TAMPERE UNIVERSITY OF TECHNOLOGY
Degree Programme in Industrial
Engineering and Management

ANTTI NUMMELA

PARAMETRIC STUDY OF THE COST ESTIMATE FOR RADIO FREQUENCY SYSTEM OF COMPACT LINEAR COLLIDER

Master of Science Thesis

Prof. Saku Mäkinen has been appointed as the examiner at the Council Meeting of the Faculty of Business and Built Environment on January 9th, 2013.

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Tässä diplomityössä tutkittiin CLIC hiukkaskiihdyttimen niin kutsuttujen RF yksikkö -kiihdytinrakenteiden kustannuksia, mikäli niiden rakennetta muokattaisiin pidemmäksi useamman vaihtoehtoisen konfiguraation pohjalta. Kyseiset rakenteet vastaavat nykyarvioiden mukaan noin 20 % koko CLIC kiihdyttimen kustannuksista, jolloin niissä saavutetut kustannussäästöt voisivat olla merkityksellisiä koko CLIC projektin kustannusten kannalta. Pidempien RF yksikkö -rakenteiden yksikkökustannukset olisivat suurempia, mutta niitä tarvittaisiin tutkimuksen lähtötilanteeseen verrattuna pienempi määrä, mikä luo mahdollisuuden kustannussäästöille. Tarkoituksena oli selvittää syntyisikö näitä kustannussäästöjä ja kuinka merkittäviä ne olisivat.

Tutkimusaineistona käytettiin pääasiassa CERN:in sisäisiä lähteitä muun muassa aiempia kustannusarvioita sekä teollisuudelta saatuja tarjouksia eri komponenttien valmistuksesta. Näihin perustuen laadittiin kustannusarviomallit kolmelle eri RF yksikkö -rakenteiden pidentämiskonfiguraatiolle. Tutkimus rajattiin koskemaan vain RF yksikkö -rakenteiden kustannuksia ja mahdolliset vaikutukset muihin rakenteisiin jätettiin maininnan tasolle. Massatuotettavien komponenttien kustannuksia arvioitaessa sovellettiin oppimisteoriaa.

Viime hetken odottamattomat muutokset hankaloittivat huomattavasti tulosten käsittelyä. Tutkituista vaihtoehtoisista pidennysvaihtoehdoista ainoastaan viime hetkellä lisättyä C vaihtoehtoa pidettiin suoraan toteuttamiskelpoisena laitteiston fysikaaliset rajoitteet huomioon ottaen. Tätä pidennysvaihtoehtoa käyttäen kustannussäästömahdollisuudet ovat kuitenkin rajoitetut, sillä kyseinen konfiguraatio johtaa laitteen kokonaispituuden ja eräiden komponenttien määrien kasvamiseen. Mahdolliset kustannussäästöt ovatkin riippuvaisia siitä kuinka paljon laitetta tulisi pidentää, jotta sen toiminnallisuus pysyisi lähtökohtaisen suunnitelman tasolla. Tämä on selvitettävä, mikäli pidentämistä kyseisen konfiguraation mukaan harkitaan.

ABSTRACT

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In this thesis the cost of so called RF units of CLIC particle collider was examined when RF units' configuration was considered to be lengthened according to several alternative scenarios. According to current estimates these structures correspond to approximately 20 % of the total cost of CLIC collider and as such the savings achieved in their cost could be significant when total cost of CLIC project is looked into. The unit cost of longer RF units would be greater when compared to the baseline scenario but as smaller quantity would be required cost savings might be achieved. The aim was to find out if cost savings would accumulate and if so, how significant these savings might be.

Research material used was mainly internal CERN resources such as earlier cost estimates and tenders received from the industry for production of different components. Based on these cost estimate models were created for three different configurations for lengthening the RF units. The research was limited to the cost of RF units and the possible effects on other systems are referred to only briefly. In evaluation of the cost of mass production of the components learning theory was applied.

The unforeseen last minute changes to the study complicated substantially the processing of the results. Out of the alternative lengthening configurations examined only configuration C was deemed as realisable when the physical constraints of the machine were taken into account. Using this configuration the cost reduction possibilities are limited as this configuration leads to increase of the total length of the machine as well as to increase of certain components' quantities. Thus the cost saving possibilities are dependent on how much the length of the machine would need to be increased in order to retain the same functionality as in baseline configuration. This is a major issue and needs to be looked into shall lengthening of the RF units be considered following the configuration in question.

PREFACE

This thesis has been a long project. The practical part of the thesis was conducted mainly during 2012 at CERN albeit last minute modifications resulted part of the work being postponed to early 2013. A great part of the foundation of this report was written in 2012, but due to structural changes resulting from the above mentioned modifications and, above all, personal scheduling issues with studies and other projects it was not completed until late 2013. Now, finally holding this report in my hands, the haunting frustrations of having it unfinished is rapidly fading.

My thanks from this thesis writing process go to Dr. Kenneth Österberg, my supervisor at Helsinki Institute of Physics and Dr. Germana Riddone, for functioning as my supervisor at CERN and providing crucial insight for various parts of this thesis. Equally I am grateful to my examiner Dr. Saku Mäkinen from Tampere University of Technology, for his guidance and advice through the project. Finally I would like to thank Laura Heinonen, for her counsel concerning the language of this thesis as well as other friends and family for their support during the thesis writing process.

Tampere, Finland 8th of December 2013

Antti Nummela

TABLE OF CONTENTS

ABBREVIATIONS

AS = Accelerating structure

CDR = Conceptual design report

CERN = European organisation for nuclear research

CLIC = Compact linear collider

CTF3 = CLIC test facility 3

DFA = Design for assembly

DFM = Design for manufacturing

HOM = High order mode

ICFA = International committee for future accelerators

ILC = International linear collider

LEP = Large electron positron collider

LF = Learning factor

LHC = Large hadron collider

linac = linear accelerator

MTBF = Mean time between failures

OFE = Oxygen-free electrolytic

PBS = Product breakdown structure

PETS = Power extraction and transfer structure

Protocost = First unit cost

RF = Radio frequency

S-AS = Super-accelerating structure

SLC = Stanford linear collider

TBM = Two-beam module

TDR = Technical design report

WBS = Work breakdown structure

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background

Compact Linear Collider (CLIC) project reached a notable waypoint in 2012 when Conceptual Design Report (CDR) was published. In the report CLIC concept, a high gradient normal-conducting accelerator employing a novel two-beam acceleration scheme, is described and status of key feasibility studies are presented. (Schmickler et al. 2012)

This study aims at examining the possible cost reductions for the Compact Linear Collider -project by reducing the cost of one of the key, and most expensive, systems it comprises, the two-beam modules. The cost of CLIC project has previously been evaluated internally at CERN and using external estimates from potential subcontractors. In these, several possible paths that could lead to notable cost reductions of this system have been identified out of which two most eminent are presented here.

The first path is reducing the machining cost of the copper disks which are the main components for the accelerating structures, one of the subsystems of the two-beam modules’ radio frequency (RF) unit. For machining of the disks the current plan is to use ultra-precision diamond machining, namely milling and turning, to counter the tight accuracy requirements. These requirements are still subject to change and therefore a study on the cost effects of possible relaxation when using diamond machining has been executed previously by Turunen (2011). The study noted that relaxation of accuracy requirements might render alternative machining methods economically more viable in comparison to ultra-high precision diamond machining. These alternative machining methods and their effect on cost remain to be examined closer.

