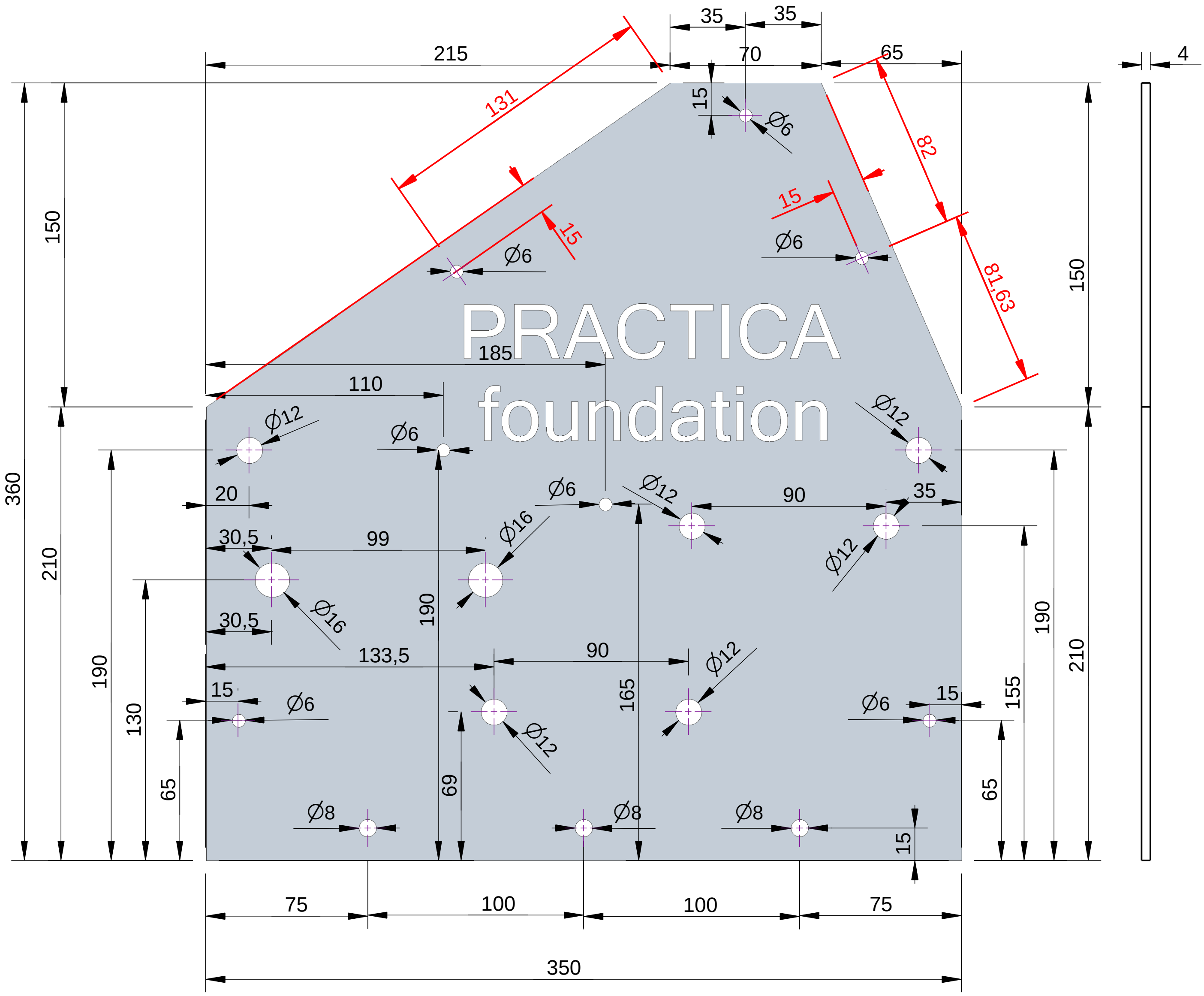
Nr	Name - material - amount needed

PRACTICA FOUNDATION

Frame (0)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	001	1:6	A4

01: Plate A



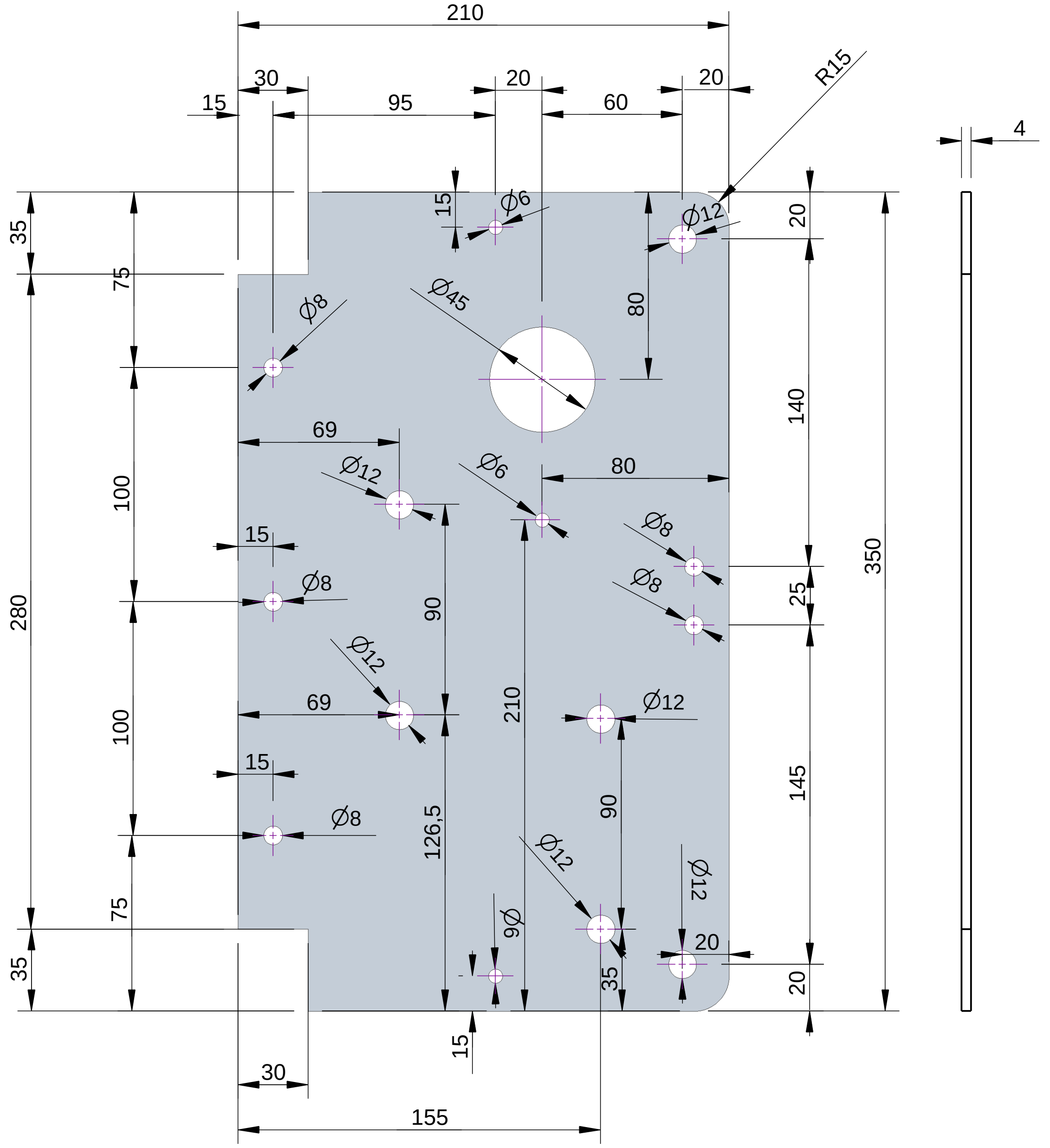
Nr	Name - material - amount needed
01	Plate A - Steel 37 - 1

PRACTICA FOUNDATION

Frame (1)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	001.1	1:3	A4

02: Plate B



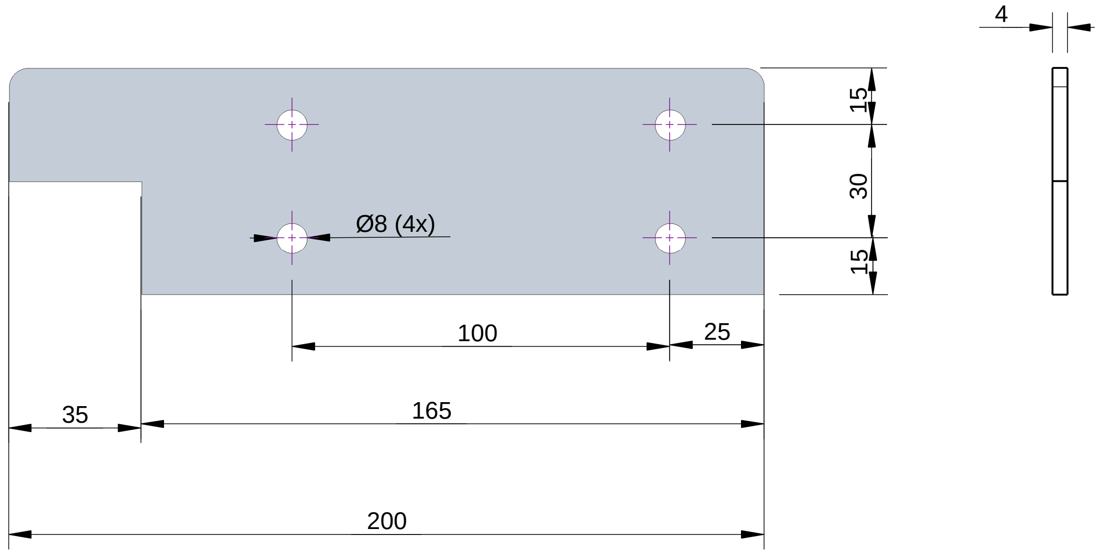
Nr	Name - material - amount needed
02	Plate B - Steel 37 - 1

PRACTICA FOUNDATION

Frame (2)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	001.2	1:3	A4

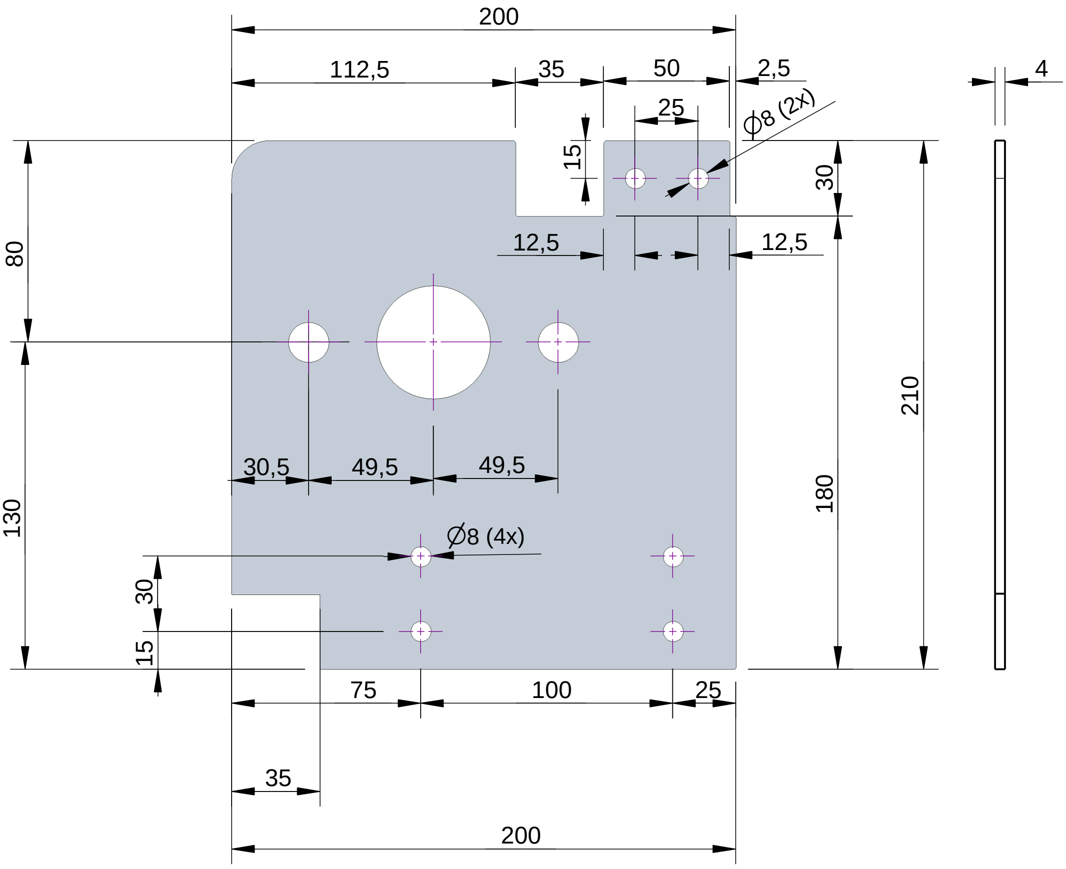
03: Plate C



Nr	Name - material - amount needed		
03	Plate C - Steel 37 - 1	PRACTICA FOUNDATION	Frame (3)

Drawn by: Ilja van Kinderen	Date: Sept 2014	Version: Draft 1.0	Dwg no. 001.3	Scale 1:2	A4

