VAASAN AMMATTIKORKEAKOULU
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THE TRANSMISSION LINE COST CALCULATION TOOL

For medium voltage

Technology and Communication

2017

FOREWORD

This thesis is made for Wärtsilä - Energy Solutions -department as part of Electrical Engineering studies in Vaasan ammattikorkeakoulu, University of Applied Sciences.

I would like to thank my thesis supervisor Jani Aurell (Senior Chief Project Engineer) and Toni Hyytinen (Installation Cost Estimator) from Wärtsilä who offered me opportunity to do this work. I would also like to thank Olavi Mäkinen (Principal Lecturer) who acted as my mentor from VAMK, University of Applied Sciences. Special thanks goes to my brother Mikko Mäkinen who sacrificed a lot of his limited spare time for helping me with the VBA - Excel Macro programming.

Furthermore, I would like to thank Jarmo Leppinen from Vaasan Sähkö Oy for the meetings we had. I received a lot of professional information from him which could not be found in books or on the internet. Also thanks to Timo Mutila and his colleagues from HeadPower for offering the student license for their databases.

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Vaasa, Finland, 12.01.2017,

Jallu Mäkinen

VAASA UNIVERSITY OF APPLIED SCIENCES
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ABSTRACT

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Today, competition is tough in almost every sector of technology. That is also the case with power production facilities. At the beginning of the project a manufacturing company should be able to define the budget for the project and also the profit margin. The scope of Wärtsilä power plant delivery may also include a transmission line from the power plant to the grid. The purpose of this thesis was to create an editable cost calculation model for the medium voltage line.

The calculation model was designed for small production plants; mainly solar and wind power plants in about 1-30 MW size range. Power in this scale can be transferred optimally with medium voltage within a few kilometers. The model was applied to be very customable; for example clearing, foundations, wiring and pole types can be customized as desired. The basic design of the tool is based on the practices in Finland. The reason for this is that it would have been impossible to create a country-specific solutions for every situation.

With the calculation model it is possible to create a have technical basis for the tendering stage. In the future there is a possibility to extend the tool with the country based settings if desired. For example the prices for materials and for work are customizable. The study was used to assess which solution is economically cost-effective to be accomplished in a specific case.

The construction of the adjustable model was successful and the documentation came fairly coherent and comprehensive.

Keywords Medium voltage, transmission line, cost calculation, power

VAASAN AMMATTIKORKEAKOULU
Sähkötekniikan koulutusohjelma

TIIVISTELMÄ

Tekijä	Janne ”Jallu” Mäkinen
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Tänä päivänä kilpailu on kovaa lähes jokaisella tekniikan alalla, niin myös voimalahankkeissa. Aina hankkeen alussa on tarjousvaihe jolloin yhtiön pitäisi pystyä arvioimaan kokonaiskustannus projektille sekä voittomarginaalit. Wärtsilän voimalatoimituskokonaisuuteen saattaa kuulua myös siirtolinja voimalalta verkkoon. Tämän työn tarkoituksena on ollut luoda muokattava kustannuslaskentamalli rakennettavalle siirtolinjalle.

Laskentamalli on suunniteltu pienemmille laitoksille; pääasiassa aurinko ja tuulivoimaloille kokoluokkaa 1-30 MW. Tämän kokoluokan tehoja voidaan siirtää keskijännitteellä optimaalisesti muutamia kilometrejä. Malliin on sovellettu erilaisia raivaus-, perustus-, johdin- ja pylvästyyppejä eli se on hyvin laajalti muokattavissa. Laskentamallin ratkaisut perustuvat suomalaiseen rakennustapaan. Syy tähän on, että maakohtaisia eroja on niin paljon, että niitä olisi ollut mahdoton sisällyttää työhön.

Laskentamallin tarkoituksena oli luoda tekninen perusta keskijännitelinjan rakennuskustannuksille tarjousvaiheessa. Tulevaisuudessa laskentamallin asetuksia voidaan muokata eri maihin sopivaksi. Muun muassa materiaali- sekä työhinta ovat säädettävissä. Opinnäytetyön avulla voidaan arvioida, mikä rakennusratkaisu on taloudellisesti kannattavaa toteuttaa missäkin tilanteessa.

Säädettävän mallin rakentaminen onnistui hyvin ja dokumentaatiosta tuli kohtuullisen johdonmukainen sekä kattava.

Avainsanoja Keskijännite, siirtolinja, kustannuslaskenta, teho

LIST OF TERMS AND ABBREVIATIONS

A	Ampere
AC	Alternative Current
CLD	Current Limiting Device
DC	Direct Current
HV	High Voltage
Hz	Hertz
I_N	Nominal Current
kV	Kilo Volt
kW	Kilo Watt
LV	Low Voltage
mm^2	Square Millimeter
MV	Medium Voltage
MVA	Mega Volt Ampere
MW	Mega Watt
MWh	Mega Watt Hour
OHL	Overhead line
PAS	Covered conductor
PEX / XLPE	Cross-linked polyethylene, plastic
S	Apparent power
s	length, distance
UV	Ultraviolet
V	Volt
VA	Volt Ampere
VAT	Value-added tax
VAMK	Vaasa University of Applied Sciences
VBA	Visual Basic for Applications, Excel macro software

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* Has been deleted from the public version due to sensitiveness.

1 INTRODUCTION

This chapter will introduce the company which provided the subject, the background and the main objective of the thesis.

1.1 Wärtsilä

Wärtsilä was established in 1834. That time it started to work as a sawmill but 17 years later the iron mill was built in the place of sawmill. Wärtsilä's operation in Vaasa started in 1936 and around the same time the company started to manufacture licensed diesel engines. /1/

Wärtsilä's business has been divided to three main partitions: Marine Solutions, Energy Solutions and Services. Marine Solutions (Ship Power) are focused on marine duties from cruises all to way to navy ships. Energy Solutions (Power Plants) covers oil and gas energy production technologies which can be nowadays working together with solar and wind technologies. Services takes care of the installations, spare parts, services and operations in the marine and energy sectors. /1/

Wärtsilä's net sales totaled 5.0 billion euros and the number of employees was 18 800 in 2015. The company has operations in more than 200 locations in nearly 70 countries around the world. Wärtsilä has been noted in NASDAQ with its share value of 42 € at the end of 2016. /1/

1.2 The Thesis

This chapter shortly introduces the objectives of the thesis, borders and limitations for the beginning and what has been already done by the other parties.

1.2.1 Background

Wärtsilä manufactures power plants. Sometimes customers can request additional items besides the plant itself. These kind of items can be deal breaker questions to the customer and that is why Wärtsilä might be required to offer more than their core business is focused on. /2/

There have been cases where customers request a connection line between the manufactured power plant and the main transmission or a distribution line. In other words, the requested connection line needs to be included in the power plant project. This way Wärtsilä is responsible for the whole project which reduces the stress and workload of the customer. The term for this kind of policy is a *turnkey contract*. /2/

Citec Oy has made a selector tool for ground cables. A former VAMK student Juho Yli-Hannuksella has done a cost calculation tool for high voltage line. My assignment is to do the same for the medium voltage line. /2/

1.2.2 Objective

The purpose of this thesis is to create a cost calculation tool for the medium voltage overhead line. This tool would be used at the tender stage to define the price for the MV OHL. The tool should be simple enough for smooth and effortless operation but at the same time include enough characteristics in order to produce price estimations as accurate as possible. Formability is also a significant feature of the tool. /2/

The other benefit of the tool is that it produces a list of the basic components which are needed for the power line. That could be an advantage at the tender-stage, because the customer can be offered at least an idea what would actually be included in the power line. By common sense it is a lot of more valuable than just a plain price estimation. Further designing is always done with terrain and more detailed info. /2/

The bottom line is that the tool offers a reasonable basis for MV transmission line budgeting.

1.2.3 Restrictions

At the beginning of this project some restrictions were made:

- Tool design is based on the Finnish transmission line building materials and practices.
- Voltage level limited between 6-45 kV.
- Power to transfer usually about 5-30 MW.

Figure 1 indicates in red which part of the system is studied. At first the electric power is generated in the power plant. Then the voltage is raised in the transformer to an appropriate level for the power transmission. After the transmission, close to the destination, the voltage level is decreased and power is distributed to the customers. This study focuses only on the transmission part.

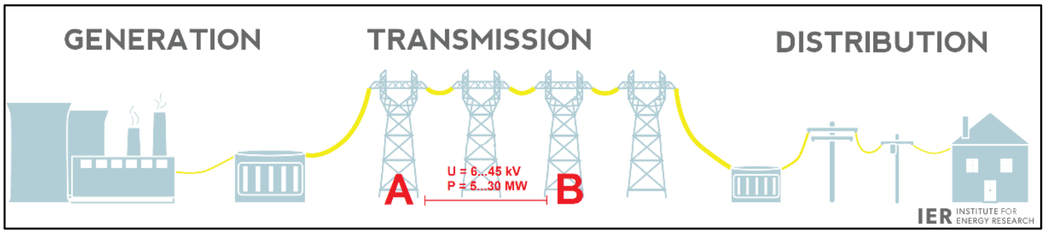

Figure 1. Connection between power plant and local grid. /4/

During the thesis some other restrictions were made which are listed here:

- Conductor types: ACSR / AAC / PAS, since they are the most common.
- Tower type: (Steel) pole, since it is used widely around the world with medium voltage. Lattice steel towers are used more often with high voltage.
- Maximum length of the line: This is defined by the voltage drop, power loss or the price by the user.
- Model does not take into account:
  - Mechanical load calculations with conductors and poles
  - Short-circuit calculations
  - Grounding of the poles
  - Pole height and span relation
  - Volume discounts with materials and work

Deeper explanations for these selections can be found in the report. It is noteworthy that during the making of the thesis some other minor restrictions also had to be set. All these are discussed in the document.

2 CALCULATION PRINCIPLES

2.1 Voltage Level

Medium voltage is defined to be between 1-36 kV by Finnish standards. In Finland the most common medium voltage level is 20 kV, but there are also some relatively rare areas with 10, 33 and 45 kV level. This analysis will focus on the voltage levels between 6-45 kV as it can be seen as a common medium voltage level range in different literature. /3/

2.2 Power Losses

According to the Ohm's Law, power losses are directly proportional to the square of the current (Formula 1):

$$P_{loss} = 3 * R * I^2 \qquad \text{(Formula 1)}$$

Where:

P_{loss}	3-phase power loss (W)
R	Resistance (ohm)
I	Current (A)

When the transferred power increases, the voltage should also be higher to reduce the current. As seen in Formula 1, by reducing the current the transmission power losses will also reduce greatly. Reducing the current is possible by increasing the voltage level.

Energy loss economy is not taken into account in this analysis as a separate subject. In this analysis the principle is that the power losses are reasonable when the voltage drop stays under the user defined value. However, the calculation tool is capable to calculate both: power losses and energy losses and its cost per year. /5/

2.3 Voltage Drop

Conductor impedance causes a voltage drop to the line. Manufacturers inform resistance and reactance values for their conductors. With these data the voltage drop can be calculated for the specified line length. The voltage drop for MV is not specified separately, but a good reference value could be 3-7 %. What is important is that the furthest end-customer's voltage meets the requirements. /6/

The voltage drop for one phase can be calculated with the Formula 2.

$$U_{drop} = \frac{P}{\sqrt{3} * U_N * cos\phi} * (R * cos\phi + X * sin\phi) \qquad \text{(Formula 2)}$$

Where:

U_{drop}	Voltage drop in kilovolts (kV)
$\cos\phi$	Power factor
P	Active power (MW)
U_N	Nominal main voltage (kV)
R	Resistance of the conductor (ohm)
X	Reactance of the conductor (ohm)

Below is an example of voltage drop calculation (Figure 2). There are other ways to calculate the voltage drop more precisely, but in this voltage level and distance this method is enough. The relative voltage drop is defined at the end of calculation.