The second path to reduce the total cost is modifying the design of the RF units, the main emphasis being in lengthening some of its subsystems. The cost saving possibilities in this scenario derives from reduction of the quantity of some of the components and following reduction of manufacturing and assembly operations. This is the path studied in this thesis. The method used is creating a parametrical model allowing the examination of the effect on cost when the layout is modified.

1.2. Research environment

CERN, the European Organisation for Nuclear Research, is a European organisation founded in 1954 by 12 Western European countries. Today CERN has 20 European Member States and is additionally collaborating with over 60 countries worldwide. With over 2400 people working at CERN and some 10 000 visiting scientists, it is the world's largest centre for particle physics. (CERN 2012) The research at CERN is concentrated on fundamental physics with the aim of finding out how the Universe works and what it is made of. Some of the research areas include the Higgs boson, supersymmetry and dark matter. The fundamental particles are studied using highly sophisticated scientific equipment, particle accelerators and detectors. Particle accelerators serve to accelerate the particles to high energy levels, after which they are collided with each other or stationary obstacles. Data from these collisions is acquired with the help of detectors and then analysed by physicists. Additionally a lot of research is conducted on other fields to enable the studies on fundamental physics and the construction and operating of particle colliders. These include, for example, cryogenics and computing. (CERN 2012)

Lately the main focus of CERN has been on Large Hadron Collider (LHC) and the experiments on it. LHC is a 27 kilometre long circular collider that accelerates two beams of subatomic particles called hadrons to near light speed and then collides them head-on in order to recreate the conditions prevailing just after the Big Bang (LHC the Guide 2009))

LHC started operation first in September 2008 (CERN Press Release 2008) but countered several problems. Therefore the first successful particle collisions at full combined energy level of 7 TeV were not seen until March 2010 (CERN Press Release 2010).

Even as today the main focus of CERN and the global particle physics community is on LHC, different teams are already looking beyond the LHC-scope. It is approximated that LHC will siege operating in 2020s, although it is possible that the lifetime of the machine will be increased with upgrades, one example being High Luminosity LHC. Compact Linear Collider, the framework of this thesis, is one of these projects for the post-LHC era. It aims to provide physicists a different perspective on phenomena revealed by the LHC (CERN 2012).

1.3. Research problem, questions and assumptions

The radio frequency (RF) units of CLIC consist of several distinct components and various manufacturing procedures are required in their production as well as assembly. The quantities of these components in final design of CLIC range from tens-of-thousands to several million pieces depending on the component in question. Being able to reduce the quantities of components could result in notable decrease in RF unit costs and it is considered that this could be done without the need to implement major design changes to the structure, leading to limited engineering effort in order to apply these modifications. The purpose of this thesis is to research the cost reductions that could be achieved when the design of the RF units is modified.

Research question this thesis aims to answer is: How will the total value of cost estimate of RF units change when their design is altered by making the RF units longer?

Further questions that arise from the research question are: Will the cost estimate of RF units be reduced or increased due to the modifications? How will the cost change for each of RF units subsystems? Are these changes of cost linear or non-linear? Can notable savings be achieved by changing the design? Which parameters have the most effect on the total cost of RF units? Which is the favoured scenario for lengthening the structures?

The scope of the thesis is limited to examining the cost of RF units. The possible engineering design modifications of the RF unit’s components that might be required as a result of design modification of RF unit are assumed to be so small that the costs resulting from them can be ignored. The cost of simple stock items (e.g. bolts, screws) is assumed to be included in the cost of main components and to be negligible compared to their cost.

It is acknowledged that changes in RF units will have effect on other systems of CLIC. From these changes cost increments or further cost reductions may result. Examples of these feature infrastructure, where tunnel length is the most notable factor, and energy consumption. Due to vast knowledge requirements, complex nature and sheer number of these possible changes they are excluded from this study and remain to be studied closer by people responsible for each system shall the modification of RF unit configuration deemed feasible for further progress.

1.4. Methodology and structure

This thesis is conducted as a parametric study. The parameters are drawn from engineering design, previous studies and subcontractors providing different parts to RF unit. As a result, a model providing the cost of alternative RF unit designs will be created. Because several of the parameter values in the model, as well as the final configuration of the RF unit, are subject to change at this stage of the project, special emphasis is given to ease of modification of the final model. Although this thesis concentrates on full length CLIC machine at energy level of 3 TeV the model allows examining also the cost of RF units for lower energy levels that can be achieved with shorter machine.

The theoretical part of this thesis comprises examination of a few mass production characteristics most relevant to the case examined and background for uncertainty calculations conducted to the cost estimate achieved in this study.

First this thesis provides insight into the Compact Linear Collider –project. In chapter three the construction and functions of the RF unit and its subsystems studied in this thesis are presented. In chapter four an overview of manufacturing processes of major RF unit subsystems is provided. Also theories for manufacturing, reliability and the major parameters used in cost estimate of the RF units are looked into. In the following chapter the theoretical framework for methods used to evaluate sensitivity and uncertainty of the cost estimate model constructed are presented.

Afterwards the different RF unit configurations that are examined in this thesis will be presented in chapter six. The cost estimate model used is afterwards described in chapter seven followed by presentation of results obtained in chapter eight. Finally conclusions are drawn in chapter nine.

2. PRESENTATION OF THE PROJECT

CLIC is a project aiming to construct a complex linear accelerator of TeV energy scale. In this chapter the common background for different linear accelerator projects is presented followed by general presentation of CLIC accelerator. A closer look is then taken into the distinguishing feature of CLIC – the two-beam acceleration.

2.1. Future colliders

The highest centre-of-mass energy lepton collisions so far have been reached at now dismantled circular Large Electron-Positron Collider (LEP) in CERN. The energy for these collisions was 209 GeV. (Schmicker et al. 2012) Leptons are subatomic particles that are not affected by the strong force, and as for current knowledge, do not consist of smaller particles. (Encyclopaedia Britannica 2013) When accelerating particles with very little mass, like the leptons, the problem of synchrotron radiation gets highlighted. This phenomenon is based on the trait that all electrically charged particles in a circular orbit emit electromagnetic radiation and as such it appears in every circular accelerator. While synchrotron radiation has several practical and scientific applications in multiple fields e.g. environment and electronics (Karlsruhe Institute of Technology 2013), in particle accelerator it leads to notable loss of operating efficiency. The approximate energy loss due to synchrotron radiation is given by formula:

$$E_{rad} \sim \frac{E^4}{m^4 r} \tag{2.1}$$

, where *E* is the energy of the charged circulating particles, *m* is their mass and *r* is the radius of their orbit. This implies sharp rise in synchrotron radiation losses when particles’ energy is made higher or mass of particles gets smaller, whereas changing the radius of the orbit does not have a great effect. (Schopper 2009)

In particle colliders striving for maximal energy for the particles to be collided, this phenomenon is obviously problematic. As the mass of leptons is minuscule, even when compared to subatomic particles like protons, operating a circular lepton collider with high energy levels of several TeV would lead to immense energy consumption unavailable from today’s energy sources. For example, when LEP was operated at just 0.2 TeV, nearly 50 % of the input energy was lost due to synchrotron radiation (CERN Press Release 1999).