04: Plate D



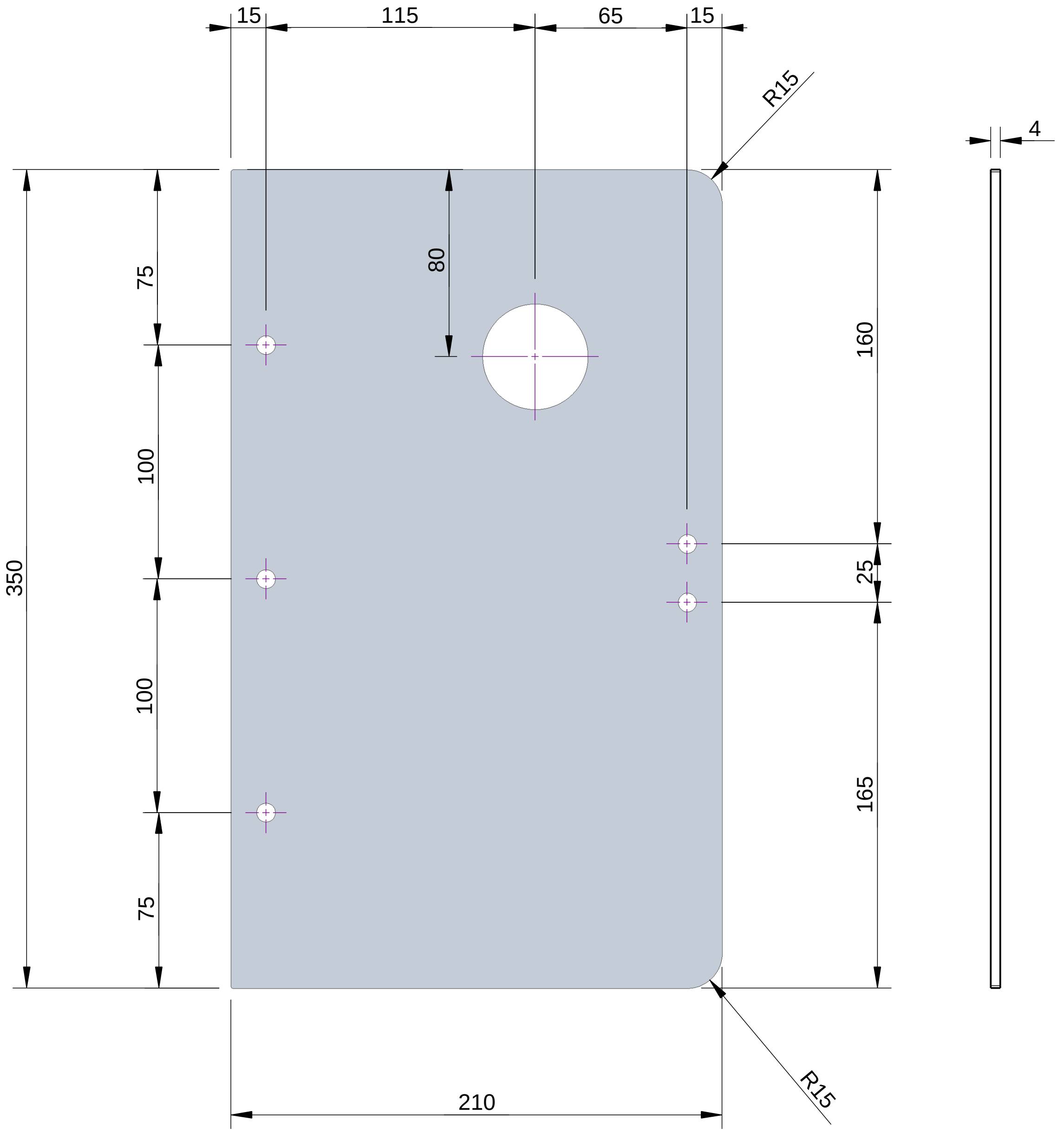
Nr	Name - material - amount needed
04	Plate D - Steel 37 - 1

PRACTICA FOUNDATION

Frame (4)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	001.4	1:3	A4

05:Plate E



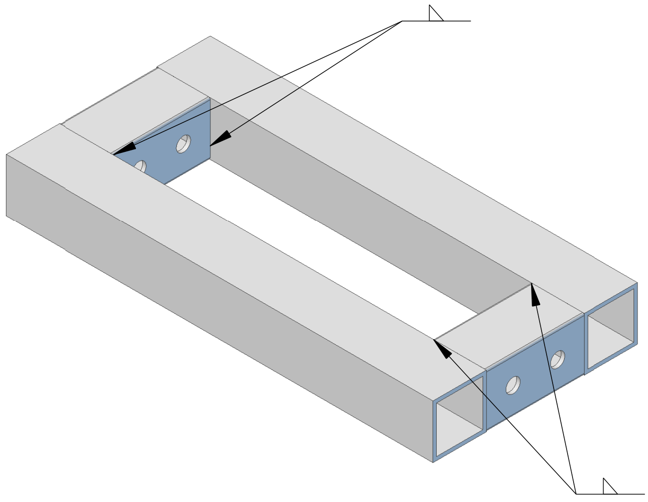
Nr	Name - material - amount needed
05	Plate E - steel 37 - 1

PRACTICA FOUNDATION

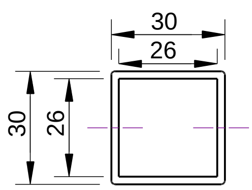
Frame (5)

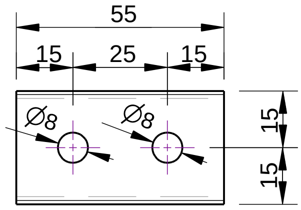
Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	001.5	1:3	A4

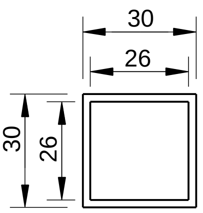
06: Engine frame

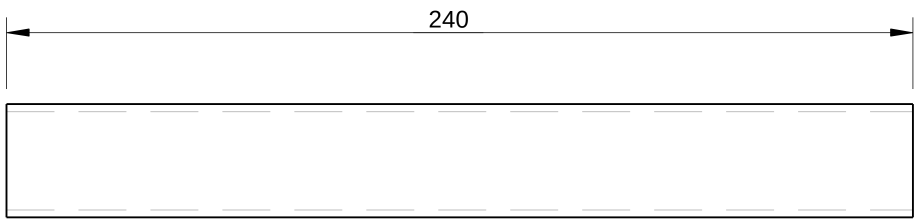


Note: Welds should be inside the frame and underneath the frame.
No welds on top. So engine can be placed correctly (= flate allignment) on frame.









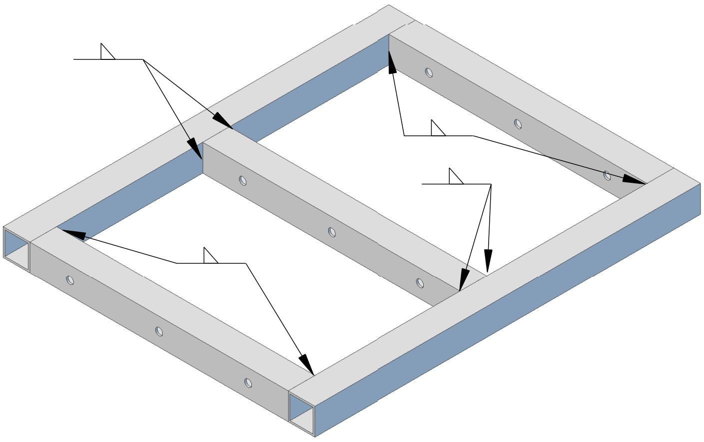
Nr	Name - material - amount needed
06	Engine frame - steel 37 - 1

PRACTICA FOUNDATION

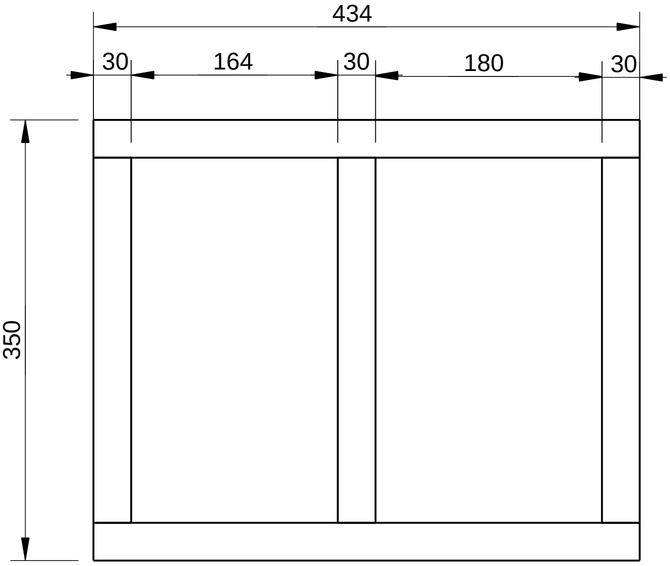
Frame (6)

Drawn by:	Date:	Version:	Dwg no.	Scale	A4
Ilja van Kinderen	Sept 2014	Draft 1.0	001.6	1:2	

07: Lower frame

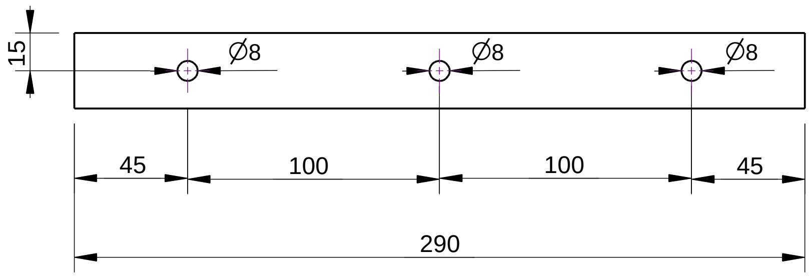


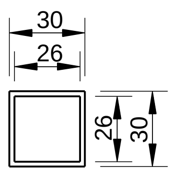
SCALE 1:6



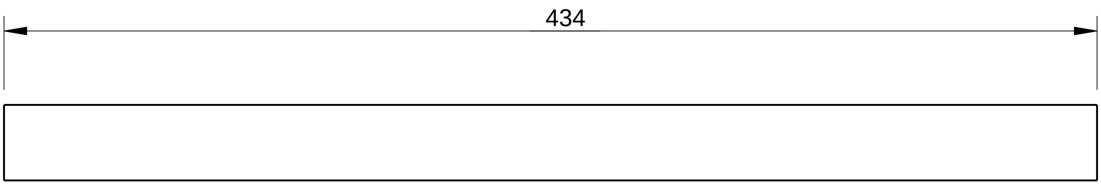
SCALE 1:6

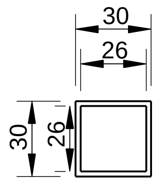
Note: weld only where specified (inside of frame).
Don't weld on the outerpart of the frame
as this will cause difficulties assembling.





SCALE 1:3





SCALE 1:3

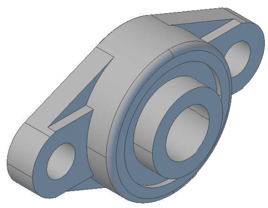
Nr	Name - material - amount needed
07	Lower frame - steel 37 - 1

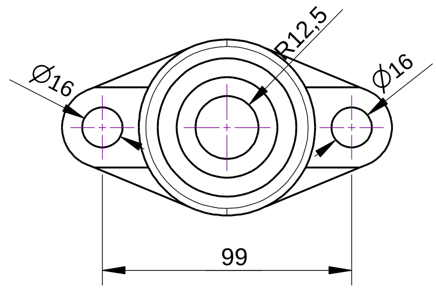
PRACTICA FOUNDATION

Frame (7)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	001.7	1:3 1:6	A4

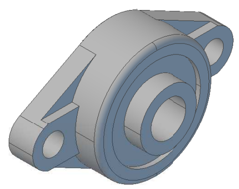
08: Bearing block 20 mm

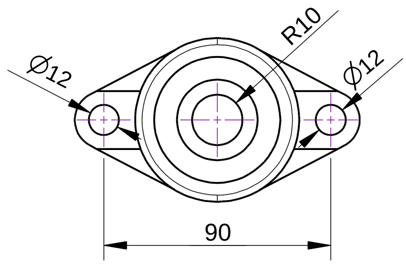




Note: off-the-shelf product. Product name: FL204
Main dimentions are given. If dimensions differ
(diameter of axis hole should not be adjusted),
holes for attachementin plate A, B and E
should be adjusted to fit new dimensions.

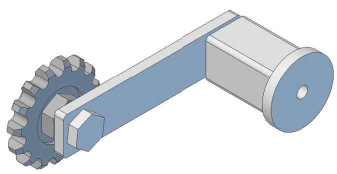
09: Bearing block 25 mm

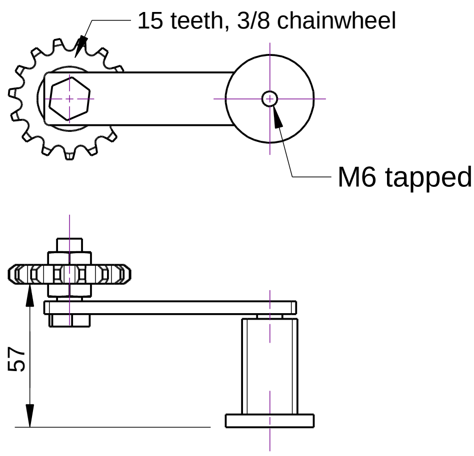




Note: off-the-shelf product. Product name: FL205
Main dimentions are given. If dimensions differ
(diameter of axis hole should not be adjusted),
holes for attachement in plate A, B and E
should be adjusted to fit new dimensions.