Initial datas:

ACSR Sparrow 34mm^2

conductor lenght (km):	$s := 3$
conductor resistance (ohm/km):	$r := 0.882$
conductor reactance (ohm/km):	$x := 0.380$
Active load (MW):	$P := 3$
Cosphi of the load:	$Cos\phi := 0.9$
Nominal main voltage (kV):	$U_N := 20.0$

Calculations:

Angle (deg):	$\phi := acos(Cos\phi) = 25.8 \cdot deg$
Reactive power (Mvar): (not needed)	$Q := tan(\phi) \cdot P = 1.453$

Voltage drop for one phase (kV):

$$U_{drop.phase} := \frac{P}{\sqrt{3} \cdot U_N \cdot Cos\phi} \cdot (s \cdot r \cdot cos(\phi) + s \cdot x \cdot sin(\phi)) = 0.277$$

Voltage drop for mainvoltage (kV):

$$U_{drop.main.abs} := \sqrt{3} \cdot U_{drop.phase} = 0.48$$

Relative voltage drop for mainvoltage (%):

$$U_{drop.main\%} := \frac{U_{drop.main.abs}}{U_N} \cdot 100 = 2.3986$$

Result: Voltage drop is ~2,4 %

Figure 2. Example calculation of the voltage drop.

3 CONDUCTORS

In Finland two types of overhead lines are commonly used with medium voltage: air insulated overhead lines and plastic covered overhead lines (PAS). For both conductors the material is aluminium. Copper is not used anymore in overhead lines because it is expensive, heavy and weak compared to aluminium. When choosing the conductor the following must be taken into account:

- Voltage drop
- Loading capacity (maximum current)
- Operational reliability
- Short-circuit withstand
- Electrical safety regulations
- Economy

This analysis will focus mainly on three of these which are; voltage drop, loading capacity and also a bit of economy. Operational reliability is something that PAS conductors can offer. /3/

3.1 Bare Overhead Lines

The most common conductors used in overhead line (OHL) are air insulated. These kind of conductors are rather cheap and they are easy to extend. There are many different types of air insulated, i.e. bare conductors, for example:

- AAAC (All Aluminium Alloy Conductors)
- **AAC** (All Aluminium Conductor)
- AACSR (Aluminium Alloy Conductor Steel Reinforced)
- ACAR (Aluminium Conductor Alloy Reinforced)
- **ACSR** (Aluminium Conductor Steel Reinforced)

These different types have some differences with the durability, conductivity and other electrical and mechanical properties. This analysis will not go deeper into those differences. The most common overhead line types in Finland are ACSR, AAC and PAS and these basic options are the ones to focus on in this analysis. The PAS will be discussed in its own chapter since it is not a bare conductor. /2/

Fallen trees cause short-circuits and earth faults with bare conductors. That is why the land clearing needs to be quite wide with bare conductors as seen in Figure 3.

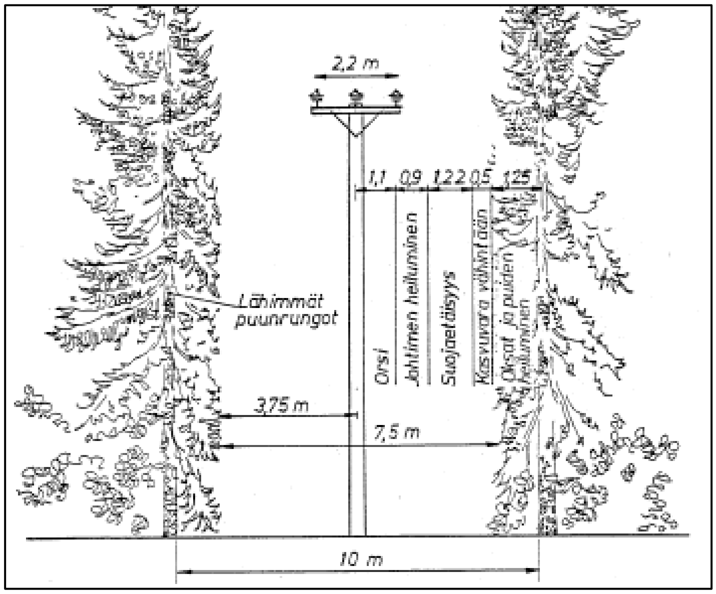

Figure 3. Needed clearance for bare overhead conductor with 20 kV. /7/

Standards for Prysmian ACSR conductors are: SFS5701, IEC61089 and EN 50182. Standards for Prysmian PAS are: SFS 5791 and EN50397-1. /16/ /17/ /18/

3.1.1 ACSR

ACSR stands for Aluminium Conductor Steel Reinforced. The core strands of the conductor are steel and outer strands are high-purity aluminium (Figure 4). The diameter and number of these strands vary for different types. The steel core offers higher strength for conductor, which allows greater mechanical tension to be applied. /10/

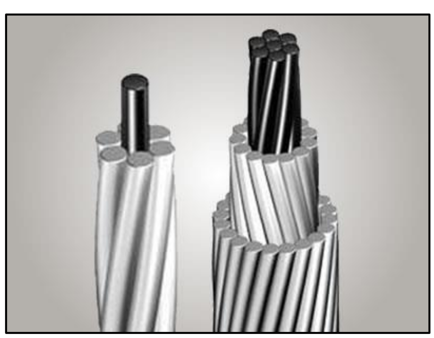

Figure 4. ACSR-conductor’s core is steel. /8/

Steel also has lower elastic and inelastic deformation properties. In some cases there may be a risk that strong wind and heavy ice loads stretch the conductors. ACSR is more suitable for these kind of environments than AAC. Also the thermal expansion coefficient is lower for steel than for aluminium. /10/

3.1.2 AAC

AAC stands for All Aluminium Conductor. This conductor type is fully made of aluminium (Figure 5). It has better conductivity than ACSR, but the mechanical strength is a bit lower.

Figure 5. AAC conductor is nothing but aluminum. /9/

AACs are used in urban area where the span is relatively short. They are also used near the sea where the air is salty and corrosive. Aluminium is highly resistant for harmful deep corrosion because it forms aluminium oxide layer on with oxygen. This layer acts as a protective shield for the material. /10/

3.2 PAS Overhead Line

In Finland overhead line with XLPE or PEX plastic cover is commonly called as PAS, but in fact the name PAS stands for a product name. Other product names for similar covered conductors besides the PAS are SAX/BLL (Finland), BLX/BLX-T (Norway and Sweden) and CC/CCT (Australia and Far East). The cover material can differ between types and region. For simplicity, the term PAS will be used in this analysis as a common name for covered conductors as it is used widely in Finnish colloquial language and literature. It is notable that with medium voltage the term “covered” implies a sheath covering only (Figure 7) and not the insulated conductor systems. /11/

The PAS overhead lines have many advantages and some disadvantages compared to regular bare overhead lines. In Finland PAS installations have some special requirements compared to the regular bare line installations. Most important of them are: /12/

- Conductors needs to be installed as ensured (tr. *varmennettu*) conductors.
- Conductors needs to be handled carefully and repairing is more difficult
- Conductor equipment needs to be approved
- Arc protection needs to be installed to the vulnerable parts of the line
- Substation needs to be equipped with tripping earth fault protection and alarming back-up protection

3.2.1 Required Clearance

The PAS line can also be installed closer to other objects, such as trees and buildings (Figure 6). In some cases, for example in forest or urban area, better operational reliability can be achieved with the PAS. In fact the PAS line passage needs only 40% of the space compared to regular air insulated line passage. /12/

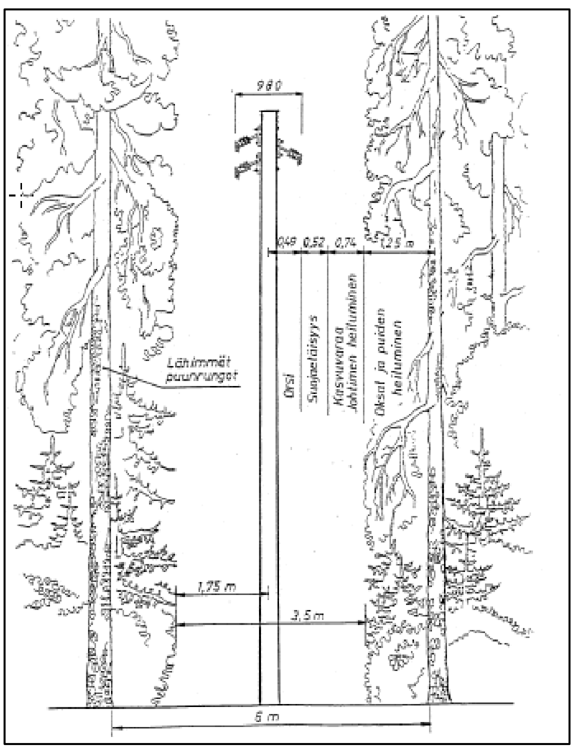

Figure 6. PAS needs less clearance. /7/

3.2.2 PAS Reliability and Safety

PAS lines can also tolerate short term touches between phase line or fallen brushwood and trees. Animals do not cause interrupts that often with the PAS. According to distribution fault statistics in Finland by using PAS overhead lines faults are reduced per year from 4.5 fault per 100 km to 0.3 fault per 100 km. /12/

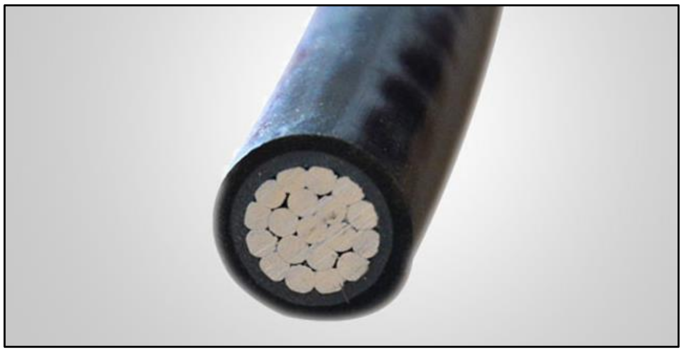

Figure 7. Covered conductor. /13/

3.2.3 Arc Flame Protection

The arc flame is generated when a lightning strikes to an overhead line or the nearby terrain. This induces an overvoltage to the conductors which is about equal in each phase. The overvoltage between the phase and ground may rise up to several hundred kilovolts. Direct lightning strikes to PAS lines are relatively rare in Finland. /12/

There are three basic methods to protect PAS line:

- Arc protection device (tr. *valokaarisuoja*)
- Power arc device (tr. *kipinävälisuoja*)
- Current limiting device (tr. *virtaa rajoittava suoja*)

The overvoltage in the conductor - caused by a direct or indirect lightning strike - discharges in the nearest cross-arm and causes an arc between the cross-arm and the conductor. With the regular air insulated conductor the arc is able to travel without restraint, but with the PAS the plastic cover prevents the travel of the arc. When the arc ignites, it burns a small hole into the plastic cover and burns on the spot until the conductor is damaged or breaks in two. The overvoltage protection installed at a proper position will offer a safe discharge pathway for the arc. /12/

The next chapters introduces these three mentioned protection methods for the PAS. Finally, it is shown that the best option for the overvoltage protection is the current limiting device, because it prevents interruptions for the supply.