In addition to energy loss, one problem arising from higher energy levels, leading to stronger synchrotron radiation, is that the strong radiation can damage the various components of the accelerator. When radiation levels are limited, absorbing structures can be used to shield the most sensitive components from the radiation, but shielding the whole accelerator to withstand intensive radiation would not be feasible as it would result in immerse costs. (Bailey et al. 1998)

To counter this major issue of synchrotron radiation a linear lepton collider has been proposed to be constructed instead of a circular one (Schmicker et al. 2012). Accelerating two beams linearly towards each other renders radiation losses from acceleration negligible. Not having to combat against synchrotron radiation losses leads the cost of linear accelerator for higher energy levels favourable when compared to circular accelerators. This is illustrated in Figure 2.1.

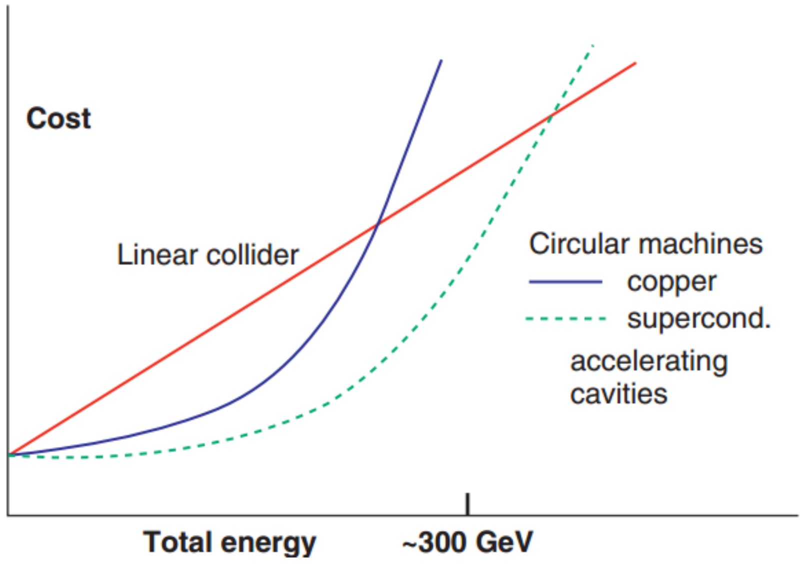


Figure 2.1. *Cost of electron-positron collider as a function of total energy (Schopper 2009).*

Below energy level of approximately 300 GeV, depending slightly on technology used (superconductive accelerating cavities or not), a circular collider is more economical than alternative linear collider. On energies above this limit the cost of circular accelerator quickly becomes colossal in comparison to linear collider.

The International Committee for Future Accelerators (ICFA) released a statement in 2004 emphasising that there exist a worldwide consensus in the scientific community that a linear electron-positron collider should be the next large accelerator-based facility constructed. Its mission would be to complement and expand the discoveries expected to emerge from LHC. (ICFA 2004)

The largest linear collider this far, Stanford Linear Collider (SLC), was operated in SLAC National Accelerator Laboratory at Stanford University in California in United States of America. It was operational from 1989 to 1998. Strictly speaking

SLC was not a true linear collider as it only had one linear accelerator (linac) which accelerated both electrons and positrons to same direction which were then bent with magnets for a head on collision (Barish et al. 2008). The maximum collision energy achieved in SLC was 91.2 GeV (Woods 2001).

During the years several projects have been launched aiming to construction of a linear electron-positron collider of high energy. Along with RF acceleration, concepts of laser, plasma and wakefield acceleration have been envisaged but all the significant, as well as the current, plans have been based on variations of conventional RF acceleration (Delahaye 1996). The collaboration between the different projects has eventually led to joining forces in order to rationalise the efforts. This has led to notable decrease in the number of projects and different alternatives for future linear accelerator. For example, in 2003 there still existed four notable designs, TESLA, JLC-C, JLC-X/NLC and CLIC (International Linear Collider Technical Review Committee 2003). Currently there exist just two rivalling designs, namely International Linear Collider (ILC), a combined effort of former TESLA and JLC teams, and Compact Linear Collider. The main difference is the technology used to provide power to RF structures that accelerate the particle beams: ILC uses superconducting RF acceleration based on conventional klystron technology whereas CLIC relies on novel principle of normal conducting two-beam acceleration. The design of ILC is notably more mature than CLIC’s but CLIC has potential for higher accelerating gradient leading to shorter machine for the same energy level achieved and eventually larger centre-of-mass energy capability for the collider (Banks 2012).

To optimise the use of limited resources the two groups working on ILC and CLIC are collaborating heavily in mutual issues like civil engineering and detector design. Recently the co-operation has been reinforced by joining the two projects on organisational level under Linear Collider Board (Banks 2012). In the future, resources are likely to be further concentrated on realising either one of these two proposed linear colliders. The decision on which of the linear colliders will eventually be constructed is largely dependent on the results to be acquired from LHC. Shall the maximum energy level of 1 TeV be deemed sufficient for obtaining the desired results from the future linear collider the ILC is the likely choice and if higher energy levels are assessed necessary it supports the choice of CLIC. (Banks 2012)

2.2. Compact linear collider

This study concentrates on Compact Linear Collider, a CERN-driven joint collaboration of 26 institutes aiming to construct a high luminosity multi-TeV linear electron-positron particle collider.

The aim of this linear collider is to further investigate fundamental physics, complementing and extending the results and scope of LHC. Proposed fields of research include, for example, the validity of the standard model and physics beyond that, such as super-symmetry and new gauge bosons. (Schmicker et al. 2012)

If chosen to be realised, according to current plans, CLIC would be constructed in three upgradeable stages. First stage is proposed to have a centre-of-mass energy level of approximately 500 GeV and the ultimate aim is to reach the centre-of-mass energy level of 3 TeV. An intermediary stage has been proposed to be implemented at approximately 1.5 TeV energy level, but the final choice of stages to be used depends on the results of LHC (Lebrun et al. 2012). The total length of the machine at the ultimate energy level would be nearly 50 kilometres.

Feasibility of CLIC-type machine has been examined in CERN since 1986 when the novel two-beam concept was first proposed and the CLIC study was started. In 2004 it received increased importance following a CERN Council initiative. (Schmicker et al. 2012) The Conceptual Design Report presenting the technical feasibility of CLIC and future progression plans of the project was issued in October 2012. The next major milestone of the project is producing Technical Design Report (TDR) specifying and optimising the technical details of CLIC. This report is foreseen to be published in 2016. Latest at this point the Go/No-Go -decision regarding the construction of the accelerator is foreseen to be made and if chosen to be realised, the first stage of CLIC would be operational in mid-2020s.

The schematic layout of CLIC at final 3 TeV energy stage illustrating the two-beam acceleration concept is presented in Figure 2.2.