10: Chain tensioner





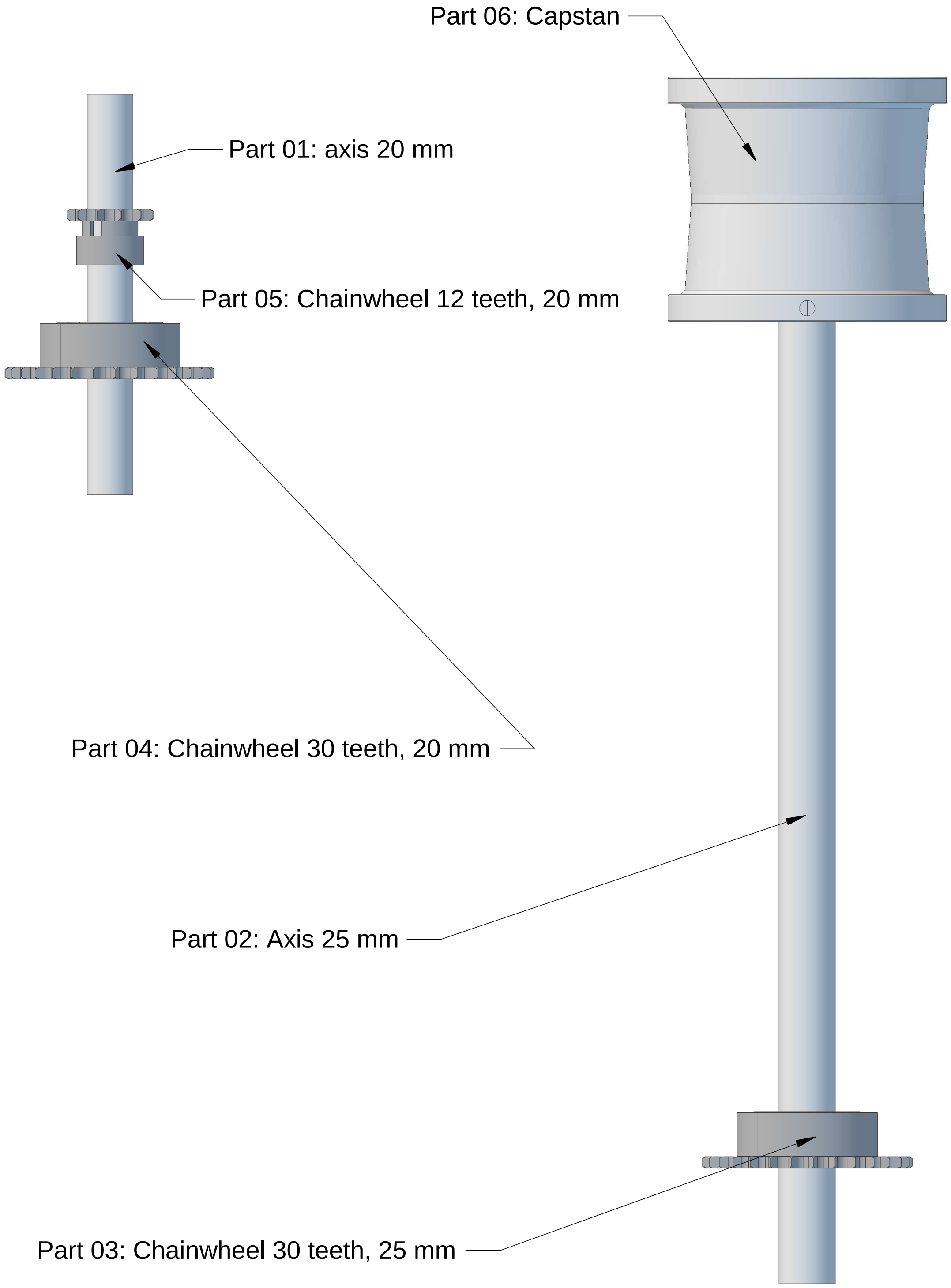
Note: off-the-shelf product. Rosta type SE 11 standard
with a 15 teeth wheel. If other chain tensioners are applied,
the design of plate A, B and E together with the alignment
of the chain wheels should be adjusted to new dimensions.

Nr	Name - material - amount needed
08	Bearing block 20 mm - n.a. - 4
09	Bearing block 25 mm - n.a. - 2
10	Chain tensioner - n.a. - 3

PRACTICA FOUNDATION

Frame (8)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	001.8	1:3	A4



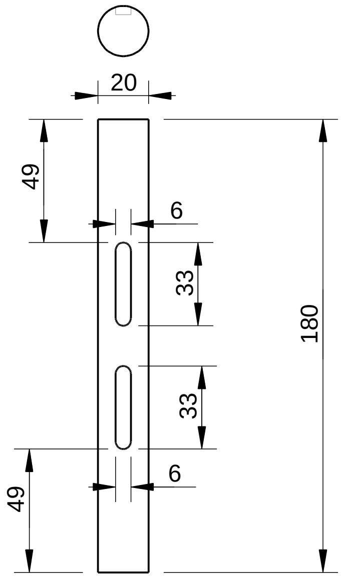
Nr	Name - material - amount needed

PRACTICA FOUNDATION

Shafts (0)

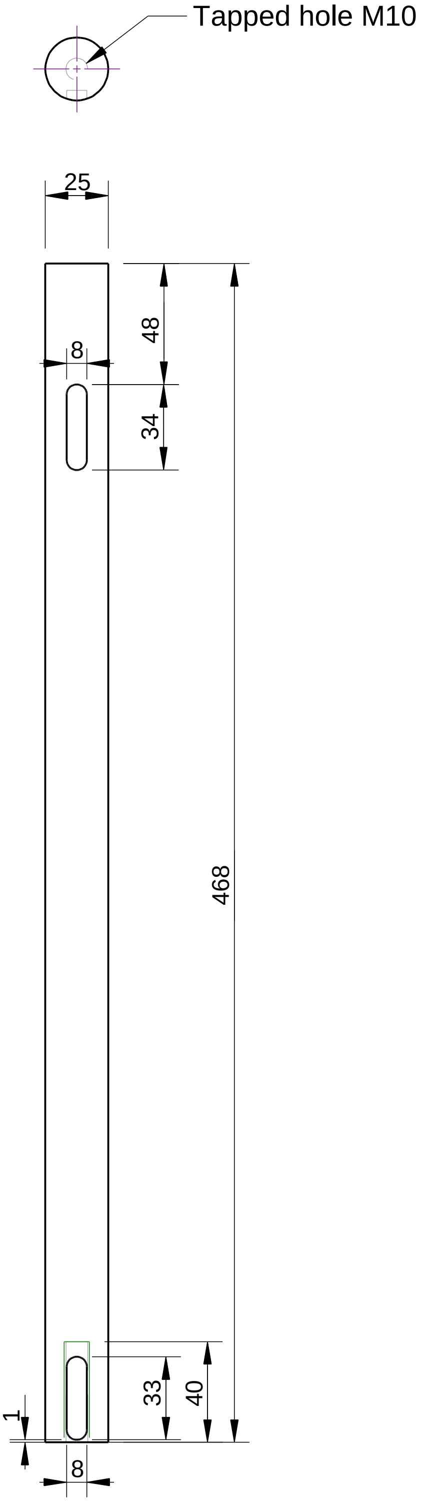
Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	002	1:3	A4

01: Axis 20 mm



Key/spline used: 6x6x32

02: Axis 25 mm



Key/spline used: 8x7x32

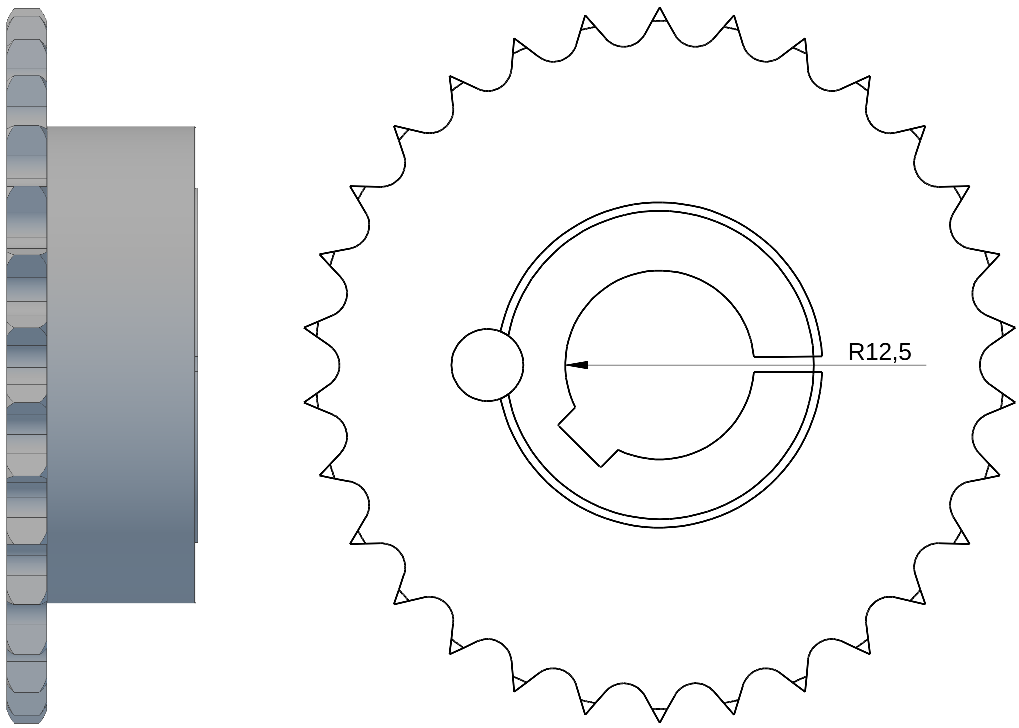
Nr	Name - material - amount needed
01	Axis 20 mm - tool steel - 2
02	Axis 25 mm - tool steel - 1

PRACTICA FOUNDATION

Shafts (1)

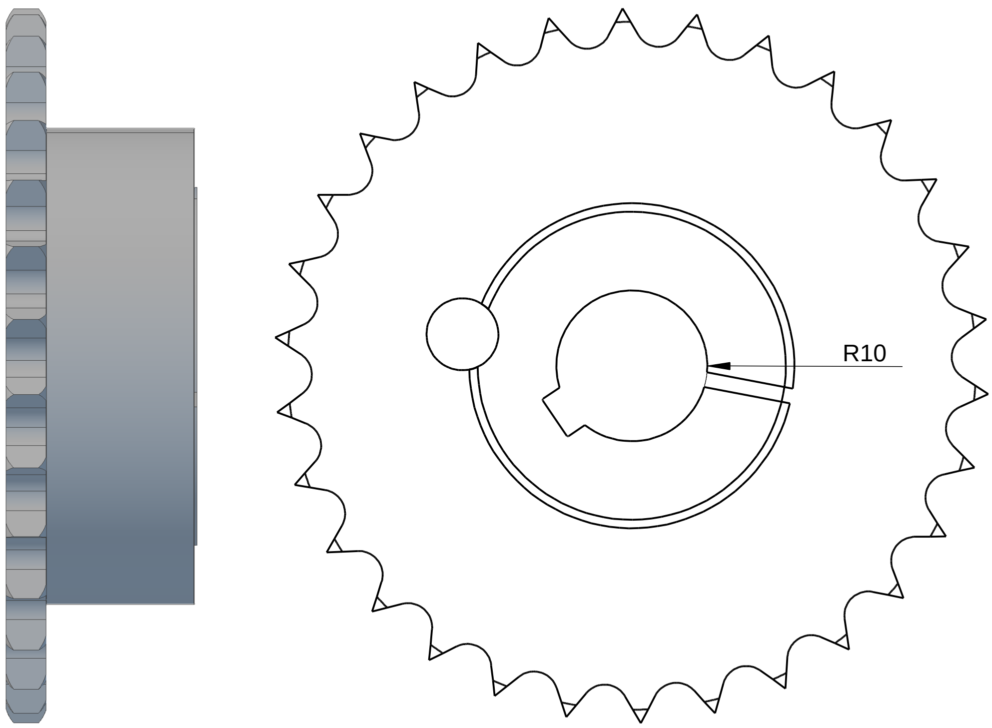
Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	002.1	1:3	A4

03: Chainwheel, 30 teeth 25 mm



Off-the-shelf part. Taper lock. Suitable for 3/8" 7/32" chain.

04: Chainwheel 30 teeth, 20 mm



Off-the-shelf part. Taper lock. Suitable for 3/8" 7/32" chain.

Nr	Name - material - amount needed
03	Chainwheel 30 T 25 mm - n.a. - 1
04	Chainwheel 30 T 20 mm - n.a. - 2

PRACTICA FOUNDATION

Shafts (2)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	002.2	1:1	A4

1	2	3	4

A

B

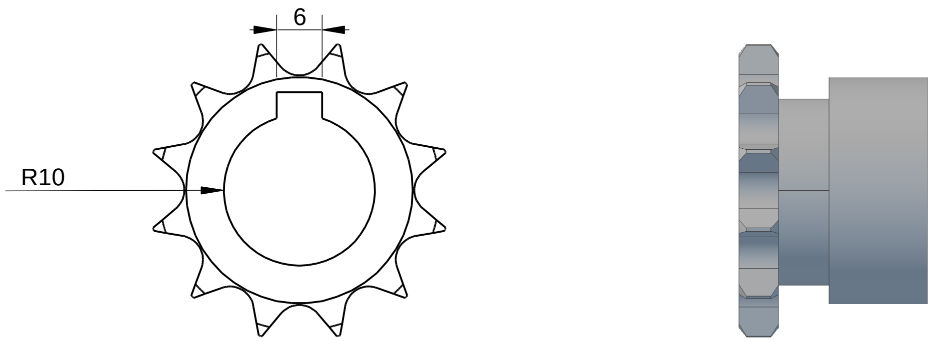
C

D

E

F

05: Chainwheel 12 teeth, 20 mm



Off-the-shelf part. Suitable for 3/8" 7/32" chain.

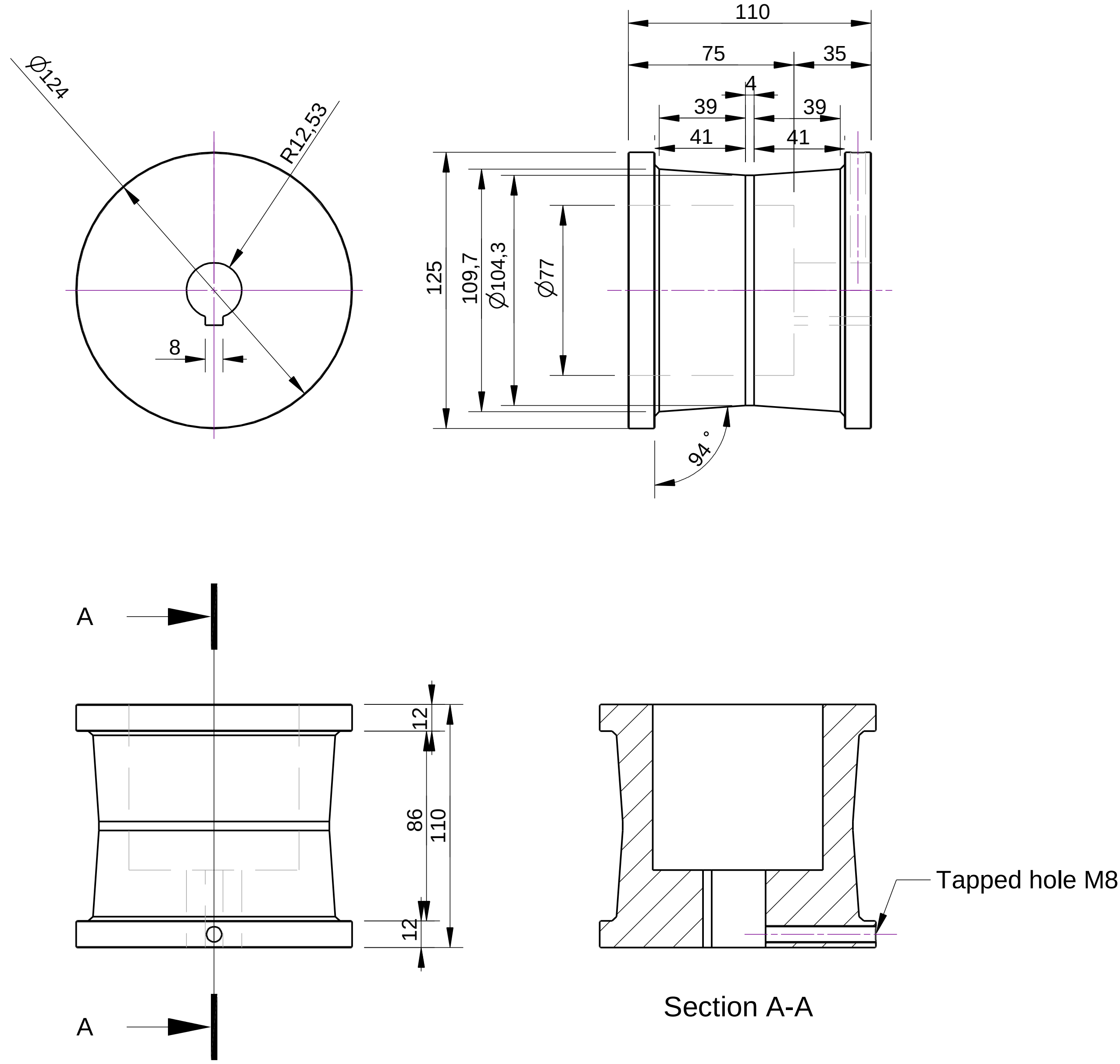
Nr	Name - material - amount needed
05	Chainwheel 12 th, 20 mm - n.a.- 2