Bare conductors do not need separate overvoltage protectors since they do not have insulation. Further protection discussion would need data about the background grid (tr. taustaverkko) and transformers. These matters are not in the scope of this study.

3.2.3.1 Arc Protection Device

The most simply and economic protection equipment is the arc protection device (tr. valokaarisuoja). This equipment is needed to be installed to the load side of the line. In the ring-type of network the power flow can be in either direction and in this case the arc protection device is installed for both sides as seen in Figure 8. If the load flow is only to one way, then two side installation is not required. /12/

Figure 8. PAS arc protection device. /14/

The formation of an arc flame is demonstrated in Figure 9. At the beginning the arc flame flares up over the insulator (1). It is noteworthy that with a low short-circuit current the arc movement can be quite slow at this section and it can cause stress to the insulator. Then the arc moves on along the aluminium wire, which is wound to the base of the insulator and finally to the arching horn (2). After that the arcing ionizes air, which becomes conductive (3), and causes a short-circuit between the phases (4). /12/

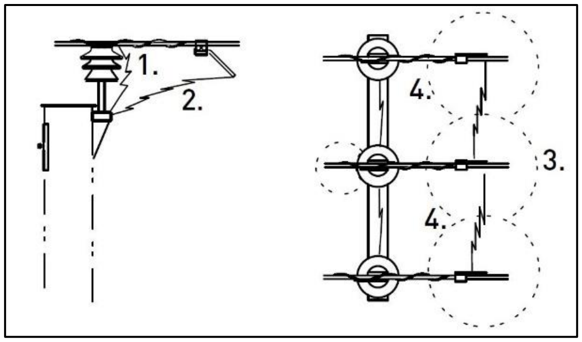

Figure 9. Operation of the arc protection device. /12/

The short-circuit activates the protection equipment in the substation and high-speed automatic reclosing (tr. pikajälleenkytkentä) happens. This means a short interruption for the electricity supply. /12/

The arching horn gaps need to be less than the gap between the phases. The arc protection device is the simplest and cheapest option for protecting the conductor, but it can be destructive for the insulator in long term. The arc protection device can handle 2-3 times 10 kA (1 s) over voltage shock and after that it must be replaced to ensure its functioning. /12/

3.2.3.2 Power Arc Device

The operation of the power arc device (tr. kipinäväli) is very similar to the previous arc protection device (tr. valokaarisuoja), but it has the flash barrier which can be seen as number 1 in Figure 10. With the power arc device the arc flame never goes over the insulator plate, so even with low short-circuit currents, the insulator itself remains undamaged. Otherwise, it works just as the arc protection device does. /12/

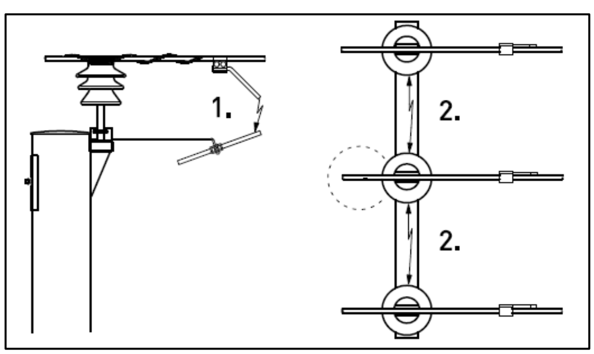

Figure 10. Operation of power arc device. /12/

The direction of the power flow does not make any difference for the installation side, as it did with the arc protection device. This means the power arc device can be installed on either side of the pole as seen in the Figure 11. /12/

Figure 11. Power arc device installation. /15/

These two protection solutions against the arc are the most economic ones and they offer protection only for the conductors. The biggest disadvantage of these two protection methods are that they always result in a short term interruption in electricity transmission. Like the arc protection device, the power arc device can also handle the same 2-3 times 10 kA (1 s) over voltage shock reliably. /12/

3.2.3.3 Current Limiting Device

The current limiting device (tr. virtaa rajoittava suoja) type of protection equipment has some advantages over the arc protection device and the power arc device. The most important is that this protection method does not cause interruption to the transmission when the lightning strikes. /12/

The current limiting device (CLD) consist of a zinc-oxide surge arrester and a power arc device which are connected in series (Figure 12). The overvoltage caused by the lightning strike goes through the zinc-oxide surge arrester and produces an arc between the spark horns. The normal operating voltage is unable to go through the protection device since the insulator has a higher withstand for spark-over voltage (tr. ylilyöntijännitekestoisuus) than the protection device with its spark gap. The arc forms a conductive pathway over the protection device and along that pathway the overvoltage is discharged to the ground. The current limiting device restrains the earth fault current followed by the arc between the spark horns. This prevents the high-speed automatic reclosing in the substation and assures electricity distribution without interrupts. /12/

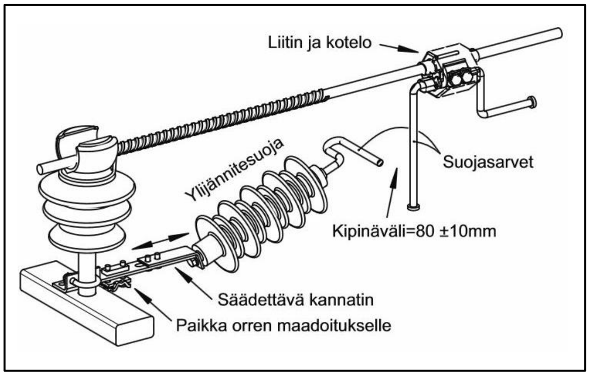

Figure 12. Current limiting device. /12/

The installation can be made on either side of the pole just like with the power arc device. The spark gap should be adjusted to 80 mm. This installation is immune to the birds, other animals and brushwood. The cross-arm must be grounded when using a current limiting protection device. The downside of this protection is that the device can be break down with high energized over voltage. /12/

3.3 Conductor Requirements

Some conductor properties which should be taken into account are presented next. The properties or limitations are from the Prysmian catalogues.

3.3.1 Voltage Level

The voltage level for the ACSR and the AAC is not limited by the conductor properties, since they do not have any insulation material which could be defected by a too high voltage. For the PAS conductors the nominal voltage level is defined to be 20 kV; however, the plastic cover is capable to withstand constant voltage of 24 kV. /16/

There are also 36 kV versions available but this analysis does not take them into account since they are not that common in Finland and would require special protection equipment. /16/

3.3.2 Temperature

The maximum continuous operational temperature for ACSR, AAC and PAS is limited to be 80 °C. That is measured from the conductor itself so ambient temperature is not limited with bare conductors. The lowest recommended installation temperature for the PAS is -20 °C limit due the fact that the plastic cover becomes brittle and fragile in cold conditions. /16/

3.3.3 Short-Circuit Current

In the short-circuit situation the conductor heats up rapidly due to extremely high current (Figure 13). The maximum short-circuit temperature and duration is always defined by the manufacturer. According to the Prysmian catalogues ACSR and PAS are capable to withstand 200 °C for temperature for 5 seconds in the fault situation. ACC conductor can withstand 160 °C for 5 seconds. The maximum short circuit current values for 1 s are usually available in the conductor datasheets. /16, 17, 18/

Figure 13. Arc at DNV GL High Power Laboratory. /19/

4 CONSTRUCTION OF THE LINE

This section will discuss different types of poles, span length and few words about cross-arm options and their differences between the single and double systems. A quick look is also taken into the line passage clearing and foundations.

4.1 Poles

There are different types of towers which are made from different materials. Most utility poles, which are used with medium voltage in Finland, are made of wood because it is the most economical option. However, tubular steel poles, steel lattice towers and reinforced concrete poles and towers are mainly used in foreign countries. Also some new composite structure technologies have become more popular but they are still quite expensive. There are also various types of cross-arm settings available for the markets as seen in the Figure 14. Most preferable options for this analysis would be options A and E because they are the most common ones. Type A could be used with the bare conductors and type E with the PAS, for example.

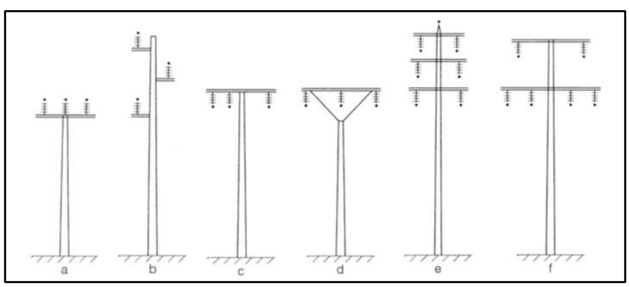

Figure 14. Example poles for MV-lines.

In a real situation the pole material and model selections are based on the mechanical strength calculations. Conductors cause horizontal and vertical loading to the pole. The mechanical loading of the pole depends on the conductor itself, cross-arm, equipment (insulators, protection devices, etc.) and the external forces which influence the conductor. These external forces are caused by wind and ice loads. This analysis will not go deeper into the mechanical calculations. The analysis includes two types of poles; single-pole and double-pole setups. /41/

4.1.1 Wooden Pole

In Finland the wooden pole is about the only pole type for medium voltage. They are cheap and suitable for the Finnish conditions. In foreign countries wooden poles might be problematic because of wood eating pests and woodpeckers (Figure 16) for example. Another problem can be caused by the wicking effect which slowly decays bottom of the pole (Figure 15). These problems can be attempted to be avoided with pesticides and preservative treatments, but eventually the moist ground will decay the base of the pole. /20/

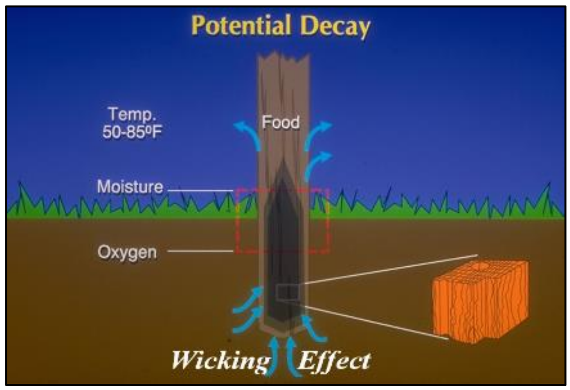

Figure 15. Potential decay of the wooden pole. /21/

Typical lifespan for the wooden pole is about 25-50 years depending on the preservative chemicals and environment conditions. The price of the wooden pole is somewhere 120-200 € per piece. /22/

Table 1. SWOT analysis for wooden poles. /22/

Strengths	Weaknesses
• Low price, 120-200 €/pcs. • Easy condition inspection. • No need for special foundations.	• Short span, about 70 m. • Lifetime relatively low, 25-50 years. • Available only in northern countries.
Opportunities	**Treats**
• Economic option. • Easy to modify. • Low carbon footprint.	• Decay and corrosion. • Animals and pests. • Hazard preservatives.