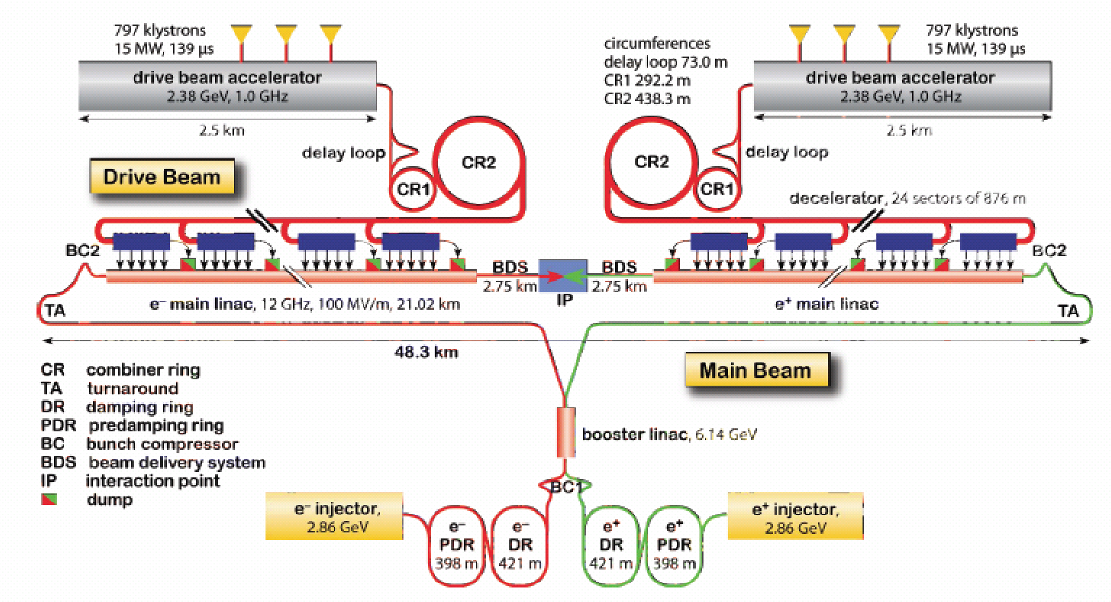


Figure 2.2. *Schematic layout of CLIC at 3 TeV (Schmickler et al. 2012).*

On the lower part of the picture is visible the main beam production facilities for electrons and positrons as well as transport structures and on the upper part includes the corresponding structures for the drive beam. Additionally, the drive beam -side of the machine implements frequency multiplication system in form of delay loop and combiner rings. These structures are used to increase the bunch repetition frequency and beam current. In the middle of the figure can be seen the linear accelerators, linacs, including the accelerating structures themselves on the main beam side and on the drive beam side the energy transfer structures needed to extract power from the drive beam and input it to the main beam. Technologies used for beams production and transport are rather conventional for this field whereas the two-beam scheme used in the accelerating and power extraction structures along the linacs has only been demonstrated in test facilities.

To divide the accelerating power from the drive beam evenly to the accelerating structures, CLIC’s linacs are divided into sectors with a length of 876 metres. The drive beam consists of short bunch trains (244 ns at frequency of 50 Hz) so that each bunch train supplies one sector with RF power. (Schmickler et al. 2012)

The main parameters for CLIC at the ultimate centre-of-mass energy level of 3 TeV are tabulated in Table 2.1.

Table 2.1. *Main parameters of CLIC (Schmickler et al. 2012, Delahaye 2010)*

Centre-of-mass energy (TeV)	3
Total (Peak 1%) luminosity ($cm^{-2}s^{-1}$)	5.9(2.0)$* 10^{34}$
Total site length (km)	48.3
Loaded accelerating gradient (MV/m)	100
Main linac RF frequency (GHz)	11.994
Bunch charge (10^9 e+/e-)	3.72
Bunch separation (ns)	0.5
Total power consumption (MW)	415

2.3. Two-beam acceleration and two-beam modules

The novel feature that CLIC employs is the use of two-beam acceleration in contrast to the klystron based acceleration more traditionally used in particle accelerators. When multi-TeV energy levels are considered the two-beam acceleration is more feasible solution, not only due to its higher accelerating gradient but also because feeding the main beam with klystrons would require approximately 35 000 klystrons together with their ancillary equipment (Schmickler et al. 2012).

High accelerating gradient is especially beneficial in linear accelerator as it allows greater energy levels to be achieved while keeping the length of machine reasonable. If klystrons would be used, in practise an additional tunnel would be required to run alongside the accelerator tunnel to house them and ancillary equipment (Delahaye 1996). The lack of this equipment evidently removes this requirement leading to decreased infrastructure costs.

In two-beam acceleration the low-current main beam is accelerated to high energy (from 9 GeV to 1.5 TeV) (Schmickler et al. 2012) by extracting RF power from a high-current, low-energy electron beam running alongside the main beam, the so called drive beam. To extract the RF power from drive beam it is decelerated. Relative high efficiency is achieved for acceleration as 84 % of the power can be extracted and just 16 % of the drive beams energy needs to be dumbed after each sector of CLIC. The energy is then transferred to accelerating structures and fed to the main beam in order to increase its energy.

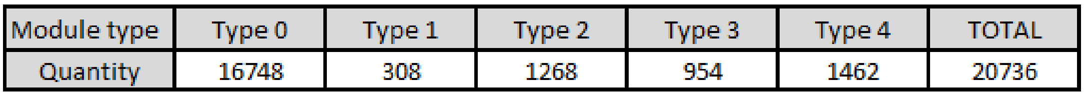
The drive beam is generated and its frequency is adjusted at central part of CLIC machine and from there transported to both ends of the machine. Same is true with the main beam where electrons and positrons are transported from the central production facility to each end of the CLIC to be accelerated and collided again at the centre.

According to today’s estimate the two-beam modules (TBM) are a main cost driver for the CLIC project representing nearly a third of the total cost of the CLIC project. For the two-beam modules the main cost drivers are the RF system (65 %) and support system including alignment (15 %). (Schmickler et al 2012) The structure examined in this thesis, referred to as RF unit, corresponds to TBM RF system for the main parts.

Other systems in the two-beam modules include vacuum system, cooling system and magnet system. Vacuum system is needed to provide vacuum conditions for both the main and the drive beam, the main function of this being the reduction of beam-gas interactions (Schmickler et al. 2012). To counter as cost efficiently as possible with, for example, the heat transformations caused by great amount of excess heat produced water cooling will be used. To do this as cost effectively as possible, the design of the cooling system of the two-beam modules needs to be optimised. Magnet system includes the magnets responsible for alignment of both of the particle beams throughout the entire CLIC accelerator. These systems are not given further emphasis here as they are outside the scope of this thesis.

As the energy of the main beam is different at the different stages of the accelerator, increasing towards the interaction point, the power of quadrupole magnets aligning the particle beam need to be adjusted correspondingly (Schmickler et al. 2012) For this reason five different types of two-beam modules are used in the linac. They differ in the amount of RF units per structure and the length of main beam magnetic quadrupole. The quantities of the modules of different types at the final 3 TeV energy stage of CLIC are tabulated in Table 2.2.

Table 2.2. *Quantities of CLIC modules at 3 TeV (Schmickler et al. 2012).*



Module type	Type 0	Type 1	Type 2	Type 3	Type 4	TOTAL
Quantity	16748	308	1268	954	1462	20736

The most common two-beam module, the Type 0 module, has the most accelerating power as it includes four RF units. One RF unit consists of one power extraction and transfer structure (PETS), two accelerating structures and radio frequency network connecting the two and enabling the energy transfer from PETS to accelerating structures. RF units are described in detail in chapter 3. Module types from 1 to 4 have, correspondingly, three to none RF units. (Riddone et al. 2011) The different types of CLIC modules are presented in Figure 2.3.