PRACTICA FOUNDATION

Shafts (3)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	002.3	1:1	A4

06: Capstan

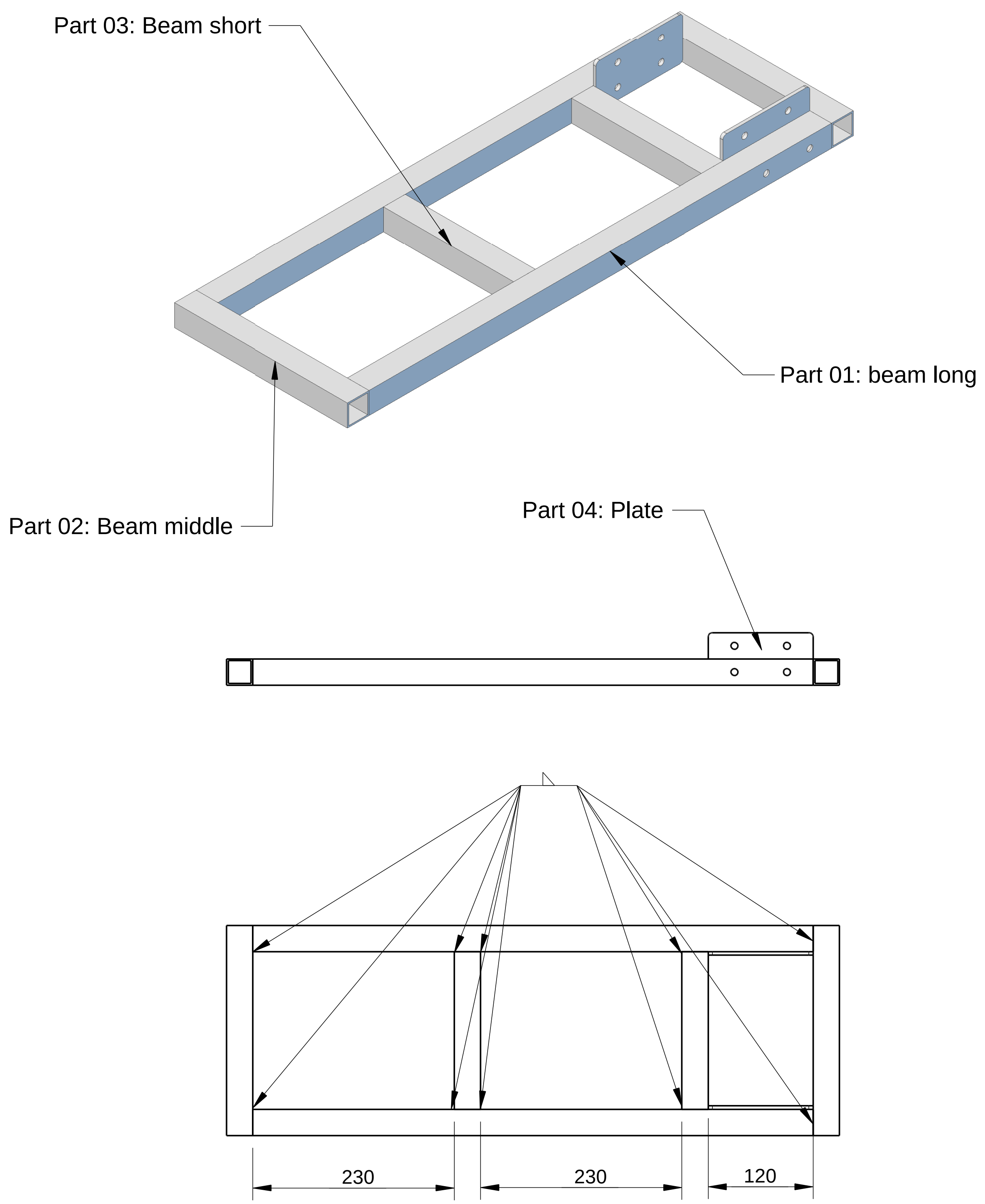


Nr	Name - material - amount needed
08	Capstan - steel 37 - 1

PRACTICA FOUNDATION

Shafts (4)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	002.4	1:3	A4



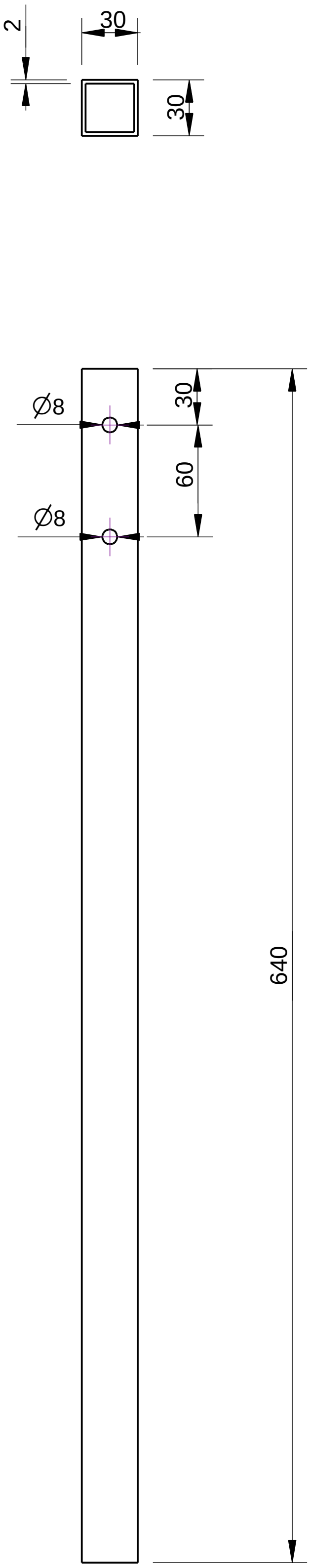
Nr	Name - material - amount needed

PRACTICA FOUNDATION

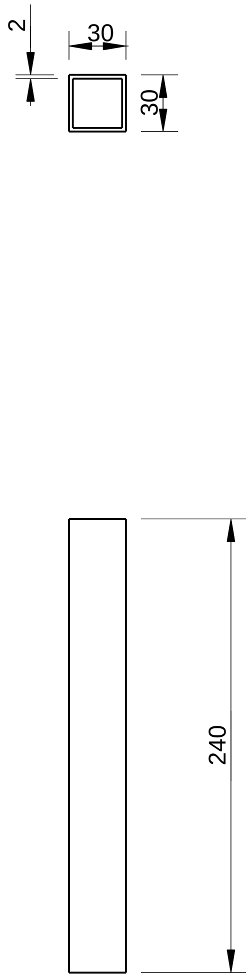
Counterweight frame (0)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	003	1:7	A4

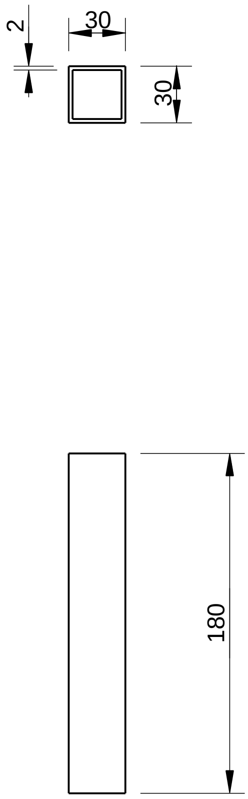
01: Beam long



02: Beam middle



03: Beam short



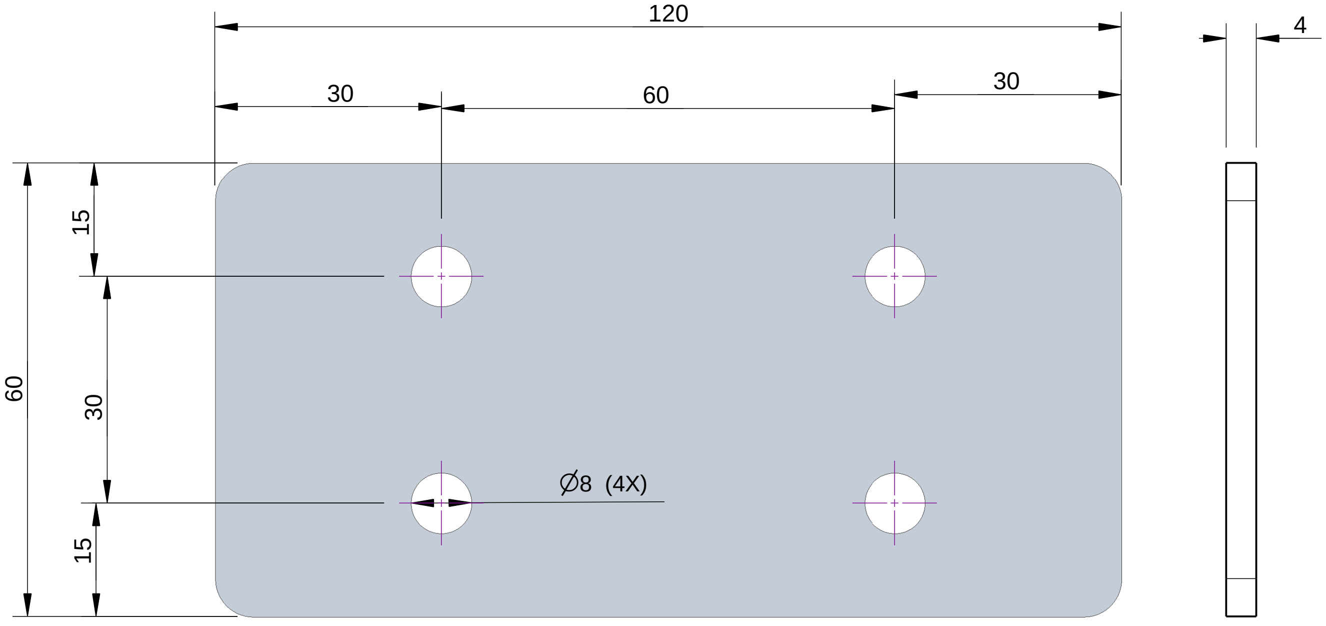
Nr	Name - material - amount needed
01	Beam long - steel 37 - 2
02	Beam middle - steel 37 - 2
03	Beam short - steel 37 - 2

PRACTICA FOUNDATION

Counterweight frame (1)

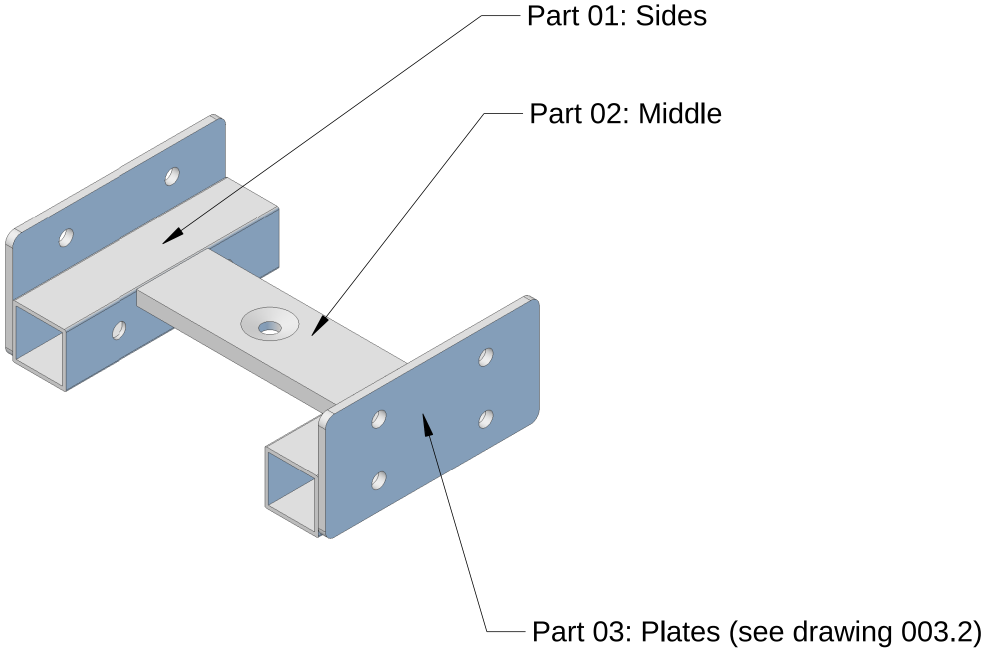
Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	003.1	1:4	A4