Wärtsilä sometimes supplies wooden poles for abroad projects but their share is only for approximately 10 %. Wooden poles are not taken into the calculation tool since they are quite rare in the foreign projects. /23/

4.1.2 Composite Pole

Composite or fiberglass poles are quite a new thing on the market and they are still a bit expensive. In future when the prices come down they might be a reckoned option. Benefits for the composite poles are light weight, corrosion, rot resistance and dielectric strength. In Figure 16 can be seen composite and wooden pole next to each other. /24/

Figure 16. Wooden pole is replaced with composite pole. /25/

The lifespan of a composite pole is up to 80 years. Composite poles are still very rare as their price is usually somewhere 700-900 € per piece. They weigh only 70-200 kg per piece, which influences the transportation costs. /24/

Table 2. SWOT analysis for wooden poles. /24/

Strengths	Weaknesses

• Maximal span length.
• Long lifetime, up to 80 years.
• Light weight, 70-200 kg/pcs.
  ○ Low cost logistics.
  ○ Low cost installing.
• Does not decay or gather rust.
  ○ Except UV radiation damages.
• Easy to modify.
	• High price, 700-900 €/pcs.
	• Requires UV-protection paint.
	• Durability of the UV protection during transport and installation.
	• Recycling is expensive.

Opportunities	**Treats**
• Long span is possible with big conductors → Less poles. • Reduced need for installation tools.	• Composite and resin price trends? • UV protection durability. ○ Protection paint may have lower elasticity than the pole itself → damaged protection.

The biggest disadvantages for the composite poles are that they need UV-protection since the sunlight can cause structural changes already in three years. Composite poles are easily damaged with harsh handling (i.e. metal grapples, forklift forks) and they can be very slippery. Benefits for the composite poles are that since they are light weight, they can be handled and installed by two to four persons without big efforts and the transportation costs are relatively low. Composite poles have been in the North-American markets about 15 years, but so far they have not become very common elsewhere. /22/

4.1.3 Concrete Pole

Concrete poles are durable and require usually very low maintenance in normal conditions. Concrete poles are well suitable for places where forest fires may occur or near the sea where the air is too salty and corrosive for steel pole. For such harsh environments manufacturers often offer some kind of protective wrappings or covers. In Figure 17 can be seen the casting process of concrete pole. /27/

Figure 17. Manufacturing of spun concrete pole. /27/

A disadvantage of the concrete pole is the heavy weight which makes the transportation very expensive. Usually concrete poles are manufactured near the installation site. The minimum lifespan of a typical high quality spun concrete pole is 50 years and the price varies a lot according to the county of origin. Concrete poles are widely used in foreign countries but in Finland they are rare. /27/

Table 3. SWOT analysis for concrete poles. /27/

Strengths	Weaknesses
• Maximal span length. • Long lifetime, over 50 years. • Need inspection only at end of lifetime.	• Heavy weight, 700-1200 kg/pcs. ○ Very expensive logistics. • Need for deeper hole in installation. • Corrosion protection is needed. • Expensive recycling. • Durability against impacts during installation? • Very hard to modify.
Opportunities	**Treats**
• Long span is possible with big conductors → Less poles. • Corrosion protection extends the lifetime.	• Manufacturing of concrete causes a lot of CO_2 emissions. • Need for special foundations in soft ground because of tilting problem.

Concrete poles weigh much and that can be a big problem if the ground is soft. Quite a typical problem is that the pole will start to tilt. Foundations are needed to be done properly to avoid this problem. Concrete poles are also sensitive for mechanical impacts as their tensile strength is not the best. /27/

4.1.4 Steel Pole

Because the tubular steel pole is durable and easy to manufacture and install, they have become a good competitor for the steel lattice towers which are often used in high voltage transmission lines. A steel pole erection can be seen in Figure 18. /27/

Figure 18. Steel pole erection. /28/

A steel pole is highly conductive so in some cases it might be able ground itself without external grounding wire. This analysis does not take into account the grounding aspect as it would need deeper research. The lifespan of the steel pole can be 60-80 years depending on the climate. Steel poles should be zinc galvanized to prevent the rust formation. /27/

Table 4. SWOT analysis for steel poles. /27/

Strengths	Weaknesses
• Maximal span length. • Lifetime over 60 years. • Reasonable price, 300-400 €/pcs. • Easy and cheap recycling process. • Medium light weight, 70-300 kg/pcs. ○ Lower transportation costs. • No need for special foundations. • Good resistance to damage.	• Grounding / special requirements. • Impacts and drilling can damage the corrosion protection (galvanization). • Not so easy to modify. • Big carbon footprint.
Opportunities	**Treats**
• Long span is possible with big conductors → Less poles. • Steel pole grounds itself, no need for external grounding?	• Steel price trend?

In the calculation tool there are two types of poles; single-pole and double-pole. The price for each can be customized as desired. It is noteworthy that mechanical calculations are not taken into account, so in fact the tool does not limit the material only to be the steel.

4.2 Span and Pole Height

The distance between poles is called the span (tr. *jänneväli*). The span and pole height goes hand in hand. A longer span requires higher poles because the sag (tr. *riippuma*) increases. The terrain also affects the pole height, for example in the situation where the line goes over the hummock. The maximum span is defined by the conductor strength, pole properties and the allowable movement of the conductors. It must be ensured that the conductors do not get too close to each other in heavy wind and cause short-circuit. /29/ /41/

With PAS a contact between conductors are allowed in heavy wind. Usually the span is between 50-100 m with medium voltage in Finland. A typical pole height with medium voltage is 9-14 m depending on the span. In this analysis span does not have an effect on the pole height. /29/

There are different cross-arm requirements for the covered PAS and for the bare conductors, such as ACSR and AAC. Bare conductor phase lines require more gap between each other than the PAS. In Table 5 some typical values for phase-gaps, spans and the tower highness are shown with different voltage levels. These values are not used as exact in the tool but they offer a guidance to the right direction. /29/

Table 5. Typical cross-arm and pole settings for bare line. /30/

Typical measurements for different voltage levels						
U_{max} (kV)	0.4	24	52	123	245	420
Phase gap (m)	0.5	1.3	1.5	3.5	6.0	11.0
Span (m)	50	80	120	240	320	360
Height of the pole (m)	7.5	8.0	9.5	15	21	23

4.3 Cross-arms and Requirements

This chapter takes an overall look of cross-arms and differences between the requirements of the PAS and bare conductors. Also the grounding point for work is discussed.

4.3.1 PAS System Cross-arms

With the 20 kV PAS configuration the minimum required horizontal gap between the phases is 400 mm but typically 750 mm is used. The vertical gap is typically 550 mm. /31/

Some different set-ups are available. In Figure 19 cross-arms for single- and parallel-line are shown. This is a good example of simple constructions where, for example, a single line assembly can sometimes be easily modified to a parallel line assembly only by installing another similar cross-arm set to another side of the pole. /32/

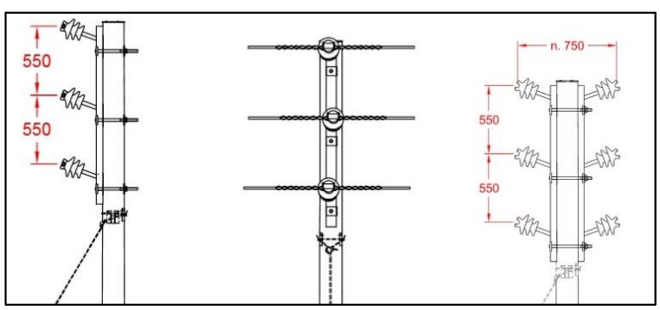

Figure 19. PAS conductor vertical cross-arms. /33/

There are also other types of cross-arm setups, but these are the suggested ones for PAS because of simple construction and ability for upgrading parallel, with certain reservations regarding mechanical withstand limits. In Figure 20 shows a 20 kV bare line system built with 110 kV components next to 20 kV double PAS-line /32/

Figure 20. 1x20kV with 110kV cross-arm setup next to 20kV 2xPAS. /34/

4.3.2 Bare System Cross-arms

With bare conductors the gap between the phases needs to be much wider than with the PAS. Examples of typical bare overhead line cross-arm systems including the measurements are shown in Figure 21. The minimum requirements must always be verified and base on the actual situation and requirements may differ by country.

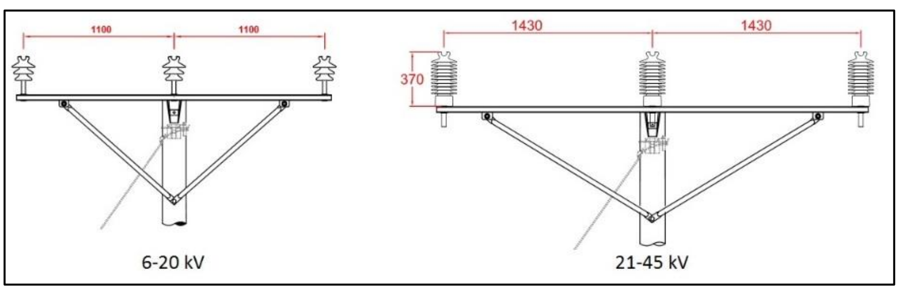

Figure 21. Bare conductor horizontal cross-arms. /35/

A steel pole with all three phases on the one side is a simple and good looking assembly for the single line solution (Figure 22). However, this is not the way how bare lines are built in Finland. That is the reason why cross-arms and mounting materials cannot be found for this installation method. This is the main reason why these kind of vertical setups for bare conductors are excluded in this analysis. /32/

Figure 22. Vertical HV single line assembly.

A great benefit of the vertical setup is that it could be easily modified to parallel assembly afterwards if needed (Figure 23). This kind of need could arise, for example if the plant would be upgraded later on, for example, with extra generators. Of course in that case it must be ensured that the pole strength, mounting and phase gaps are suitable for upgrading to double system. In fact Figures 22 and 23 are from high voltage lines but the same assembly methods are known to be possible for medium voltage. /32/

Figure 23. Vertical HV double line assembly.

As stated before, in Finland the horizontal cross-arm (tr. taso-orsi) setup is the only option for MV bare conductors (Figure 21). That is why only horizontal cross-arms are included in this analysis for bare systems. /32/

4.3.3 Grounding Point for Work

A (temporary) grounding point for work (tr. työmaadoituspiste) is needed for safety reasons when doing maintenance for line. The PAS line needs a grounding point for work at least in every 3 km. It is good to note that the PAS line has the current limiting devices (CLDs) which include grounding points for work. Consequently, if the current limiting devices are installed more frequent than every 3 km, then separate grounding points for work are not needed with the PAS. In the analysis CLDs are installed in every angle suspension pole and the dead-end poles. Angle suspension poles are 25 % of all poles by default. Basically, the CLD is installed about in every 250 m if the line length is 1 km and span 50 m. That makes additional grounding points for work unnecessary in this model. Bare conductors do not have protection equipment in this analysis. Because conductors are bare, the temporary grounding point for work is easy to install nearby the fault location and that is also the common practice in the field. /32/

4.4 Mounting and Foundations

In Finland wooden poles are mounted to the ground simply by dropping the pole to the drilled hole. The depth of the hole is defined by the pole height (Table 6). However, these values are not concerned in the analysis. In the tool depth of 2 m is used. /36/

Table 6. Hole depth by pole height with wooden poles. /36/

Hole depth by pole height with wooden poles							
Pole height (m)	7-8	9-10	11-12	12-13	13-14	14-15	≥18
Hole depth (m)	1,8	1,9	2	2,1	2,2	2,3	2,6

Another option is to use some kind of a foundation base. Concrete is common material for making the foundation. In this analysis these two option are available; hole only or concrete base. The concrete base also requires the drilling. These matters in the tool are discussed in Chapter 5.4.1.