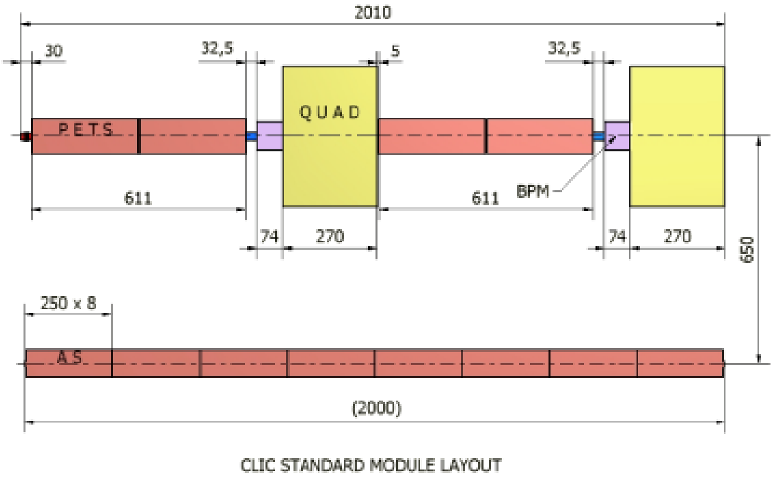


Fig. 3.38: Schematic layout of a two-beam module.

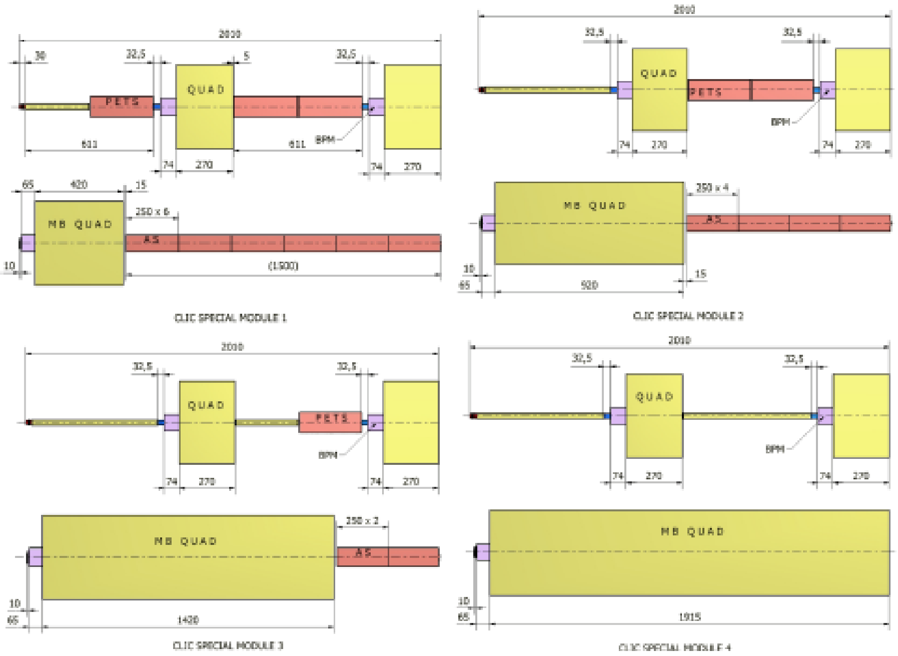


Fig. 3.39: Schematic layouts of the modules that contain quadrupoles.

Figure 2.3. *Different types of CLIC modules (Schmickler et al. 2012).*

To align the beams on the drive beam side of the linac two magnetic quadrupoles are used in every module type. Similarly, for focusing the main beam, there is one magnetic quadrupole on the main beam side of the two-beam module in each module regardless of its type, excluding the Type 0 module where there is no quadrupole. The length of this main beam quadrupole varies depending on the type of the module so that it always fills the space of the linac where there are no accelerating structures. The RF units are identical in every module type; the only difference is their quantity.

3. STRUCTURE OF RF UNITS

The smallest modular part of the RF system is called an RF unit. This thesis concentrates on cost of these parts and therefore RF units are described in detail in this chapter. According to current plans, at the ultimate energy level of 3 TeV there will be over 71 000 RF units in CLIC.

The RF unit is the structure responsible for transferring the power from drive beam to main beam. The layout of an RF unit is illustrated in Figure 3.1.

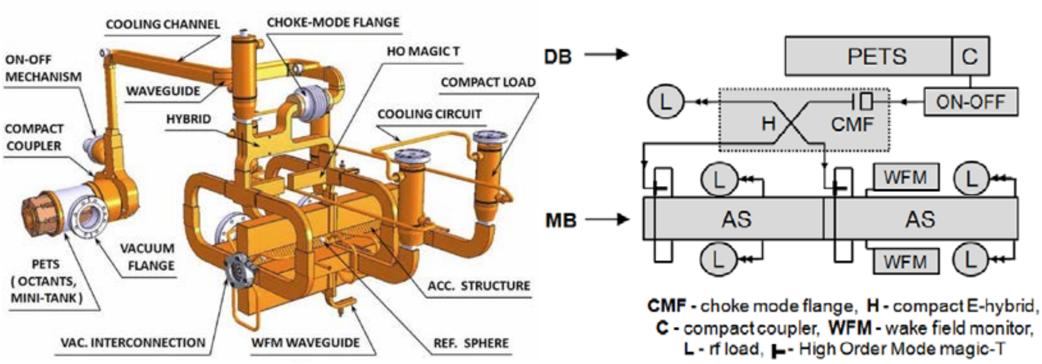
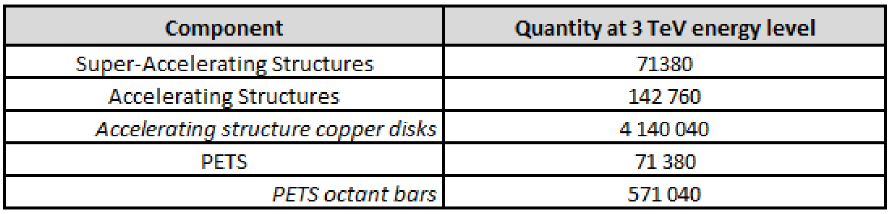


Figure 3.1. *3D model and schematic view of a CLIC RF unit layout (Schmickler et al. 2012).*

As RF unit is not a separate entity, but a part of RF system, there are obviously structures and components having a supportive role for RF unit that could be classified either as a part of RF unit or other structures. For example, in this study cooling circuits that can be seen in the 3D model in Figure 3.1 are considered as part of cooling system, not the RF unit. The components which are considered as parts of the RF unit in this study are presented more closely when subsystems of RF unit are looked into later in this chapter. The three major subsystems RF unit can be divided into are power extraction and transfer structures, radio frequency network and super-accelerating structures (S-AS).

The quantities used in this study for these subsystems as well as few of their most notable components are presented in Table 3.1.