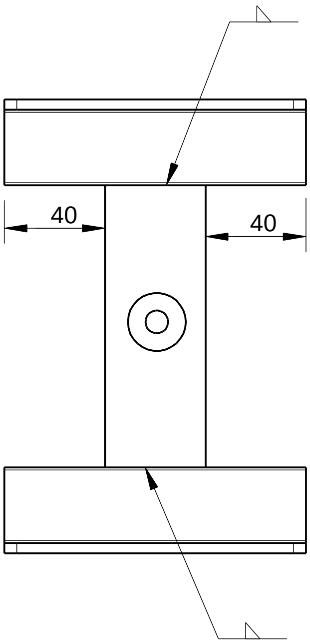
04: Plate

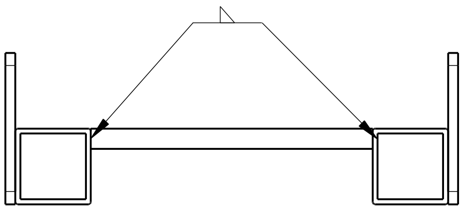


Nr	Name - material - amount needed		
04	Plate - steel 37 - 4	PRACTICA FOUNDATION	Counterweight frame (2)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	003.2	1:1	A4







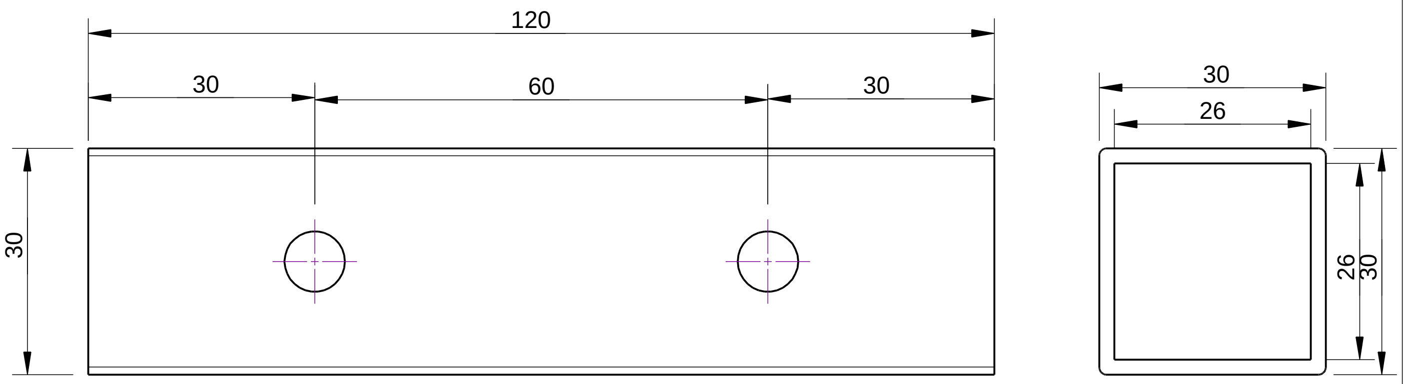
Nr	

PRACTICA FOUNDATION

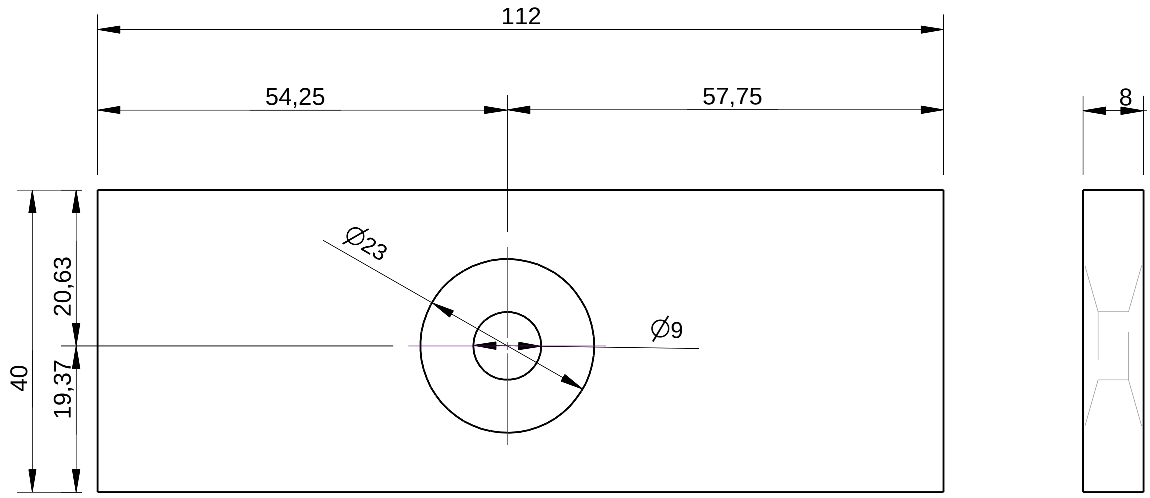
Tripod connector (0)

Drawn by: Ilja van Kinderen	Date: Sept 2014	Version: Draft 1.0	Dwg no. 004	Scale 1:3	A4

01: Sides



02: Middle

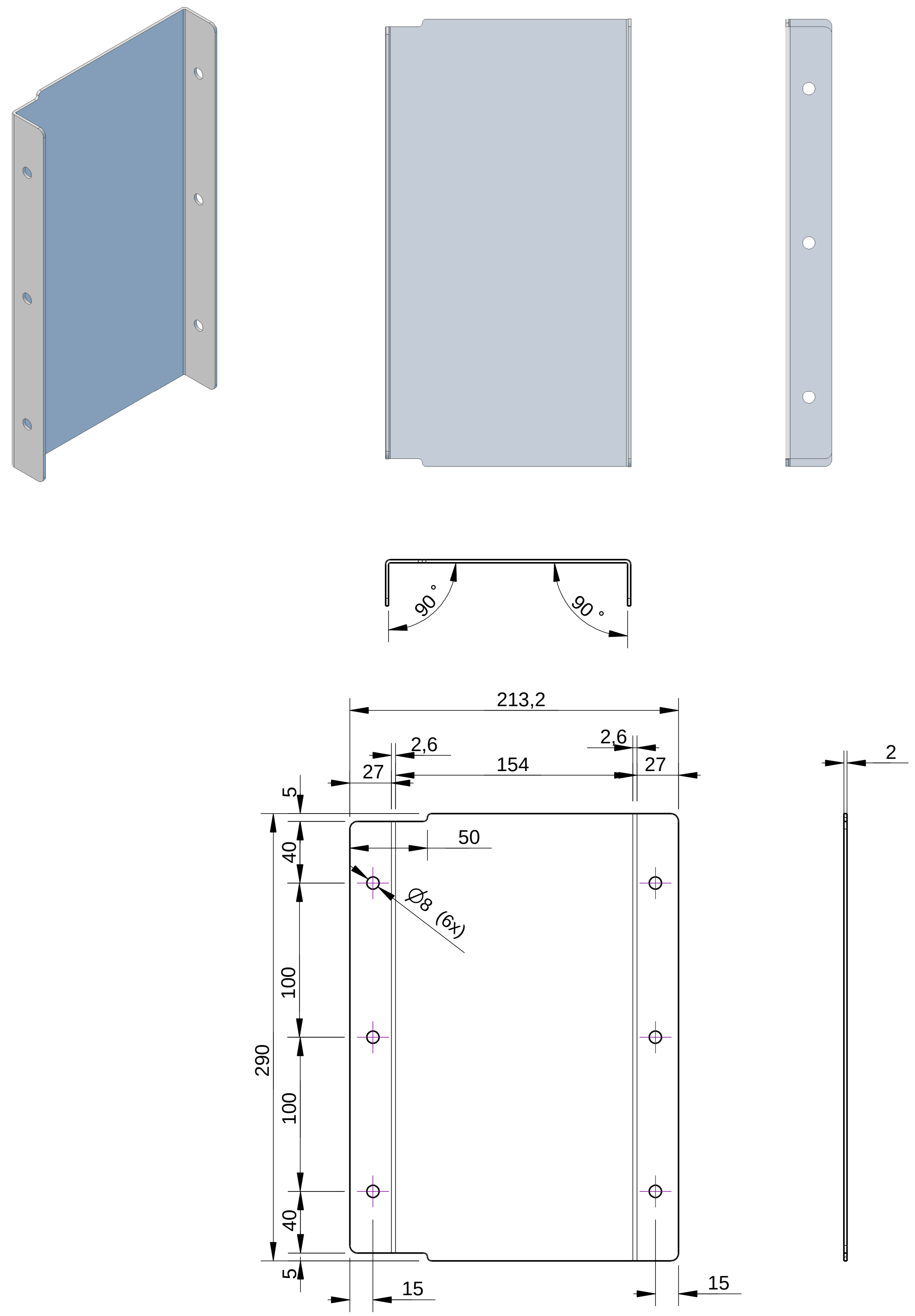


Nr	Name - material - amount needed
01	Sides - steel 37 - 2
02	Middle - steel 37 - 1

PRACTICA FOUNDATION

Tripod connector (1)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	004.1	1:1	A4

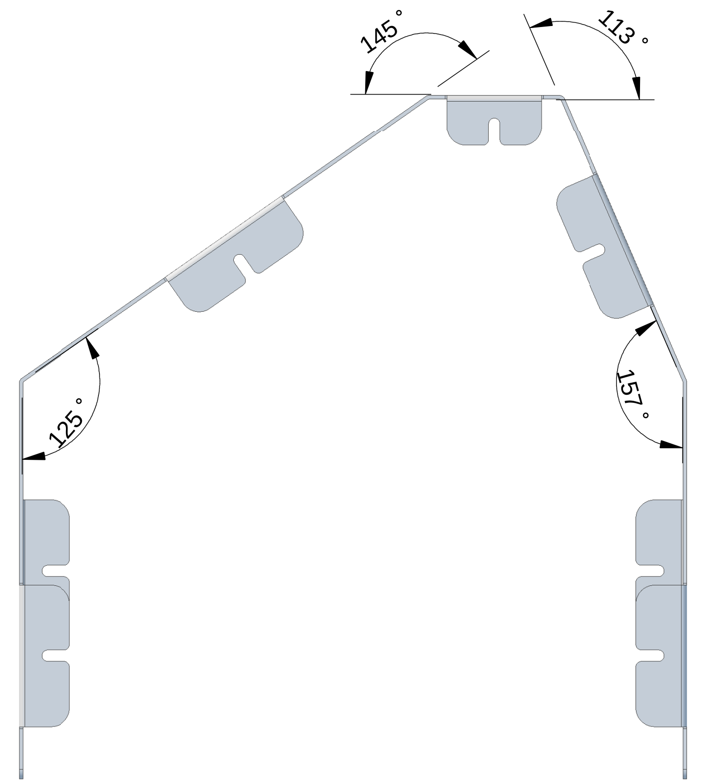


Nr	Name - material - amount needed
01	Sheet metal bottom - steel 37 - 1

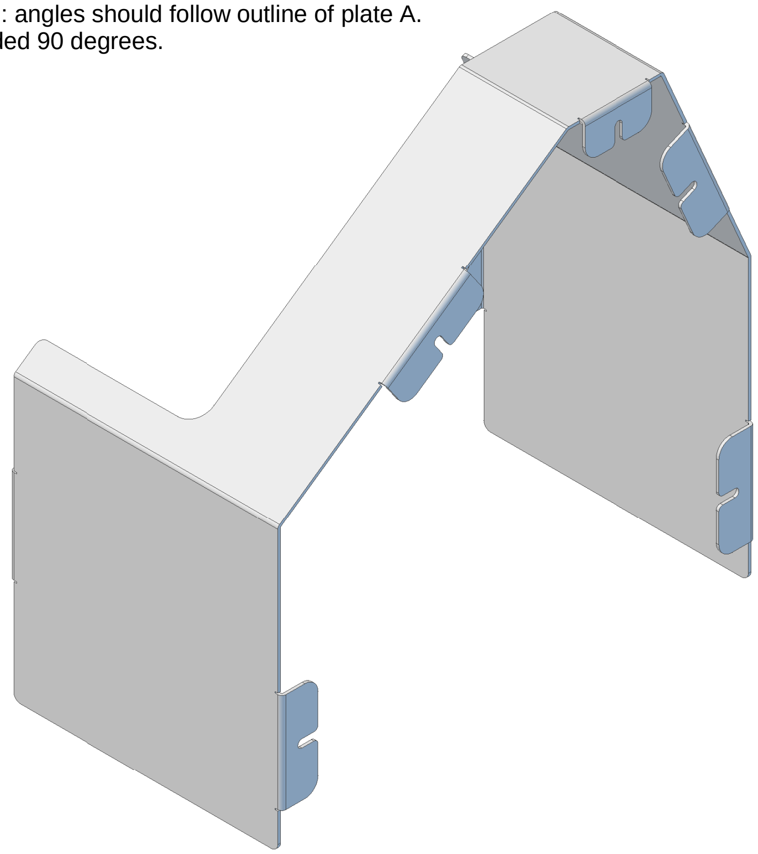
PRACTICA FOUNDATION

Sheet metal bottom (0)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	005	1:4	A4



Angels given as indication.
For practical application: angles should follow outline of plate A.
Flanges should be bended 90 degrees.