5 BASIC STRUCTURES AND MODULES

Basic structures (tr. vakiorakenteet) were invented by the HeadPower Oy to make designing and ordering simpler and standardized in order to avoid misunderstandings between customer and supplier. There are codes for these different basic structure cross-arm setups. The following chapters will introduce the construction of the model. /37/

5.1 General Overview

As seen in Figure 24 the overview of the model consists of four sections defined by the voltage level, conductor type and pole type. Each of the section has four different basic structures (=cross-arm modules). The figure also shows with arrows how the CLDs and guy-wire modules are linked to some of the cross-arm modules.

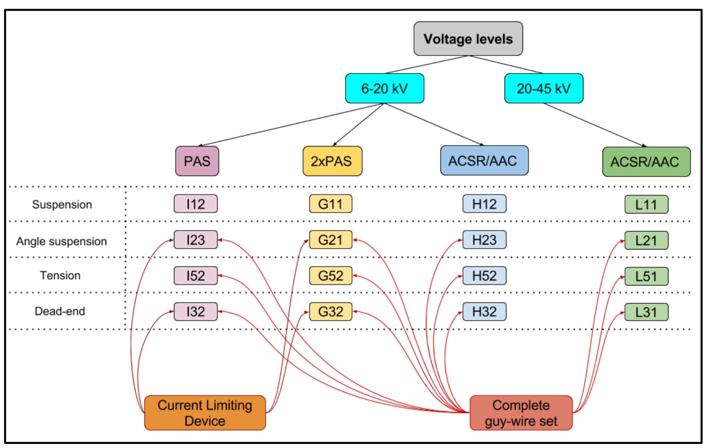

Figure 24. General overview of the model.

Figure 25 shows default quantities for CLDs and guy-wires per module. In the model they are called auxiliary equipment. The pole type for each module is also stated. These default values can be changed and saved on the Misc-sheet.

Default quantities for equipemts with different crossarm setups												
	suspension			angle			tension			dead-end		
	pole	CLD	Guy-w.	pole	CLD	Guy-w.	pole	CLD	Guy-w.	pole	CLD	Guy-w.
1xPAS	single	-	-	single	1	1	double	-	2	double	1	4
2xPAS	single	-	-	double	2	2	double	-	4	double	2	4
6-20kV Bare	single	-	-	single	-	1	double	-	2	double	-	4
20-45 Bare	single	-	-	double	-	2	double	-	2	double	-	4

Figure 25. Default auxiliary equipment for different setups. /38/

The above table is compiled based on the expert comments. For example, the minimum amount of guy-wires is hard to define without mechanical calculations. That is why it is important to note that the numbers are based on estimations and they can be modified if better knowledge is achieved later on. /38/

5.2 Basic Structure Data

It would be a good idea to take a look at the basic structures through an example. Basic structures are also called as modules in this analysis depending on the context. This is due to the fact that the basic structures from HeadPower are basically transformed to modules in the Excel model.

The HeadPower web based software was used to define the needed parts for each pole type. An example of the simple module H12 is shown below in Figure 26.

H12 Kannatusrakenne (PAS pystyorsi) (kpl)
(Luotu 15.2.2000 16:32, Muokattu 18.8.2009 13:17)

Työhinta: 89,25€
Tarvikehinta: 124,38€
Kokonaishinta: 213,63€

Valokaari- ja pieneläinsuojaus valitaan tapauskohtaisesti ryhmästä 424. Pylväät, harukset ja tukirakenteet valitaan tapauskohtaisesti ryhmästä 6.

Rakenne | Tarvikelista | Lisätiedot ja ohjeet

Tunnus	Nimi	Määrä / Rak	Yks. hinta	Huomautus
	Kampanaula 40 x 2,3 mm	4,00 kpl	0,02	
	Kilpi 'Hengenvaara' 120x300	1,00 kpl	3,30	
	PAS Pystyorsi PO-1 kiinnitystarvikkeineen	1,00 kpl	58,00	
	Tappieristin, PAS 24 kV	3,00 kpl	21,00	

Figure 26. Basic structure H12 prices example. /39/

The module H12 consist of nails, warning-plate, PO-1 vertical PAS cross-arm with mounting kit and the pin-insulator. More accurate prices can be achieved by contacting the supplier and making a request for quotation. This has been done and the data is implemented to the Excel model. The Excel model does not include cheap parts, such as nails and warning plates since they do not significantly affect total price of the transmission line.

Besides the contents of the basic structure, HeadPower offers installation times as seen in Figure 27 marked with a red oval. Some of the modules require special machine for installation. For example, the complete guy-wire set with its anchor needs to be mounted into the ground and therefore a digger is needed.

Part prices and installation time (plus additional machine time) are used in the Excel-model. The machine rent price per hour can be adjusted separately from ‘installation time’ in the Excel model Calculator-sheet. More information about this can be found in Chapter 6.1.2.

Figure 27. Basic structure H12 work time example. /39/

HeadPower also provides structural drawings (tr. rakennekuva) of the modules as seen in Figure 28.

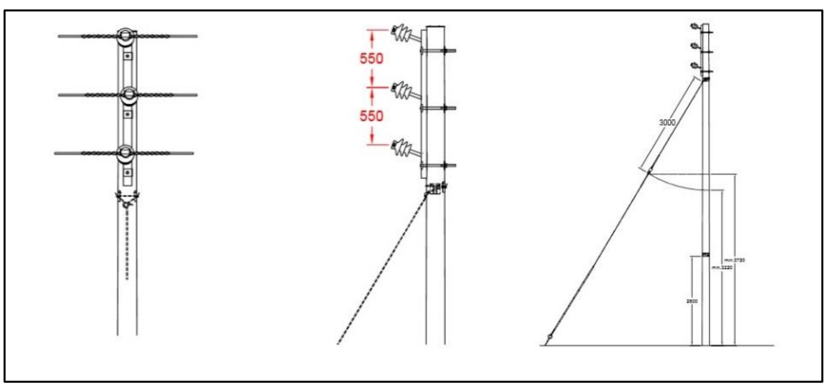

Figure 28. H12-module structure view. /39/

These structural drawings are very helpful for line designers since they provide a good overview of the module and they also usually include most important measurements. More specified information can be found with the unit supplier or the manufacturer.

5.3 Modules

Basic structures are basically transferred with little modifications to the Excel model as modules. An example of more advanced angle suspension I23 basic structure or module is seen in Figure 29. Basically the unit is separated into five different sections which are discussed next.

HeadPower-module	snro	code	remarks	I23 Angle suspension setup (2xPAS, angle crossarm, double pole)	qty	á price (€)	tot. price (€)
I23	5020464	SH182		2xPAS Angle crossarm PJK-2 (6x suspension hook) for double-pole w	[redacted]		
	5043106	SO181.6		PAS Angle suspension clamp 50-150mm2			
	5010250	SDI90.150		Tension insulator 24kV			
	5800568	PEK68		Connection rail			
Guy-wires	2	pcs		T22B Complete guy-wire set	guy wire price		
Current Limiting Device	2	pcs		4248 Current limiting protection device with grounding wire	Aux. equip. price		
Foundation type	Concrete				Foundation price		
Pole-type	Double-pole	weight (kg)	1800		pole price		
work time (h)	[redacted]	work price (€)	[redacted]		material price		
machine time (h)		machine price (€)			**total price**		

Figure 29. Example of complete I23 pole with aux. equipment.

The first section is the HeadPower-module itself (I23) which consist of four different parts in this case: the cross-arm, clamps, insulators and connection rail. In Finland electrical products have unique electrical codes (tr. sähkönumerot). This code is mentioned in the Excel for making the offer requests possible.

The second section is guy-wires. Because the module acts as an angle suspension pole, it needs guy-wiring. Since the pole is double-pole, it needs two guy-wires – one for each pole. Guy-wires are always in complete sets, which means they also include the anchor to the ground. The guy-wire construction, which is a separate module, can be seen in Figure 30.

The third section is the current limiting device. It is previously defined that 'PAS angle suspension pole' is equipped with current limiting device (CLD) in Figure 29. Since I23 is parallel-PAS, it needs two CLD sets.

The fourth section is the foundation type. It is initial data and can be chosen from the Calculator-sheet. The foundation type can be either 'hole only' or 'concrete'. Changing the foundation type changes the type for all modules at once, so there is no possibility to make a model which has both hole only and concrete foundations.

The fifth section is the pole type. The pole type is defined previously for each module. For the I23 pole type is a double-pole. This data influences the foundation price. The double-pole requires two holes and therefore two times more work and concrete.

Pole properties, complete guy-wire set and CLD data can be found in Poles&Aux-sheet in Excel (Figure 30). These are also modules which consist of smaller parts like the basic structures does. CLD is equipped with a grounding wire set because it always needs it.

				Auxiliary equipment			
code	subcode	code2	remarks	4248 Current limiting protection device with grounding wire	QTY / pcs	á price / €	tot. price (€)
4248	5020674	SDI46.7		Current limiting protection device for PAS 20kV	[redacted]	[redacted]	[redacted]
	5024122	PSS469-P		Arc protection horn	[redacted]	[redacted]	[redacted]
	5043387	SP16		Insulating cover for 50-240mm2	[redacted]	[redacted]	[redacted]
	5043146	SEW20.3		Temporary earthing connector PAS 50-157mm2	[redacted]	[redacted]	[redacted]
	5043133	SLW25.2		Insulation piercing connector for PAS 35-157mm2	[redacted]	[redacted]	[redacted]
8536	0105327	CU-25.K500	500m spool	Ground-wire CU25 (1 meter)	[redacted]	[redacted]	[redacted]
	-	-		Fastener for protective tube	[redacted]	[redacted]	[redacted]
	-	-		Protective tube for ground-wire	[redacted]	[redacted]	[redacted]
	-	-		Grounding circle FE	[redacted]	[redacted]	[redacted]
work time (h)	[redacted]	work price (€)	[redacted]		material price		[redacted]
machine time (h)	[redacted]	machine price (€)	[redacted]		total price		[redacted]
HP-code	snro	code	remarks	T22B Complete guy-wire set	QTY / pcs	á price / €	tot. price (€)
T22B	5021028	HL60	Lujabetoni Oy	Guy-wire concrete slab	[redacted]	[redacted]	[redacted]
	5021211	SH81		Guy-wire concrete slab hook LS20	[redacted]	[redacted]	[redacted]
	0126902	FE25.7x2.12	100m spool	Guy-wire FE25.7x2.12 (1 meter)	[redacted]	[redacted]	[redacted]
	1360620	60x60x5		Guy-wire washer 60x60mm	[redacted]	[redacted]	[redacted]
	5010309	SDI70.72		Guy-wire insulator 45 kV	[redacted]	[redacted]	[redacted]
	5021382	CHK25.1		Guy-wire tensioner, CHK25.1	[redacted]	[redacted]	[redacted]
	5024039	5200.7x2.12		Guy-wire 7x2.12 (25 mm2) end clamp	[redacted]	[redacted]	[redacted]
	5021495	SH25		Guy-wire label set	[redacted]	[redacted]	[redacted]
	5024109	SH525.1		Guy-wire bended stay-link HR52 with thimble	[redacted]	[redacted]	[redacted]
work time (h)	[redacted]	work price (€)	[redacted]		material price		[redacted]
machine time (h)	[redacted]	machine price (€)	[redacted]		total price		[redacted]

Figure 30. CLD and Guy-wire set modules.