Table 3.1. *The quantities of CLIC RF unit's subsystems and few major components.*



Component	Quantity at 3 TeV energy level
Super-Accelerating Structures	71380
Accelerating Structures	142 760
Accelerating structure copper disks	4 140 040
PETS	71 380
PETS octant bars	571 040

3.1. Power extraction and transfer structures

Power extraction and transfer structure is a passive microwave device which extracts RF power from the drive beam to be used in accelerating the particles of the main beam. When the electrons of the drive beam pass through PETS they are decelerated and their kinetic energy is transformed into electromagnetic energy. This energy is then collected at the end of the structure from where it is forwarded to waveguides. (Sánchez et al. 2011) At the nominal design each PETS will produce a power of 135 MW (Toral et al. 2011).

The main components of PETS are copper rods, compact coupler and minitank. For one PETS eight rods machined out of oxygen-free electrolytic (OFE) copper are required. This high purity oxygen free material is traditionally used in room temperature accelerator applications (Heikkinen 2010) to be able to optimise the electrical conductivity and to eliminate the possibility of included elements vaporizing to the operating vacuum and possibly disturbing the operation of the accelerator. (Aurubis 2013) The tolerances for manufacturing the rods are tight; the shape tolerance requirement is +-15 µm (Schmickler et al. 2012) and surface roughness requirement 0.4 µm (Sánchez et al. 2011). The tight accuracy in fabrication, as well as assembly, is required because looser specifications could affect the power production due to detuning of the synchronous frequency. Albeit being tight the machining accuracy can be achieved with conventional 3D-milling machine. (Syratchev 2008) Despite this, the tight accuracy requirements make copper rods the most challenging part of PETS from manufacturing point of view. For CLIC test facility 3 (CTF3) rods were produced with high speed milling with small ball cutter. Additionally, intermediate stress relieves were conducted by baking the rods twice at 180 degrees Celsius for one hour. (Toral et al. 2011) Similar manufacturing method is planned to be used also when manufacturing copper rods for CLIC's PETSs.

In assembly phase the eight bars are electron beam welded together to form a cylindrical structure. This structure is illustrated in Figure 3.2.

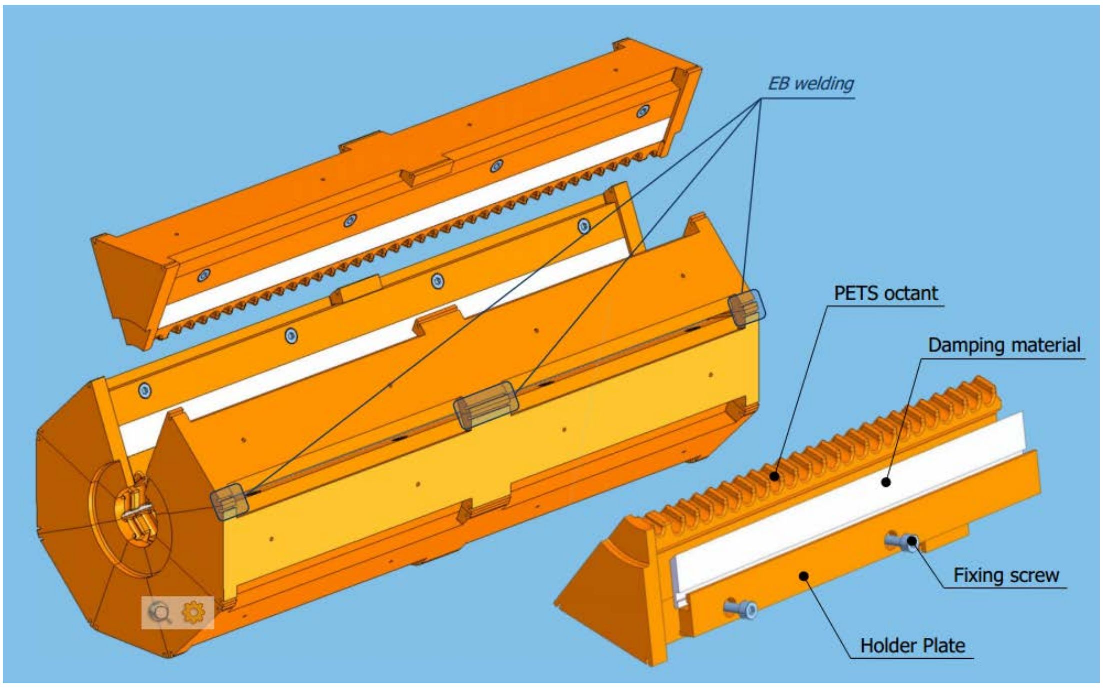


Figure 3.2. *Assembled PETS structure (Soldatov et al. 2010).*

The electron bunches of the drive beam travel through the small 23 mm aperture in the centre of the structure (Riddone 2011). The rods have periodic oscillations (i.e. cells) every 6.253 mm, which induce the RF power production due to the interaction with the beam (Toral et al. 2011).

To absorb the high order modes (HOM) generated by the interaction of the beam with the structure, damping features need to be applied between each octant bar. For this ceramic silicon carbide shims are attached to lateral surfaces of the bars as seen in Figure 3.2. (Soldatov et al. 2010)

To prevent particles form going astray from their trajectories and to avoid energy losses due to collision with the particles in the air the particle beam on the drive beam needs to travel in a vacuum. To ensure beam stability in the main linac a very low pressure of 1 nTorr is required (Jeanneret et al. 2010). To provide air tight enclosure for PETS enabling this low pressure to be achieved, a cylindrical stainless steel structure called minitank is used. This tank is connected to the vacuum network permitting the air to be pumped out and creating a vacuum.

At the downstream end of each PETS a compact coupler is brazed. It collects and forwards the RF energy extracted from the drive beam by the structure composed of eight PETS bars. Compact Coupler also implements the so called on-off mechanism, which provides the capability to reduce the output power of individual PETS in case of local breakdown in the adjusted accelerating structure (Cappelletti 2008). By doing this the on-off mechanism helps to maintain the overall luminosity in case of breakdown. (Schmickler et al. 2012)

Currently the estimated cost of PETS corresponds to 25.6 % of the estimated total cost of the RF units. Approximately half of this cost (50.1 %) comes from machining of the copper bars. Machining of minitanks contributes also a portion of cost over 10 % (12.6 %), while rest of the components are considered to have portions below 10% of the total cost of PETS subsystem.

3.2. Radio frequency network

The radio frequency network is considered consisting of all the components that are responsible for transferring the RF power within the RF unit. This means structures used for transferring energy after extraction by PETS from drive beam to accelerating structures, but also the components responsible for dumping the remainder energy that could not be transferred to main beam by accelerating structures. The part of RF network between PETS and accelerating structures are presented in Figure 3.3.