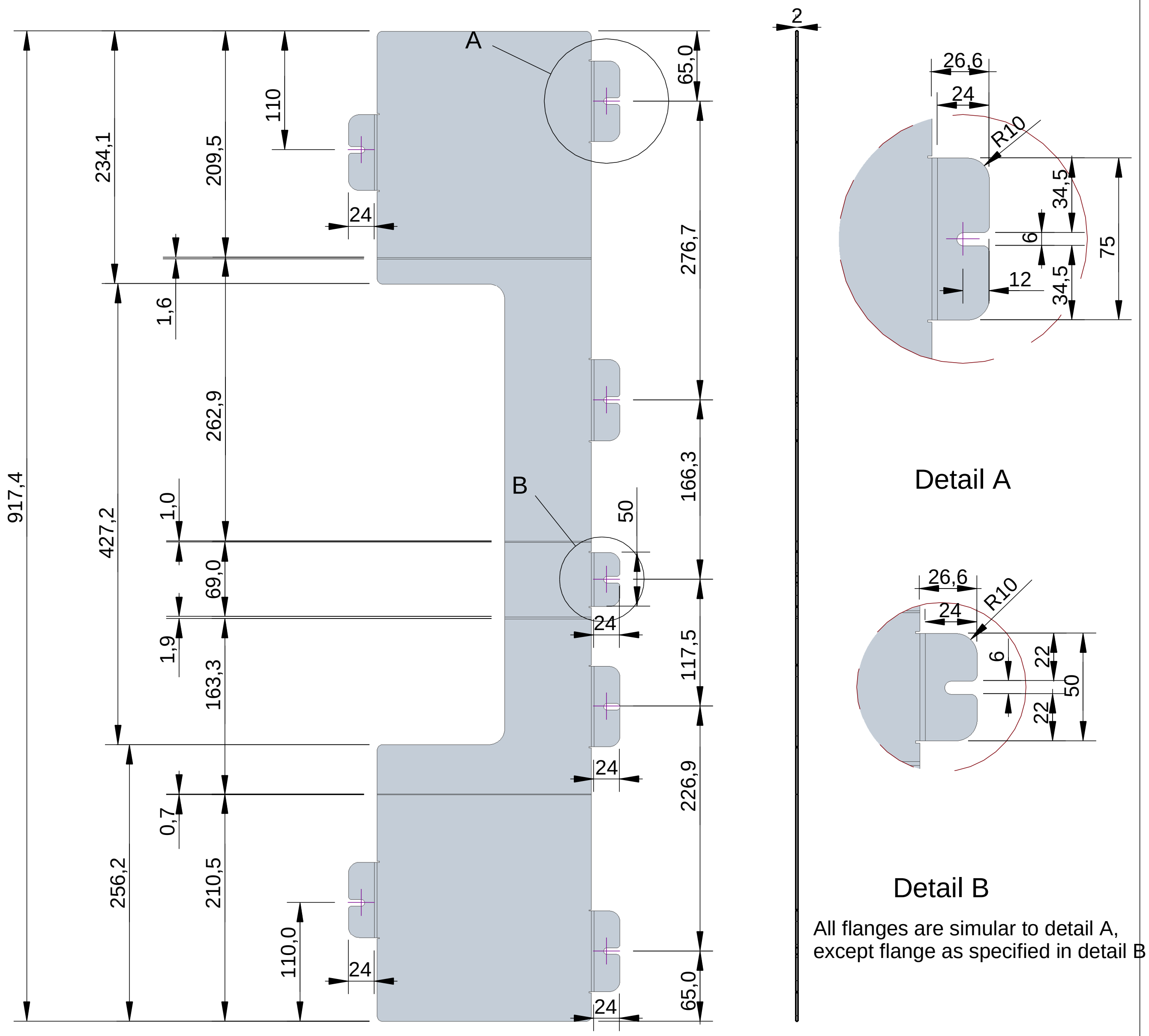
Nr	Name - material - amount needed

PRACTICA FOUNDATION

Sheet metal top (0)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	006	1:4	A4

1	2	3	4



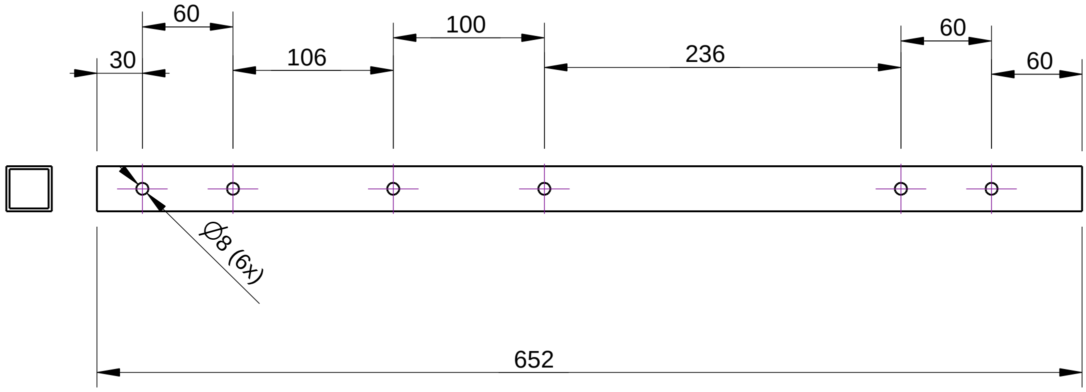
All flanges are simular to detail A, except flange as specified in detail B

Nr	Name - material - amount needed
01	Sheet metal top - steel 37 - 1

PRACTICA FOUNDATION

Sheet metal top (1)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	006.1	1:6	A4

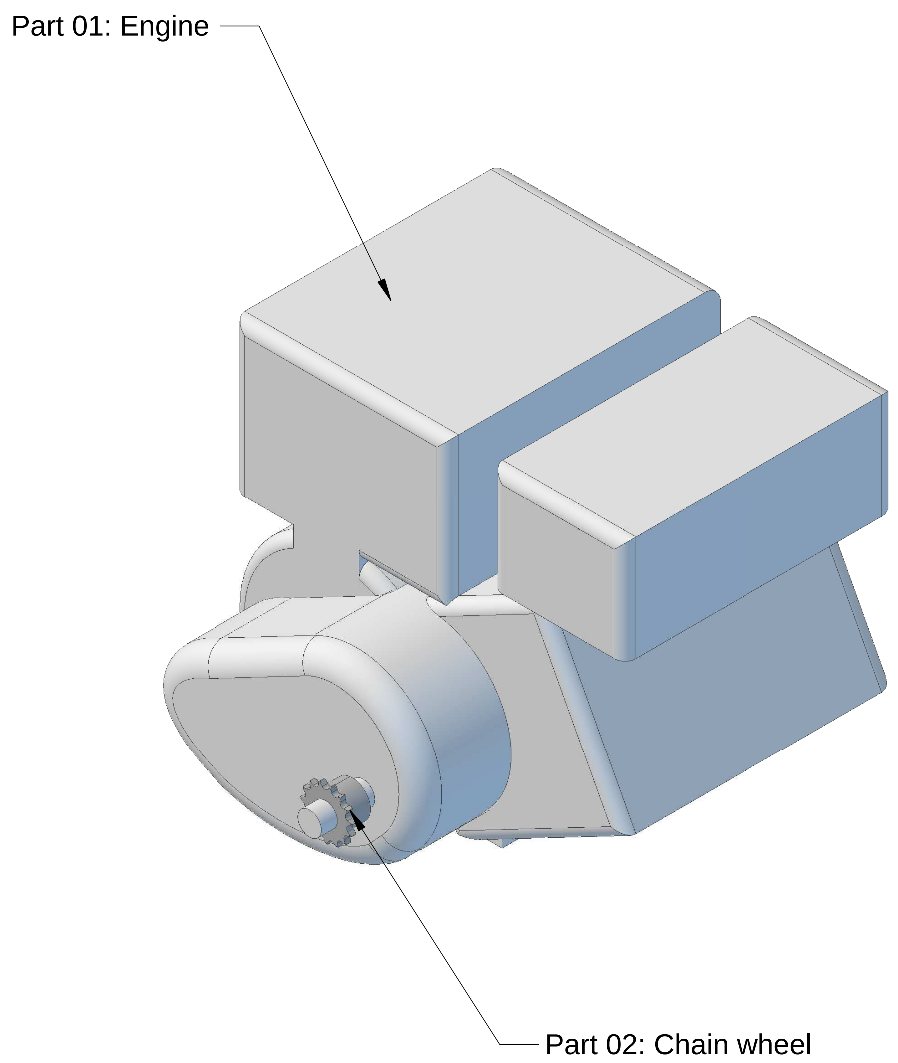


Nr	Name - material - amount needed
01	Connector rod - steel 37 - 2

PRACTICA FOUNDATION

Connector rod (0)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	007	1:5	A4



Nr	Name - material - amount needed

PRACTICA FOUNDATION

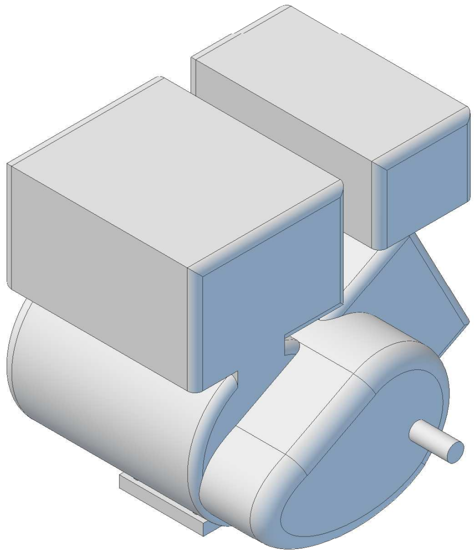
Engine (0)

Drawn by:	Date:	Version:	Dwg no.	Scale	
Ilja van Kinderen	Sept 2014	Draft 1.0	008	1:5	A4

1	2	3	4

A B C D E F

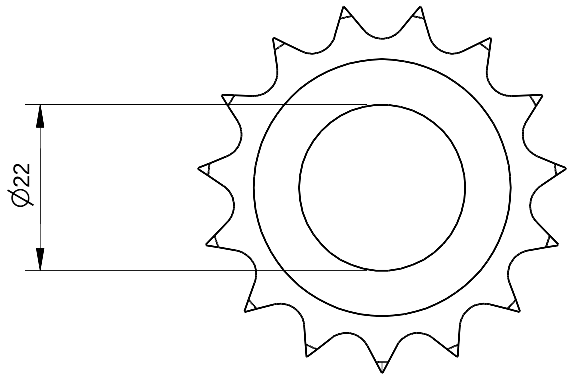
01: Engine

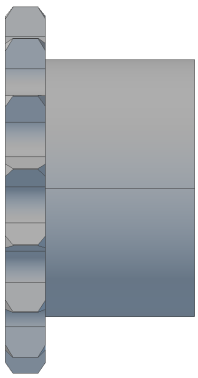


SCALE 1:7

Off-the-shelf PTM200Pro engine with 1:2 centrifugal clutch reduction.

02: Chainwheel





SCALE 1:1

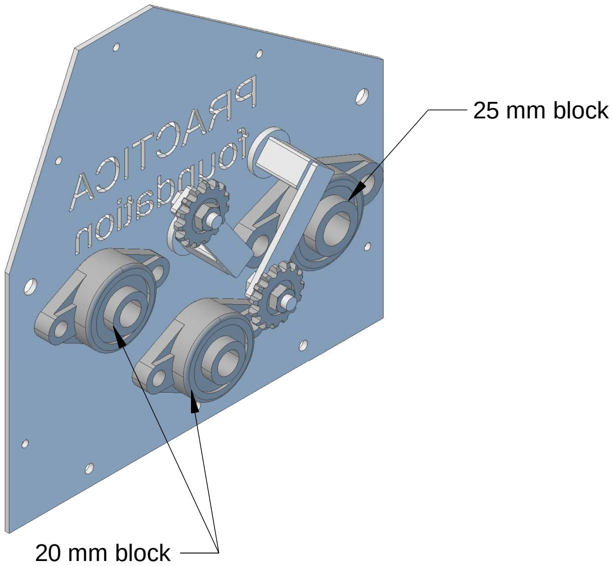
Chainwheel suitable for 3/8" 7/32" chain. 15 teeth.
Diameter center hole based on axis PTM engine.

Nr	Name - material - amount needed
01	Engine - n.a. - 1
02	Chainwheel - n.a. - 1

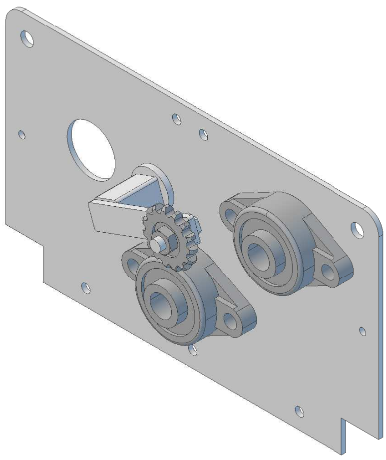
PRACTICA FOUNDATION

Engine (0)

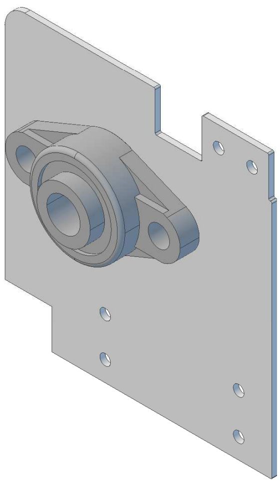
Drawn by:	Date:	Version:	Dwg no.	Scale	A4
Ilja van Kinderen	Sept 2014	Draft 1.0	008.1		



STEP 1
Bolt 2 bearing blocks for the 20 mm axis to plate A. Use M12x30 bolts.
Bolt 1 bearing block of the 25 mm axis to plate A. Use M16x30 bolts.
Bolt 2 chain tenstioners to plate A using M6x25 bolts.



STEP 2
Bolt 2 bearing for the 20 mm axis to plate B. Use M12x30 bolts.
Bolt 1 chain tenstioners to plate B using M6x25 bolts.

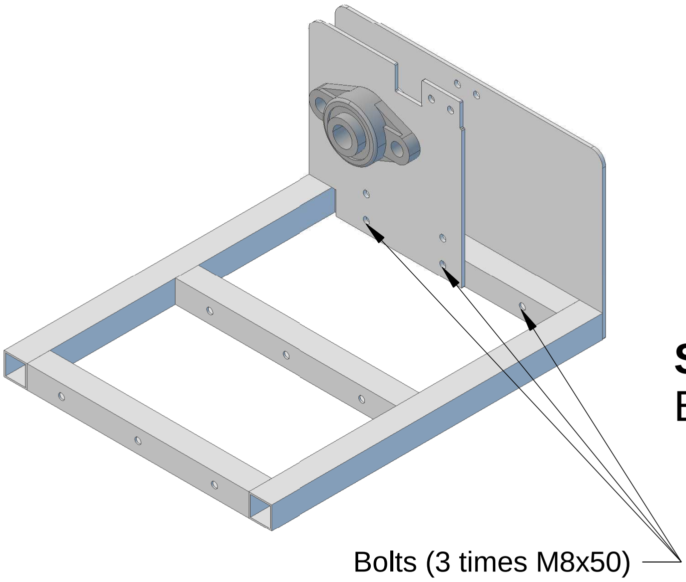


STEP 3
Bolt 1 bearing block of the 25 mm axis to plate D. Use M16x30 bolts.