Module I23 includes these modules two times because the double-pole requires double guy-wires and the parallel PAS-line requires two CLDs, as stated before. Both CLD and guy-wire set needs 'machine time' and 'work time' which are given per module as a static value. Prices for both are calculated automatically with Calculator-sheet input data. This so called installation price calculation is explained later on.

5.4 Civil – Foundations and Clearance

Foundations and clearance are counted as Civil-works in this analysis. Wärtsilä's Jonas Fröberg from Civil-unit has done the base for both clearance and foundations costs databases. Prices from Fröberg were not as accurate as was desired; they were too high according to further research.

5.4.1 Foundations Costs

Foundations costs are divided into two sectors; drilling is counted as ‘installation costs’ and the rest is counted as ‘material costs’ in the Results-table (Figure 43). That means if the user has selected for example ‘hole only’ option, then there will be only the installation costs in totals. The foundation cost database can be seen in Figure 31 and these costs only match with basic ground as clay, sand or soil. There is a higher drilling price for the bedrock (tr. kallioperään) which is not included in this analysis. All yellow fields can be adjusted as desired including the hole depth.

Foundation	Unit Cost	Unit	Foundation cost for **1 Tangent** transmission pole (**single-pole**).	Foundation cost for **1 Section** transmission pole (**double-pole**).
Excavation (Drilling)	[redacted]	€/m	[redacted]	[redacted]
Formwork	[redacted]	€/m2	[redacted]	[redacted]
Reinforcement	[redacted]	€/kg	[redacted]	[redacted]
Concrete	[redacted]	€/m3	[redacted]	[redacted]
Hole depth (m)	**Total material cost**		[redacted]	[redacted]
2	**Total**		[redacted]	[redacted]

Figure 31. Foundations costs –database.

The foundation cost calculation is divided into four different scenarios:

- Single-pole, hole only
- Single-pole, concrete base
- Double-pole, hole only
- Double-pole, concrete base

The excavation (drilling) price has been obtained from Exane Oy. This price includes also transportation to the site and erection of the pole besides the drilling. Material unit prices (formwork, reinforcement and concrete) are obtained from Jonas Fröberg and they also contain all the work including the casting, etc. This means that with the ‘concrete base’ option the work cost is already included in the price but the ‘concrete base’ can be seen only as material cost in the Excel-tool.

5.4.2 Clearing Costs

During the project it turned out that clearing prices obtained from Civil-unit were a bit high. A Finnish company called Korpelan Voima performs clearance services and when requested they kindly offered prices for the clearance per square meter with regular Finnish forest. Together with Jonas Fröberg these prices were finetuned to correspond more realistic prices. There are four different settings for clearing; no clearing, small vegetation, medium vegetation and heavy vegetation.

The wideness of the line passage can be set by the user. Free space measurements are obtained from the Verkostosuositus RJ 21-92. In Figure 32 below the clearing price database can be seen. All yellow cells can be modified as desired.

Clearing	Cost €/m2	Cost for 1 km of transmission line clearance		
Line type category		6-20kV PAS	6-20kV bare	20-45kV bare
Free space needed (m)		4,5	7,5	17
Small vegetation	[redacted]			
Medium vegetation				
Heavy vegetation				

Figure 32. Clearing price -database.

It is noteworthy that the values do not indicate the closest possible tree trunks but the closest bushes. To get a better idea about this please see Figures 3 and 6 in Chapter 3.1 and 3.2. In Figure 33 shows how the fine trimming is done with the helicopter in Finland.

Figure 33. Helicopter trimming for line passage in action. /40/

6 EXCEL MODEL BASIC FUNCTIONS

This part is the user's manual for the model; formulas are explained among other things. The operation of the tool is demonstrated through examples. There are comments on some cells which offer valuable information to the user. The Macro VBA functions are commented in the VBA editor but not separately in this document because the code and comments would take up to 50 pages.

6.1 Initial Data to Fulfill

It is important that the user enters values line by line from top to downwards. Otherwise some automatic functions may not work and an error message might appear. Only the yellow cells act as variable inputs for the model and only those should be modified by the user. The user must not relocate or move any cells to avoid the Macro dysfunctions.

6.1.1 Initial Electrical Data

At the very beginning the user has to fill the yellow fields which are: the line-type from dropdown-list, the maximum allowed voltage drop, the conductor length for one phase, the nominal voltage level, the feeder active power and the power factor. Based on given values the tool calculates instantly the phi-angle, the reactive power, the apparent power and the current without use of any Macros (Figure 34).

These yellow fields have some restrictions in ranges to avoid possible misspellings. This safety system can be turned off in Excel by selecting the cell and navigating into the Ribbon -> Data -> Data Validation -> Clear.

Initial electrical data				
short	title	unit	range	value
-	Line type	-	-	ACSR
$U_{DROP.LIMIT}$	Max. allowed voltage drop	%	0,1-10	3,0%
s	Distance	km	0,5-30	2
U_N	Nominal voltage point A	kV	6-45	16,0
P_{LOAD}	Power of Load	MW	1-30	6,0
Cos φ_{LOAD}	Powerfactor of Load (ind)	-	0,7-1	0,90
φ_{LOAD}	Phi angle of Load	deg	-	25,8
Q_{LOAD}	Reactive power of Load	Mvar	-	2,9
S_{LOAD}	Apparent power of Load	MVA	-	6,7
I_{phase}	Current per phase	A	-	241

Figure 34. Example initial electrical data.

Some of the limitations are made as discussed earlier in this document. For example, the maximum voltage for PAS is 20 kV and this is limited by the macro. The range column shows the value which is possible to enter to the system. These value limitations can be changed from Misc-sheet in the Excel. That is the database for all static values. Some values are not restricted at all so the user has to pay attention when using the tool.

6.1.2 Initial Work and Pole Data

The initial work and pole data (Figure 35) does not need much explanations. The user can choose the work and machine hourly rates depending on the general rate of pay level in the destination country. Wärtsilä has a large database of country specific pay levels which may be utilized in the tool.

Initial work and pole data				
short	title	unit	range	value
	Work price	€/h	[redacted]	[redacted]
	Machine price	€/h	[redacted]	[redacted]
	Pole weight price	€/kg	[redacted]	[redacted]
	Pole foundation type	-	-	Hole only
	Clearing for powerline	-	-	Medium vegetation
	Span	m	50-100	50
	Amount of angle-poles	%	5-50	25 %

Figure 35. Initial work and pole data.

The pole material price is calculated by the material price per kilogram times the material weight. The pole weight can be adjusted by pole type from the Poles&Aux-sheet. The user defines the foundation type between 'hole only' and the 'concrete base'. Also the need for clearance have to be assessed. The clearing includes four options. Each of the options has its own price per square meter which can be adjusted on the Civil-sheet as explained better in Chapter 5.4.2.

The span is usually between 50-100 m. It is impossible to give more precise recommendations of the value since it depends on the terrain, pole height and mechanical strengths. With PAS the maximum span is 80 m and this is limited by the tool. The settings can be changed from the Misc-sheet. The span has an effect on the pole quantity and that way to the total price of the line.

The number of angle poles can be entered as percentage value. This can have a significant effect on the price especially with PAS as the CLDs are always installed for the angle poles (and dead-end poles) only. The angle poles are about twice as expensive as the suspension poles.

6.1.3 Power / Energy Loss Calculator

The power and energy loss calculator needs only two inputs; the utilization period of maximum load (tr. huipunkäyttöaika) and the local price for loss energy per MWh (Figure 36). Usually regular power plants operate 4000-5000 h per year with the maximum output. In most cases this information or approximation is easily available from the company since it is one of the key figures of the power production plant. Conductor power loss is not used in the selection of the conductor, it is only for user information. The energy loss calculator evaluates losses based on the worst case scenario; in other words ‘continuous 100% power plant output’, which is not necessarily the case in practice.

Power / Energy loss calculator				
short	**title**	**unit**	**range**	**value**
hka	Utilization period of maximum load	h	0-8760	4500
$Price_{energy}$	Energy loss price	€/MWh	-	60,00
$P_{3ph.loss}$	Power loss of 3-phases	kW	-	117
$P_{3ph.loss.year}$	Energy losses per year	MWh	-	528
$P_{3ph.loss.year.€}$	Total energy loss price per year	€	-	31709
$P_{LOSS\%}$	Relative transmission power loss	%	-	1,96 %

Figure 36. Power / Energy loss calculator.

6.2 Conductor Selector VBA

After the inputs have been given the VBA starts to operate. The macro software is launched automatically at the background and in the first step it will find the suitable conductor based on the conductors “Fixed rated current” and the “maximum allowed voltage drop” defined by the user. The macro-function called getSelectedCable works in the CableChooser-sheet. It takes user inputs from Calculator-sheet and the conductor electrical data inputs from the Conductor_data-sheet and outputs suitable conductor size to Calculator-sheet as seen in Figure 37.

ConductorSuggestor	
title	**value**
Line type	ACSR
Suggested size	ACSR 85/14 Pigeon
Total amount of poles	40

Figure 37. Suggested conductor example.

The table in the Cable_chooser-sheet (Figure 38) should not be moved in any direction. This is because the VBA works through numbered columns and rows, and by moving the table these crosslinks do not function properly anymore. New conductors can be added to the list by adding them to Conductor_data-sheet and then refering them in the Cable_chooser-table.

	Cable selector table (incl. Macro, dont modify or move)											
	ACSR				AAC				PAS			
	Title	$I_{1ph.max}$	U_{drop} (%)	$P_{3ph.loss}$ (kW)	Title	$I_{1ph.max}$	U_{drop} (%)	$P_{3ph.loss}$ (kW)	Title	$I_{1ph.max}$	U_{drop} (%)	$P_{3ph.loss}$ (kW)
	ACSR 34/6 Sparrow	210	4,85 %	296	AAC 107 Aluminium	435	2,05 %	93	PAS SAX-W50	245	4,89 %	310
	ACSR 54/9 Raven	280	3,36 %	187	AAC 132 Aluminium	495	1,81 %	76	PAS SAX-W70	310	3,55 %	213
	ACSR 85/14 Pigeon	360	2,38 %	117	AAC 201 Aluminium	645	1,43 %	50	PAS SAX-W95	370	2,78 %	157
									PAS SAX-W120	430	2,33 %	125
These are not available, lift up if want to include as option	ACSR 305/39 Duck	845	1,16 %	33	AAC 346 Aluminium	920	1,10 %	29	PAS SAX-W150	485	2,00 %	101
	ACSR 565/72 Finch	1250	0,88 %	18	AAC 638 Aluminium	1340	0,88 %	16	2x PAS SAX-W120	860	1,17 %	63
									2x PAS SAX-W150	970	1,00 %	51

Figure 38. Cable_chooser table.