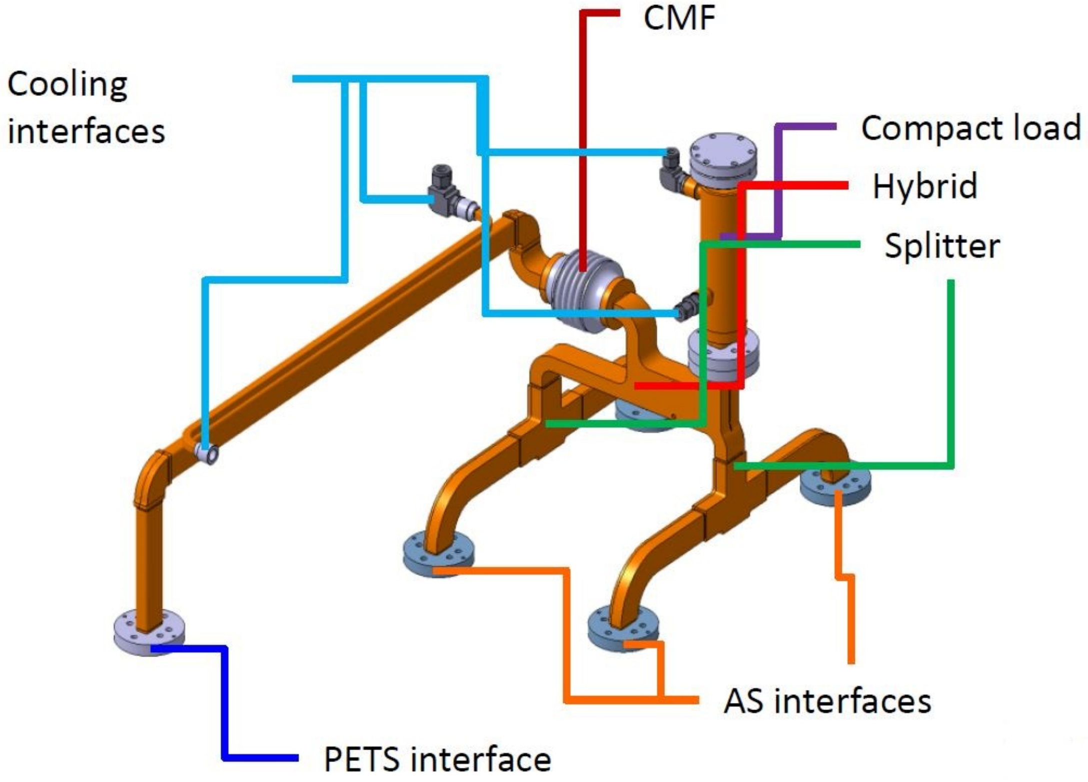


Figure 3.3. *Illustration of RF unit's radio frequency network (Riddone et al. 2011).*

The main component for the energy transfers are waveguides along which the RF power is conducted from PETS to accelerating structures. Also, transferring the remainder RF power from accelerating structures to compact loads is done via waveguides. Other major structures of the RF network include choke mode flange, hybrid and splitter. Choke mode flange provides a way of transferring the RF power without electrical contact. This enables individual alignment of drive and main beam. (Schmickler et al. 2012) Hybrid is the structure responsible for dividing the RF power to the two accelerating structures powered by single PETS, whereas splitter divides the RF power destined to single accelerating structure so that it can be fed into the structure from the two opposite sides.

To prevent the remaining RF power, that is not transferred to main beam by accelerating structure, interfering with the acceleration it needs to be dumped after the accelerating structure. To do this, the remainder RF power from accelerating structures is further directed via waveguides into compact loads. Two compact loads per accelerating structure are used to avoid the scenario where an unwanted HOM could be trapped at the structure’s output coupler region and thus reduce the peak power level per load. Hybrid employs also one compact load in order to terminate the differential port of the hybrid. (Schmickler et al. 2012)

The value of RF network in current cost estimate is clearly inferior when compared to the other two subsystems of the RF unit. It contributes only 17.7 % of the cost of the RF unit. Nearly two thirds of this cost (64.4 %) comes from compact loads after accelerating structures used for dumping the remainder energy. The rest of the components considered contribute smaller than 10 % portions of the total cost of RF network.

3.3. Super-accelerating structures

Accelerating structures are the key system for all particle accelerators responsible of the energy input to the particles to be collided. In CLIC each RF unit employs two accelerating structures and this entity is called super-accelerating structure. As both accelerating structures of a super-accelerating structure are practically identical a single accelerating structure is described in this chapter. One accelerating structure is shown in Figure 3.4.

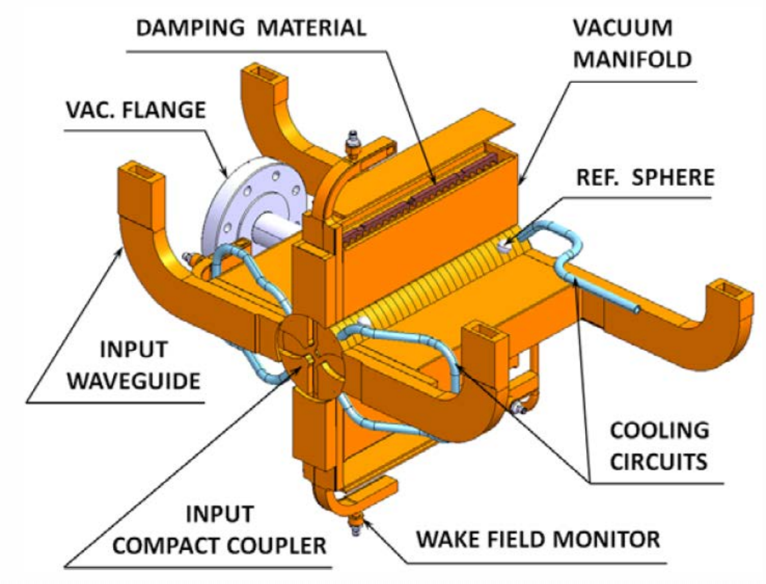


Figure 3.4. *A schematic view of CLIC accelerating structure (Schmickler et al. 2012).*

The main components for accelerating structures are copper disks and vacuum manifolds. In the current design each accelerating structure (AS) consists of 29 copper disks that are stacked and then diffusion bonded together to form a cylindrical structure (Riddone 2011). There exist seven different types of disks in each super-accelerating unit each having a slightly different design. For example, coupler disks at the ends of the accelerating structure have two open waveguides to allow input and output of RF power to/from the accelerating structure. Also, the radius of the iris through which the main beam travels is variable from 3.15 mm at the input end to 2.35 mm at the output end of the accelerating structure (Riddone 2011). When manufacturing and cost are considered, the differences of the various disks designs are minuscule and therefore all the accelerating disks are considered as a single component in cost estimates conducted previously and in this thesis alike.

The material used for machining the disks is OFE-copper for the same reasons it is used for copper bars of PETS (see chapter 3.1.). The required accuracies for the disks are even higher than for PETS bars as flatness of 1 µm, form accuracy of 5 µm and surface roughness of Ra 25 nm are required. Vacuum manifolds are brazed on disk stacks to provide vacuum for main beam. The manifolds also include damping features to damp the high order modes. Similarly to damping in PETS the damping material used is silicon carbide. From the downstream end of AS the remaining RF power, not transferred to the main beam, is directed via waveguides and dumped into compact loads as a part of RF network subsystem presented in chapter 3.2.

In the current plan the total amount of accelerating structures for CLIC at 3 TeV will be over 142 760. As well as being the most numerous of the RF unit subsystems the accelerating structures are also the most costly with 56.7 % of the RF unit value deriving from it. High precision machining of the accelerating disks contribute 60. 9 % of this cost making it the single most expensive component of RF unit value estimate, 34.5 % of the total RF unit cost. Machining of the damping material contributes 15.0 % of S-AS cost the rest of the components having proportions of less than 10 % of the cost of S-AS.