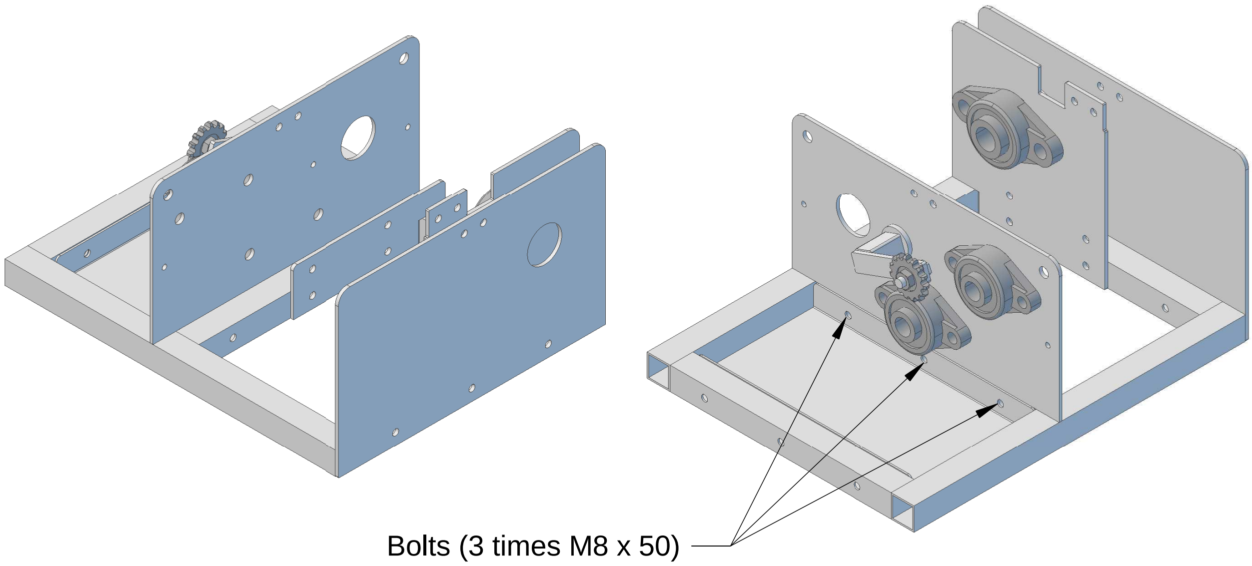
Note: Spring washers or nyloc nuts are advised for all nuts used in the complete assembly..

PRACTICA FOUNDATION		Assembly guide (1)		
Drawn by: Ilja van Kinderen	Date: Sept 2014	Version: Draft 1.0	Dwg no.	Scale	A4

1	2	3	4

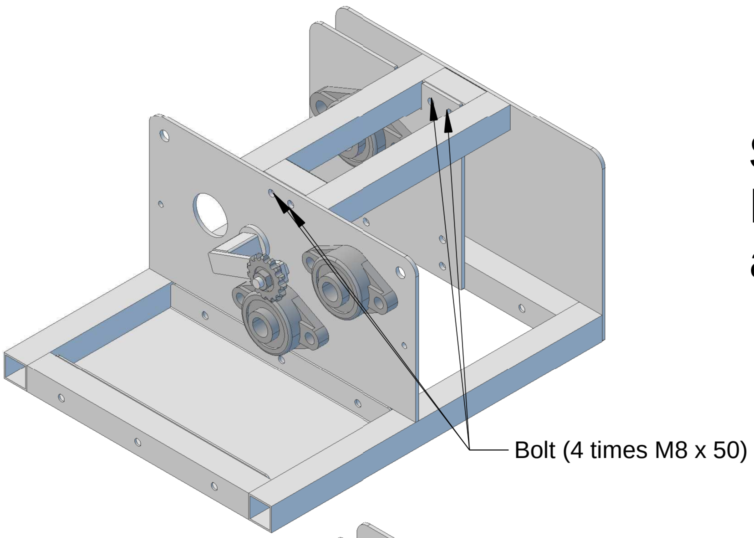


STEP 4
Bolt Plate D and E to the frame.

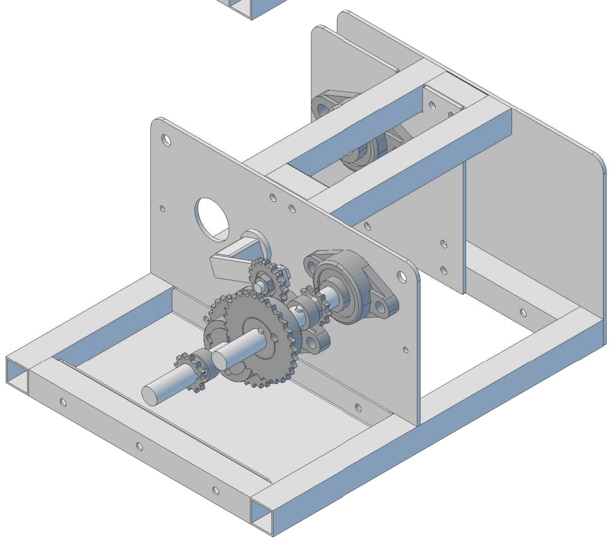


STEP 5
Insert the bottom plate gearbox in the frame together with plate B.
Bolt Plate B and C to the frame.

		PRACTICA FOUNDATION	Assembly guide (2)	
Drawn by: Ilja van Kinderen	Date: Sept 2014	Version: Draft 1.0	Dwg no.	Scale	A4

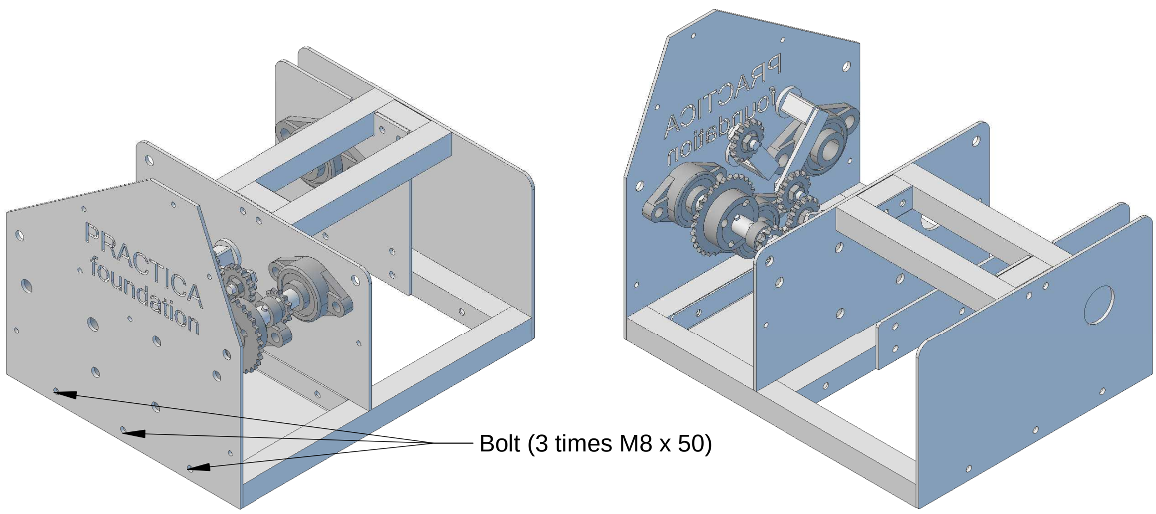


STEP 6
Bolt the motor frame to the assembled frame



STEP 7
Insert assembled 20 mm axes in the bearin blocks.

STEP 8
Insert axes in bearing block of Plate A
Bolt Plate A to assembled frame.

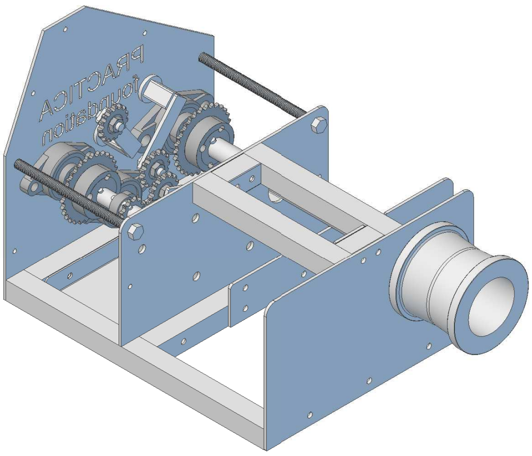


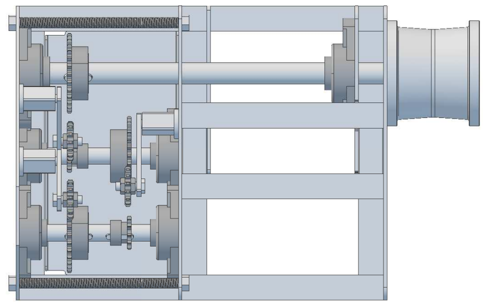
Assembly guide (3)

Drawn by:	Date:	Version:	Dwg no.	Scale	A4
Ilja van Kinderen	Sept 2014	Draft 1.0			

STEP 9

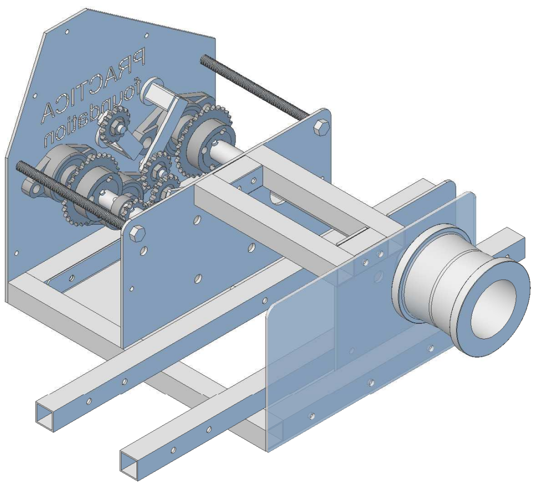
Insert 25 mm axis with Capstan assembled.
Place chainwheels on axis it before fastening.
Make sure all chainwheels are nicely alligned.
Place threaded rods (2x).





STEP 10

Place frame connector rods on assembled frame.
Rods are bolted to frame C and D.

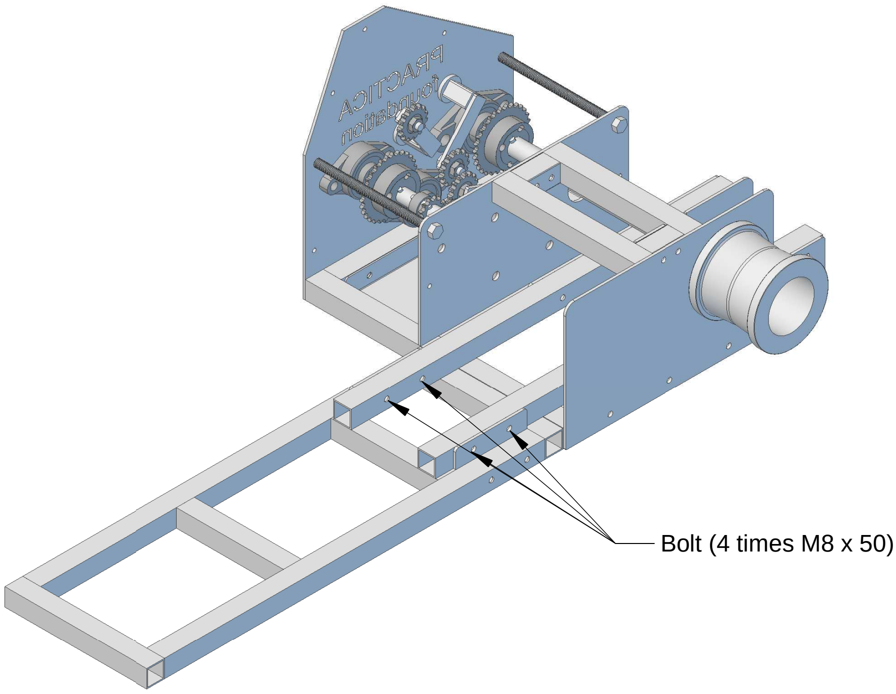


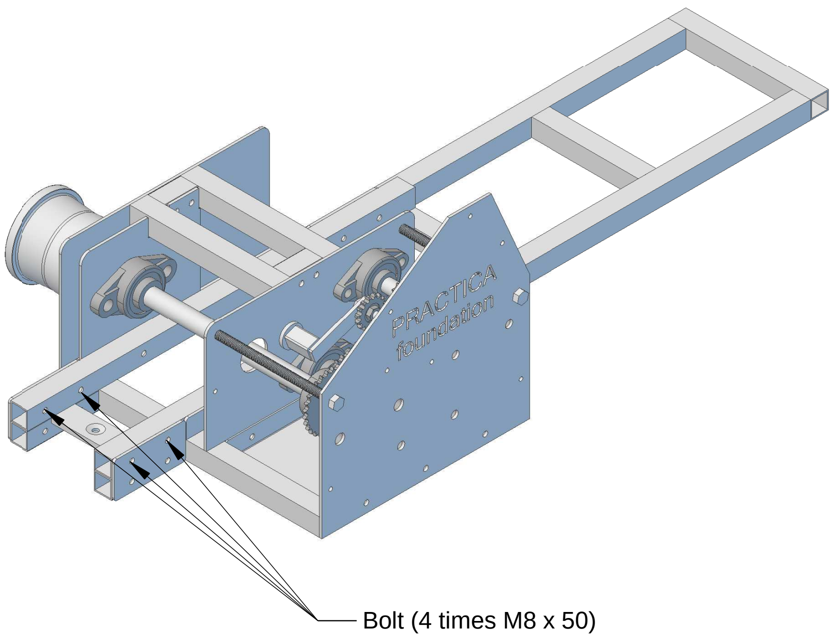
PRACTICA FOUNDATION

Assembly guide (4)

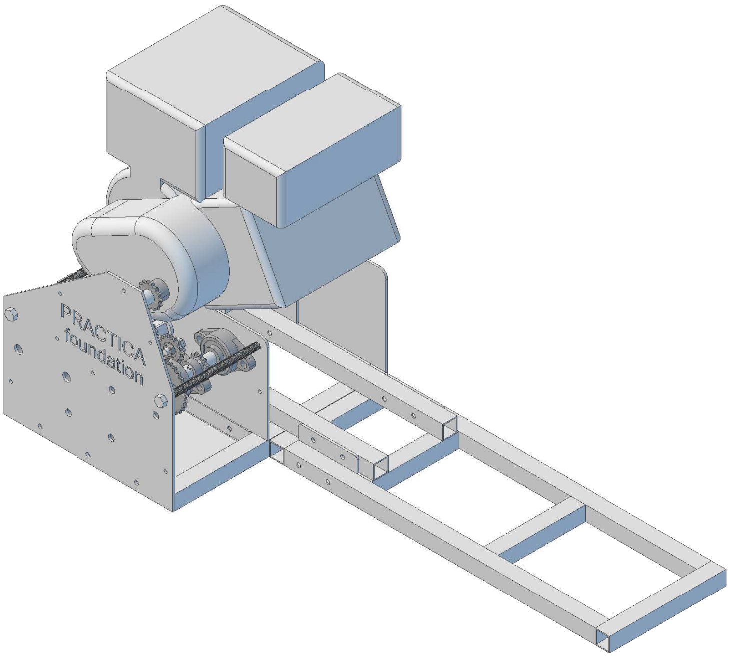
Drawn by:	Date:	Version:	Dwg no.	Scale	A4
Ilja van Kinderen	Sept 2014	Draft 1.0			

STEP 11
Attach Counterweight frame and Tripod frame

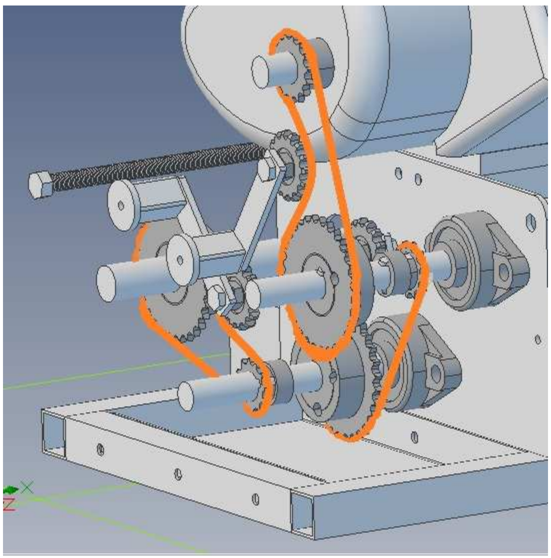




		PRACTICA FOUNDATION	Assembly guide (5)		
Drawn by: Ilja van Kinderen	Date: Sept 2014	Version: Draft 1.0	Dwg no.	Scale	A4



STEP 12
Place motor on motorframe. No detailed drawings are supplied for this step as every engine has other dimensions. Additional flanges might have to be welded on the engine frame.
Place the engine as such that the chainwheel is inline with the chainwheel it will be connected to. Connect the chainwheels with a 3/8" x 7/32" chain. The lower picture shows the way of connecting. Fasten the chaintensioners.