The Duck and Finch (ACSR) and 346 and 638 (AAC) conductors (Figure 38), for example, can be added to the tool easily by shifting them upwards. The VBA starts to look for the suitable conductor from the top and moves downwards row by row until it finds an appropriate option. If it is unable to find any suitable option, then the text "No available conductor, current too high" or "No available conductor, voltage drop too high" appears to the Calculator-sheet. The green cell background indicates that the conductor is suitable and red color that it exceeds the limitations. These colors are only to show if the calculator works correctly or not. The user does not need to enter into the Cable_chooser-sheet during the normal operation of the tool.

In Figure 39 the $I_{1ph.max}$ is the "Fixed rated current" (i.e. allowed maximum current) from the Conductor_data-table (Figure 41). The $U_{drop\%}$ defines the voltage drop according to Formula 4. The $P_{3ph.loss}$ defines the 3-phase power loss according to Formula 6. Only the current and the voltage drop are used when finding the suitable conductor (Figure 39). It is assumed that the power loss stays on a reasonable level when the voltage drop is accepted by the user.

ACSR			
Title	$I_{1ph.max}$	U_{drop} (%)	$P_{3ph.loss}$ (kW)
ACSR 34/6 Sparrow	210	4,85 %	296
ACSR 54/9 Raven	280	3,36 %	187
ACSR 85/14 Pigeon	360	2,38 %	117

Figure 39. Cable-chooser ACSR example data.

Power losses can be used to define price for losses, for example, during the year (Figure 36). These can be seen as extra-information which was not in scope of this analysis.

Below example is explained with Figure 34 initial data. In the example as seen in Figure 39, the Sparrow is unsuitable option because the rated current is too low (241 A > 210 A) and the voltage drop is too high (4.85 % > 3.0 %). The Raven is acceptable for the current (241 A < 280 A), but the voltage drop is too high (3.36 % > 3.0 %). The only suitable option for this setting is the Pigeon; the rated current (241 A < 360 A) and the voltage drop (2.38 % < 3.0 %) are both in the allowable range. Other suitable conductors with these numeral limitations would have been AAC 107 and PAS SAX-W95 as seen in Figure 38.

An example of the VBA code and its comments can be seen in Figure 40. Every single function is commented carefully. The code is is not available in this public report due to its sensitiveness.

```
'[RATED CURRENT CHECK FOR CONDUCTOR]:
'------------------------------------

'This function checks the adequacy (=riittävyys) of the conductor rated current.
'If suitable conductor cannot be found, then text "no available conductor, current too high" text appears.

'This function gets inputs from the current table row and column number.
Sub getCableCurrent(currentMaxTableRow, currentMaxTableColumn)

'This is the calculated (required) current based on the defined power and voltage level.
'This value needs to be less than conductor's rated current.
'Otherwise the conductor would be overloaded.
current = Worksheets("Calculator").Cells(15, 6)

'This is the default value which is shown if no suitable conductor is available due the exceeding current.
selectedCable = "No available conductor, current too high"

'This is the loop that runs as far as there are values available in the table
Do While Worksheets("Cable_Chooser").Cells(currentMaxTableRow, currentMaxTableColumn) <> ""
    'Boolean expression
    'If the selected current is less than or equal to rated current of the conductor,
    'then the boolean expression is 'true'. Otherwise this entry will be skipped.
    If current <= Worksheets("Cable_Chooser").Cells(currentMaxTableRow, currentMaxTableColumn) Then
        'Boolean expression is 'true', that means the suitable conductor has been found due the current requirement.
        'Cable name is set from the adjacent (=vierekkäisestä) cell (rownumber -1).
        selectedCable = Worksheets("Cable_Chooser").Cells(currentMaxTableRow, currentMaxTableColumn - 1)
        'Because suitable cable was found, we can leave this loop at this point.
        Exit Do
    End If
```

Figure 40. Example of the conductor VBA and comments.

6.2.1 Current Formula

The phase current is calculated according to Formula 3 (and it is rounded up to the nearest integer for avoiding the risky error in the calculation):

$$I_{phase} = \frac{P*1000}{\sqrt{3}*U_N*cos\phi} \qquad \text{(Formula 3)}$$

I_{phase}	Current for one phase (A)
P	Active power (MW)
U_N	Nominal main voltage (kV)
cosϕ	Power factor

In the Excel this formula is on sheet: Calculator, cell: F15.

6.2.2 Voltage Drop Formula

The voltage drop in the figure 39 is calculated based on the Formula 4 (and it is rounded up to two decimals for avoiding the risky error in the calculation):

$$U_{drop} = \frac{P}{\sqrt{3}*U_N*cos\phi} * (s * r * cos\phi + s * x * sin\phi) \qquad \text{(Formula 4)}$$

Where:

U_{drop}	Voltage drop in kilovolts (kV)
cosϕ	Power factor
P	Active power (MW)
U_N	Nominal main voltage (kV)
s	Length of the conductor (km)
r	Resistivity of the conductor (ohm/km)
x	Specific reactance of the conductor (ohm/km)

And the relative voltage drop is calculated with Formula 5:

$$U_{drop.\%} = \frac{\sqrt{3}*U_{drop}}{U_N} * 100 \qquad \text{(Formula 5)}$$

In the excel this formula is on sheet: Cable_chooser, columns: H, L, P.

It is noteworthy that the calculator cell F15 is actually amps instead of original formula. $I = \frac{P}{\sqrt{3}*U_N*cos\phi}$.

6.2.3 Power Loss Formula

3-phase power loss is calculated based on Formula 6:

$$P_{loss} = \frac{3 * I^2 * (s * r)}{1000} \qquad \text{(Formula 6)}$$

Where:

P_{loss}	Three phase power loss (kW).
s	Length of the conductor (km)
r	Resistivity of the conductor (ohm/km)
I	Phase-current of the load (A)

In the Excel this formula is on sheet: Calculator, cell: F34.

6.3 Conductors

The prices for conductors were requested from SLO Oy. The prices do not include VAT by default. The Excel-model has a feature which allows to change all the conductor prices at once by giving a correction factor. All the conductor properties - including the 'work time' per meter - can be found on Conductor_data-sheet (Figure 41).

6.3.1 Static Conductor Data

The conductor data (Figure 41) is based on the Prysmian catalogues. For example, conductors Duck and Finch are optional and they are not included in the model by default. They can be added to the model as explained in Figure 38. The bolded data is used in the calculations in the model. Other data is only for extra information.

Aluminium Conductor Steel Reinforced (Prysmian)					
Preferences	ACSR 34/6 Sparrow	ACSR 54/9 Raven	ACSR 85/14 Pigeon	ACSR 305/39 Duck	ACSR 565/72 Finch
Area (mm^2)	34	54	85	305	565
Mass (kg/km)	137	216	344	1151	2123
Rated Current at 80 °C (A)	210	280	360	845	1250
Fixed Rated Current (A)	210	280	360	845	1250
DC Resistance at 20 °C (ohm/km)	0,848	0,536	0,337	0,095	0,051
AC Fixed Resistance (ohm/km) [1)]	0,848	0,536	0,337	0,095	0,051
AC Reactance at 20 °C (ohm/km)	0,383	0,368	0,354	0,314	0,280
Rated Strenght (kN)	12	19	29	97	174
Max Short-circuit Current for 1s (A)	3700	5800	9200	32500	60100
Price (eur/km) [5)]	[redacted]				
Reinforced max. Span (m) [3)]	80	100	140	N/A	N/A
Installation time for 3ph (h/m)	0,04	0,05	0,07	0,12	0,16

Figure 41. Conductor data for ACSR-type.

6.3.2 DC Resistance to AC Resistance

The Prysmian catalogues, like many other catalogues too, inform only the DC resistance at 20 °C ambient temperature for ACSR and AAC conductors. Basically the AC resistance of the cable conductors is the DC resistance corrected for proximity and skin effects. The AC resistance is typically 1.5-8 % higher than the DC resistance when all the AC's affecting factors are taken into account. This correction in Excel can be done by giving the correction factor to the 'Resistance DC->AC' –cell (Figure 42). /30/

This correction takes place with ACSR and AAC conductors. In other words it does not have an effect on the PAS conductors because for them the AC resistance at 80 °C was provided in catalogues. Correction for the reactance is not available since it is mainly defined by the phase gap.

6.3.3 Temperature Correction

The previous DC->AC resistance correction does not take into account the temperature effect. The resistance increases when the temperature rises. All the given catalogue resistance values for the ACSR and the AAC are based on the temperature of 20 °C. If the operational temperature is 80 °C, the resistance can be up to 25 % bigger than the original catalogue value. That is why the *Temp. Fix for AC Resistance* correction factor could be for example 1.24 to surely remove the possible restrictive error in hot conditions with voltage drop calculations. In this example no correction was used (Figure 42).

Correction coefficients		
Type	**default**	**factor**
Resistance DC -> AC 1) 2)	1,04	1,00
Temp. Fix for AC Resistance 3)	1,24	1,00
Rated Current Margin	1,00	1,00
Price (i.e. incl. VAT)	1,24	1,00

Figure 42. Temperature correction for resistance.

The PAS-conductors had the AC resistance values available at 80 °C so the *Temp. Fix for AC Resistance* and the *Resistance DC->AC* corrections do not affect them in the model.

7 EXCEL MODEL RESULTS

The results with graphs are discussed in this chapter. First it is good to point out that there are some basic key-figures on the Calculator sheet also besides the Result-sheet, because that way the user sees immediately how changing the settings affects the prices. This is only for making the tool more user-friendly; there is no need to change sheets when adjusting inputs.

7.1 Results Table

The Results-table can be found from Results-sheet in Excel, but only when the Macro has calculated everything properly. If there is an error on input settings, the Results-sheet would not be visible. This is a safety function that secures that the results are calculated correctly and therefore the user does not have an option to print out the false results. The Results-table offers exact information of the installations, module-quantities and material costs (Figure 43).

	Material name	code	á price (€)	quantity	unit	Machine time (h)	Work time (h)	Total inst.costs (€)	Material costs	Total costs (€)	Remarks
Conductor											
	ACSR 85/14 Pigeon	-	[redacted]		km	0	140	[redacted]			
Cross-arm setups			[redacted]								
	G11 Suspension cross-arm (1xACSR/AAC , max. 20kV	G11	[redacted]		pcs	0	57	[redacted]			
	G21 Angle cross-arm (1xACSR/AAC , max. 20kV)	G21	[redacted]		pcs	0	21	[redacted]			
	G52 Tension cross-arm (1xACSR/AAC , max. 20kV)	G52	[redacted]		pcs	0	7	[redacted]			
	G32 Dead-end cross-arm (1xACSR/AAC , max. 20kV)	G32	[redacted]		pcs	0	12	[redacted]			
Guy-wires	cross-arm setups total:			[redacted]	pcs	0	97	[redacted]			
	T22B Complete guy-wire set	T22B	[redacted]		pcs	12	20	[redacted]			
Current Limiting Devices											
	4248 Current limiting protection device with ground	4248	[redacted]		pcs	0	0	[redacted]			
Poles											
	Single-pole	-	[redacted]		pcs	37	37	[redacted]			
	Double-pole	-	[redacted]		pcs	5	5	[redacted]			
Civil	poles total:			[redacted]	pcs	42	42	[redacted]			
Foundations	Hole only	-	[redacted]		pcs	0	0	[redacted]			
Clearance	Medium vegetation	-	[redacted]		m2	0	0	[redacted]			
TOTAL								[redacted]			

Figure 43. Results-table for 6 km of ACSR-line with under 20 kV.

The Results-table is cleared and re-calculated every time automatically when yellow inputs from the Calculator-sheet are changed. That means it refreshes itself automatically. However, if the default-values (Misc-sheet) or data in the modules or conductors are modified, then the tool does not automatically re-calculate. In this case the user has to press macro-button to re-calculate with the new default settings.

7.2 Part List

The Part list shows all materials for the cross-arm setups, guy-wire sets and CLDs (Figure 44). The macro collects information from the used modules, calculates quantities, combines and transfers the information to the Part list –table.

Part list						
electrical number (FIN)	Material name	code	á price (€)	quantity (pcs)	total price (€)	Remarks
[redacted]						
				Total	[redacted]	

Figure 44. Part list for 6 km of Pigeon with under 20 kV.

The part list is something that can be valuable when the company, for example, examines the subcontractor's quotation and material list. In short it provides the basic idea of the main components that are used for the line construction.

7.3 Charts

The tool provides three basic charts (Figure 45) on the Calculator-sheet.

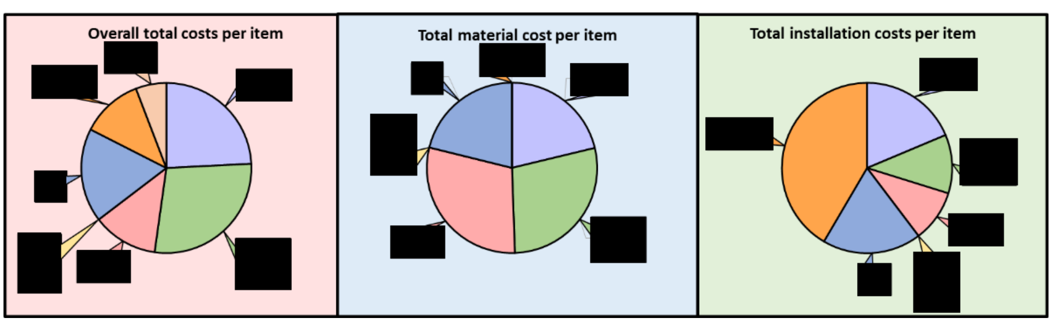

Figure 45. Three main result-charts.

The first chart indicates the total installation costs as percentage for the whole project per item. The second chart shows how material costs are divided for the whole project. From the third chart the overall costs can be seen. Above these there is the same cost information in the table format with rounded values.

Other charts can be found from the Results-sheet. The chart in Figure 46 indicates all above information in a single chart. This chart looks a bit confusing, but after the user's eye gets used to it, it will be a very useful for tracing the small differences between different calculating scenarios since the information in one chart.

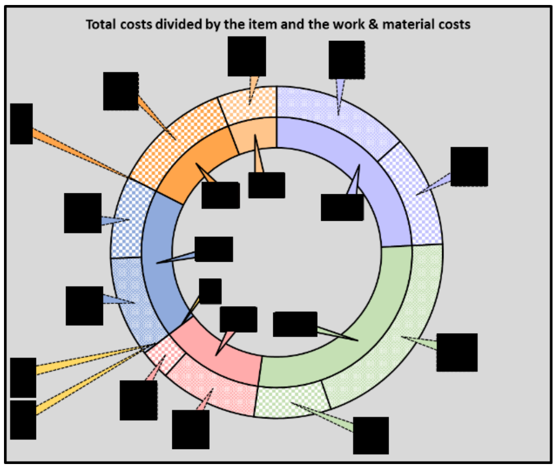

Figure 46. Total costs divided by the item and the work & material costs.

The chart in Figure 47 offers data in a more readable format, but it is missing the total costs. The basic idea was to offer different types of charts and let the user decide which to use.

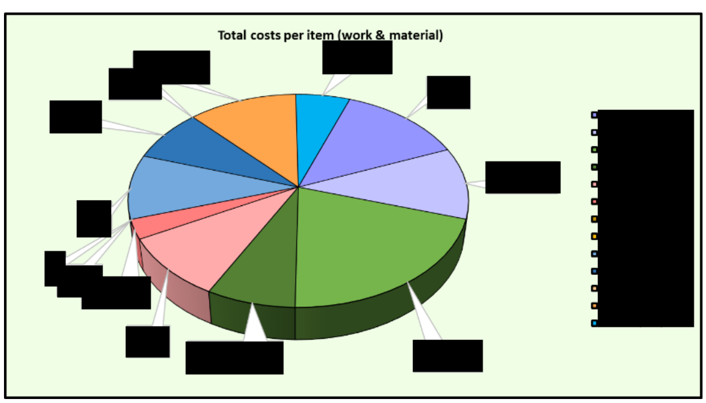

Figure 47. Total installation costs per item.

8 CONCLUSIONS

This final part will discuss the conclusions of the analysis., what was difficult and what could have been done better. The development proposals are also outlined. In overall the cost calculation tool (Excel-model) and this report was very successful. The thesis supervisor from Wärtsilä told that the targets were met and even exceeded. Also the supervisor from school was very satisfied with the overall work.

8.1 The Accuracy of the Results

The test scenarios have been modified to conform Finnish conditions. For example, pole prices have been set to 120 €/pc for a single-pole and 200 €/pc for a double-pole instead of much more expensive steel poles. The work price is set to 40 €/h and the machine price to 60 €/h. The foundation type is 'hole only' as it is typically used with wooden poles. The clearance is set to 'medium vegetation'. The number of the angle poles have been set to default 25 % and the span to 50 m. The voltage level used in the test is 20 kV. Basically everything is as it would be by default factory settings, except the pole prices.

Tool estimation vs Realized cost		
1km of Sparrow		
Calculated total	[redacted]	Error
Realized total		11,9 %
1km of Raven		
Calculated total	[redacted]	Error
Realized total		0,2 %
1km of Pigeon		
Calculated total	[redacted]	Error
Realized total		0,4 %
1km of AAC-132		
Calculated total	[redacted]	Error
Realized total ("132 or larger")		-6,5 %
1km of PAS-W50		
Calculated total	[redacted]	Error
Realized total ("35-70")		1,8 %
1km of PAS -W95		
Calculated total	[redacted]	Error
Realized total ("95 or larger")		4,5 %

Figure 48. Calculated costs compared to realized costs 2015 (VAT 0%).

The tool performs very well as can been seen in Figure 48. The most significant inaccuracies takes place with the 34mm^2 ACSR (Sparrow) and the 95mm^2 PAS. It should be noted that with the AAC 132 the error is not really -6.5 % because the realized price is calculated for "ACC 132mm^2 and larger conductors". Larger conductors are always more expensive, which increases the reference value, which in turn reduces the real error in this case. With the 95 mm^2 PAS the situation is the other way round and the inaccuracy is more than 4.5 %.

An accuracy check has not been made for the 45 kV systems as there is not any cost reference values available for the comparison. The 45 kV system cross-arm setup material prices are estimated. Estimated material prices in the Modules-sheet are marked with red and can be adjusted easily whenever more exact price data is available.

8.2 Development Proposals

Some improvements for the model are discussed here.

8.2.1 Item Database and Quantity Discounts

Usually volume discounts are offered when products or services are ordered in large quantities. This is not taken into account in the model. The model would need a separate item-datasbase for all the parts of the modules. In the model the parts are directly in the modules so there is no separate database which would be easier to keep updated. The volume discounter would be easy to add besides the database.

8.2.2 More Pole Options

The tool has only two pole options; single-pole and double-pole. There could be more options for example taller ‘river crossing pole’ or stronger ‘dead-end pole’. However, more pole options would make the tool more complex to use and actually the cost estimator staff would need a terrain map to be able to choose the correct amount of certain pole types. That was not the purpose of the thesis. The terrain designers eventually design the route of the line, correct pole types and another things based on the terrain. That happens after the company has won the tender stage because it takes time and costs money.

The pole height has an effect on the required span and to the hole deepness. This is not taken into account in the tool. The span has an effect on the quantity of the poles which has a big effect on the total price of the line.

8.2.3 More Automation to the Model

The model does not automatically choose or calculate the most economical conductor solution, but it could do that by going through all the results based on the input data. However, this would need much more effort to the VBA code and would make the tool much more straight-forward which is not always a good thing. Now it offers, for example, the power and energy loss values for the user who is then able to make further investigations based on his/her expertise. It has to be kept in mind that the excessive automation is sometimes more harm than good.

8.2.4 DC as Option

In future Wärtsilä may build small sized solar power plants. Solar power plants produce DC power. DC transmission line is much more economic due to about 30 % smaller power losses and 30 % lower conductor investments. However, the converter stations are very expensive and therefore, it is still more economical to transfer the power with AC systems. This may change in the future when the DC converter station prices come down. /11/

8.3 Problems and Difficulties

Problems and difficulties which has been encountered are dealt with in this chapter.

8.3.1 Poles

It was very hard to get price estimations for the steel poles. Over 10 pole manufacturing companies were contacted. All of them refused to provide any price estimations without more detailed mechanical loading datas. Later on I succeeded to obtain some technical drawing examples of MV steel poles from ABB with Jani Aurell's contact suggestion. These drawings did not provide prices but they provided the weight information of the poles. That is the reason for the "steel pole material price (€/kg)" –variable in the tool. It would be possible to estimate the pole price by the material mass and cost. In fact Wärtsilä has a separate kilogram price value in their database for steel constructions which included the welding and drillings by default.

8.3.2 45kV System

Since 45 kV cross-arm setups are not commonly used in Finland, it was hard to find information about them. Material prices were requested from several different retailers and manufacturers across the Europe and the USA. Only a few companies replied and the answer was ‘it is not possible to offer anything based on this initial information’. It can be seen understandable as the given input data was very inadequate.

8.3.3 Energy Loss Calculator

The energy loss calculator is based on the worst case scenario; it calculates the losses with the calculated maximum output current which can be seen on the bottom line in Figure 34. In fact the power plants may not necessarily run at the full power during the operation.

It would be possible to get more realistic energy loss data by using an estimation of the load curve of the plant and making the current approximations based on that. However, I think this would be too onerous a task for cost estimators compared to the total benefits. These kind of economical matters were not the core questions of the analysis and the whole energy loss calculator should be seen more as an extra item.

8.3.4 Documenting

Difficulty in this report was to produce a clear coherent whole without jumping around from topic to topic; the fact is that many subjects are associated with each other. Also a lot of background research and reading had to be done to get a comprehensive overview of different subjects. Many written reference went much too deep into the subject so obtaining an overall picture of things was laborious at time to time.

At the beginning of the thesis only a few restrictions were specified. Further restrictions were set by the backround research and meetings with experts. The author believes that in spite of the problems, the documentation is successful and provides a fairly clear picture of the issues that need to be taken into account when building the line as well as during the use of the calculation model.

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