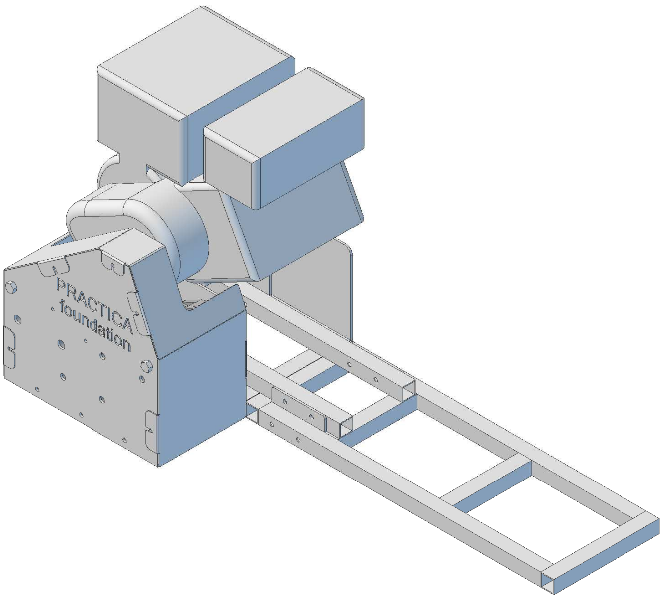
PRACTICA FOUNDATION

Assembly guide (6)

Drawn by: Ilja van Kinderen	Date: Sept 2014	Version: Draft 1.0	Dwg no.	Scale	A4

STEP 14

Put the cover over the reduction box and fasten itwith wing nuts.



Drawn by: Ilja van Kinderen	Date: Sept 2014	Version: Draft 1.0	Dwg no.	Scale	A4

Appendix 2

Cost calculation fabrication

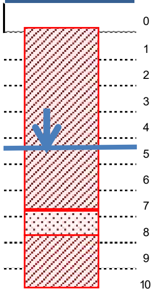
I. Capstan kit		Cost (€)
(A).Capstan materials	Engine & Clutch reduction	793,75
	Sheet metal top & bottom	15,13
	Frame	31,13
	Bearing block	100,00
	Chain tensioner 15teeth	37,50
	Axis	12,50
	Chainwheel	92,19
	Capstan (drum)	48,44
	Bolt and others	35,31
	Material cost (A).	**1.165,94**
(B).Percussion materials	Tripod & pulley	114,13
	Bailer	19,69
	Percusion bit	59,38
	Rope, shackle, hook…	39,82
	Material cost (B).	***233,01***
(C).Labour	Man power (13manpower/day)	89,38
	Workshop operating cost (hire lathe machine, other...)	131,25
	Profit margin of the Workshop (35%)	566,85
	Labour cost (C)	***787,48***
Total cost (A+B+C)		**2.186,43€**

Appendix 3: Drill logs

Manual percussion

Profil lithologique

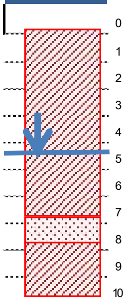
N° Identification	Capstan Test2	Technique:	Manual Percussion
Commune:	Ambohimanambola	Diam (mm):	
Localité:	Forage test 0	L tube plein (m):	
Durée	11 jours	NS (m):	3,5
Pre-casing	no	Débit (litres/min):	



Soil type	Duration (day)	Depth (mètre)	Soil description	Hard/tender fine/coarse	Color(s)
		0	TN		
	5,5j		Latérite	Hard/Coarse	red/Brown
			Clay+Sand	Tender/fine	
		7,5	Clay+Sand (Mica)	Hard/fine	
	4j	8,5	Sand (S1) +Clay + Quartzi	Hard/fine	
	1,5j	10,0	Clay + Mica	Hard	

Obervations
From 7,5m: hard layer. Slow progression: 0,25m of progression per day. We decided to stop the drilling at 10m (layer of consolidated clay). The drillers are exhausted and demotivated.

Legend	
Permeable	Static level
Semi permeable	
Impermeable	

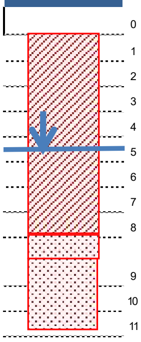


Soil type	Duration (day)	Depth (mètre)	Soil description	Tools used	daily performance based on layers
		0	TN		
	5,5j		Latérite	Hand auger	0,5 day to make 2m => 0,4m/ hour
			Clay+Sand	Hammer bit Bailer	5 days to drill 5,5m => 1,1m/ day
		7,5	Clay+Sand (Mica)		
	4j	8,5	Sand (S1) +Clay + Quartzite		4days for 1m => 0,25m/day
	1,5j	10,0	Clay + Mica		1,5 days for 1,5m => 0,75m/day

Percussion with capstan

Profil lithologique

N° Identification	Capstan test3	Technique:	percussion with Capstan
Commune:	Ambohimanambola	Diam (mm):	
Localité:	Forage test 0	L tube plein (m):	
Duréé	6,5days	NS (m):	5,5
Pre casing	Yes	Débit (litres/min):	



Soil type	Duration (day)	Depth (mètre)	Soil description	Hard/tender fine/coarse	Color(s)
		0	TN		
	4,5j		Laterite	Hard/coarse	red/Brown
			Clay+Sand	Tender/fine	
		8,5	Clay+Sand (Mica)	Hard/coarse	
	0,5j	9,0	Consolidated formation (Quartzite)		White/yellow
	1j	10,7	Sand S2 + Clay+ Mica		

Obervations

From 4,5m: acquifer: The free fall is stoped by the water. Use of pre-casing at 5m (dans l'aquifère)
Layer of quartzite at 8,5m till 9m: 0,5m of progression/ half a day
We stop the drilling at 10,7m because of the slow progression due to the Buoyancy

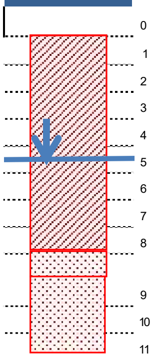
Légende

Perméable

Semi perméable

Imperméable

Static level

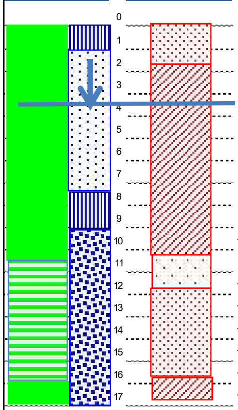


Soil type	Duration (day)	Depth (mètre)	Soil description	Tools used	daily performance based on layers
		0	TN		
	4,5j		Laterite	Hand auger	0,5 day to make 2m => 0,4m/ hour
			Clay+Sand		4 day to drill 6,5m => 1,625m/ day
		8,5	Clay+Sand (Mica)	Hammer bit + bailer + Capstan	
	1j	9,0	Consolidated formation (Quartzite)		1m/ day
	1j	10,7	Sand S2 + Clay+ Mica		1 day to make 1,7m => 1,7m/day

Rotary jetting and rota-sludging combined with capstan

Profil lithologique

N° Identification	Capstan test3	Technique:	Combinaison (Jetting+sludge+capstan)
Commune:	Ambohimanambola	Diam (mm):	140
Localité:	Forage test 1	L full pipe (m):	11,5
GPS:	X Y	L screen (m):	5,5
Duration	9,5 days	Water table (m):	3,5
Pre-casing	No	Yield (litres/min):	5



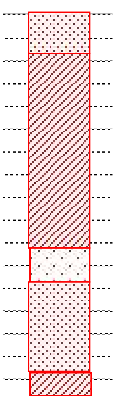
Duration (day)	Depth (meter)	Soil description	Hard/tender fine/coarse	Couleur(s) du sol
	0,0	Tn		
	2,0	laterite	tender/fine	red/brown
		Clay	tender/fine	red/brown
3 days	10,5	Clay+Mica	Hard/fine	red/brown
1,5 days	11,5	Quartzite	Hard/coarse	red/white
3 days	15,5	Sand (S2) with clay+Mica	Hard/coarse	Green/white; yellow/white
2 days	16,5	Clay+Mica	Hard/fine	yellow/white

Obervations

- Rotary jetting technique is used until 10.5m. Adding a weighted pipe
- Introduction of the capstan engine to lift the heavy drilling pipe at 10,5m
- the water still turbide after 8h of developpment (Mica in the water)
- With Rota sluge + Rotary jetting alone, we would have given up drilling at 10.5m.

Légende

Perméable	gravel pack	Plain pipe
Semi perméable	Seal	filter Screen
Imperméable	Back fill	Water table



Duration (day)	Depth (meter)	Soil description	Hard/tender fine/coarse	Techniques used	daily performance based on layers
	0,0	Tn			
	2,0	laterite	tender/fine	Hand Augering	0,5 day to make 2m => 0,4m/ hour
		Clay	tender/fine	Rotary Jetting	3 days to make 8,5m => 2,8m/day
3 days	10,5	Clay+Mica	Hard/fine	Rotary Jetting	
1,5 days	11,5	Quartzite	Hard/coarse	Combination of Tecniques with Capstan	1,5 days to make 1m => 0,6m/day
3 days	15,5	Sand (S2) with clay+Mica	Hard/coarse	Combination of Tecniques with Capstan	5 days to make 5m => 1m/day
2 days	16,5	Clay+Mica	Hard/fine	Combination of Tecniques with Capstan	

Appendix 4: Cost calculations

Labour cost

Assumptions made:

- labour cost per worker per day: €3,50

Consumables

Consulables exist of petrol, oil and rope. The petrol consumption was measured. A petrol price of 1,60 euro per liter was assumed. A 10% cost increase was added to cover the oil cost. The following table gives the overview of the petrol and oil costs.

Petrol & oil cost			
	Liter petrol per meter drilled	*cost (euro) per liter petrol plus 10% oil*	*euro per meter*
Manual percussion soft	0	1,6	0
Manual percussion hard	0	1,6	0
Percussion with capstan soft	0,6	1,6	0,96
Percussion with capstan hard	0,9	1,6	1,44
Sludging/jetting with capstan soft	0,5	1,6	0,80
Sludging/jetting with capstan hard	1,85	1,6	2,96

For the price calculation of the rope limited data was available. It was indicated in the field trial that for manual percussion a rope would last for 6 wells and for the mechanized version of percussion the rope would last for 3 wells.

Firstly the cost of the rope per well was determined based on the cost price of a full length of rope (36 euro). It was assumed the soil formation would exist of 16 meter ‘soft formation’ and 1,5 meter ‘hard formation’. Based on this date the hours needed through these formations were calculated per method. The percentage of time used for penetrating the layer was used to calculate the cost of the rope for that particular layer assuming a constant wearing of the rope.

For the use of the capstan in combination with rotary jetting there was no proper data available. Therefore it was assumed to be tripe the price of the cost of the rope used during percussion given the higher weight and longer drilling time.

	Cost of rope	Length formation		Time to drill		Percentage		Cost of rope absolute		Cost of rope per meter	
	per well	*soft formation*	*hard formation*	*soft formation*	*hard formation*	*soft formation*	*hard formation*	*soft formation*	*hard formation*	*soft formation*	*hard formation*
manual percussion	6	16	1,5	14,5	6	0,7	0,3	4,2	1,7	0,27	1,17
capstan percussion	12	16	1,5	10	1,5	0,9	0,1	10,4	1,5	0,65	1,04
jetting percussion										0,00	3,13

Depreciation hardware

The following table shows the investment costs per kit used in the field.

Kit	Investment cost	Description hardware
Manual percussion	365	Bailer bit, tripod, pulley
Percussion with capstan	2200	Manual percussion set plus capstan kit
Jetting kit	1750	Jetting kit
Sludging/jetting with capstan	3750	Capstan kit plus jetting kit plus tripod

To determine the depreciation cost it was assumed that drilling in the hard formation will depreciate a kit 5 times faster than drilling in a soft formation. The assumption was that a kit would last 25 wells drilling in a soft formation. It was assumed one well is about 20 meters deep to come to a figure of depreciation cost per meter. The following table shows the cost overview.

Method	Investment cost (euro)	Depreciation (nr wells)	Average depth well (m)	Depreciation cost per meter (euro)
Manual percussion soft formation	365	25	20	0,73
Manual percussion hard formation	365	5	20	3,65
Percussion with capstan soft formation	2200	25	20	4,4
Percussion with capstan hard formation	2200	5	20	22
Jetting soft formation	1750	25	20	3,5
Jetting hard formation	3750	5	20	37,5