4. PRODUCTION OF RF UNITS

In this chapter the production of RF units is described. A short overview of the manufacturing processes of PETS and accelerating structures is first provided following by justification of this study by design for manufacturability (DFM) and reliability theories. After that, a presentation of the theoretical background of the most important factors affecting the cost of the production is provided.

4.1. Overview of the manufacturing processes

When manufacturing is considered, the RF network is not seen as major issue and the main focus is thus on PETS and accelerating structures. This is firstly because of RF network’s less tight manufacturing requirements and more mature manufacturing technology compared to other subsystems. It is also considerably less expensive than the other two subsystems which is likely another reason why not so much importance has been paid to it in the previous studies. Therefore also here are presented manufacturing outlines only for PETS and accelerating structures.

For accelerating structures the process consists of following stages as described by Saifoulina & Uusimäki (2010):

- Manufacturing of disks and couplers, including needed heat treatments
- Geometrical control of disks
- Cleaning of disks and couplers
- Diffusion bonding of disks
- Manufacturing of cooling circuits
- Manufacturing of vacuum manifolds
- Assembly of damping loads
- Assembly (brazing) of vacuum manifolds
- Assembly (brazing) of cooling system
- RF check
- Vacuum baking (650°C)

Many of these stages have several substages. For example, in manufacturing of disks there are several different milling, turning and baking phases.

PETS manufacturing process has following main stages (Saifoulina & Uusimäki 2010, Sánches 2011):

- Manufacturing of octants, including needed heat treatments : high-speed milling with diamond tools and 2 intermediate stress relieves at 180 degrees Celsius

- Geometrical control of octants
- Manufacturing of coupler : composed of 3 OFE copper parts machined with high precision diamond tools and 2 intermediate stress relieves joined by vacuum brazing
- Manufacturing of mini-tank
- Cleaning of all parts
- Assembly of octants : is done in vertical position
- Assembly of damping loads
- Assembly and EB welding of mini-tank with coupler : once octants are assembled coupler and mini-tank are added
- RF check: several tests were conducted for prototype structures ensuring PETS's specifications and function. (In mass production these extensive test cannot be conducted for all over 70 000 PETS structures.)
- Vacuum baking (cleaning)

It needs to be highlighted that the stages are described here in very general level. For example, bonding of disks is complicated process where issues like misalignment and bookshelfing need to be considered (e.g. Samoshkin 2011) not to mention the bonding process itself (e.g. Moilanen 2013).

4.2. Design for manufacturability

Design for manufacturability can be defined as a designing process that aims optimising the areas of manufacturing already prior to manufacturing is commenced. These areas include manufacturing, assembly, testing, procurement, transport and maintenance. Another thing DFM takes into account is that shortcomings in product manufacturability do not endanger its functionality or delivery. (Anderson 2004) DFM is not a new concept albeit the term was not widely adopted before 1985. The first proofs of its use date to 1788 (interchangeable musket parts by LeBlanc). The beginnings of industrial mass production in the early 20th century enabling production lines to be applied into manufacturing (Model T by Henry Ford) can be seen as a starting point to method's widespread use. (Bralla 1999)

Traditionally in the literature it has been considered that 80 %, or even more, of the lifecycle costs are committed during early phases of the product development, namely the product conception and design phases (e.g. Lindholm & Suomala 2007, Kaplan & Atkinson 1998). The scheme for committed and incurred costs is often presented by different variations of graph seen in Figure 4.1. (E.g. Kaplan & Atkinson 1998, Anderson 2004).

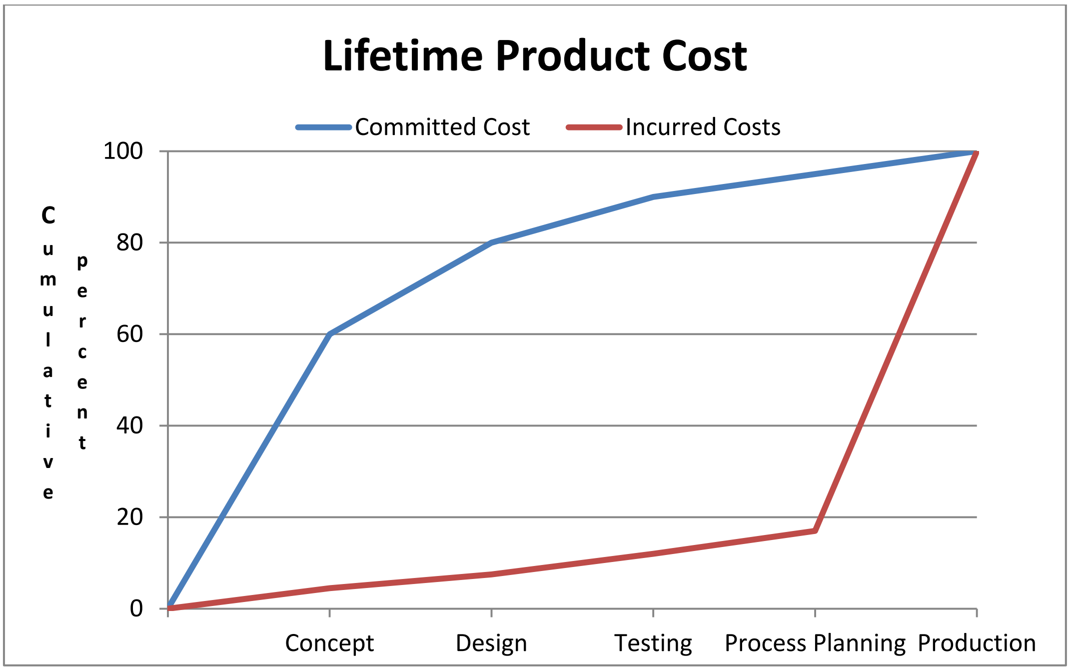


Figure 4.1. *Committed and incurred costs in product development (Based on Anderson 2004).*

In the figure there is illustrated when the costs of a product, or project, are committed to (upper line) and when these costs are realised (lower line). The graph illustrates that conception is by far the most influential factor when committed cost are examined. For example, in CLIC's case this would mean the specification of requirements such as the energy level, particles to be accelerated and acceleration scheme. The design, how to achieve the specified requirements, is the second most influential factor of the committed cost. This thesis's focus can be considered to be on the design issues of CLIC.

The claim of this high proportion of conceptualization and design costs has also been criticised (Labro 2006, Jeacle and Mitchell 2003), for lacking empirical evidence and not taking into account the variation of these proportions for different industries. Nevertheless, the criticism is mainly directed at highlighting that notable cost savings can be achieved also later in the process. Having claimed this, the critical papers do still acknowledge the importance of the design and planning phases and estimate that the committed costs resulting from these are clearly the largest proportion of all the committed costs for majority of industries. Therefore, albeit one should not take the 80 % rule as a standard, it is relatively safe to assume that for most industries the majority of life cycle costs are still determined in these early stages of the life cycle.

When looking at the phenomenon of committed costs from the customer's perspective an important remark is that after making the purchasing decision the customer commits largely to the costs that will occur later including, for instance, costs resulting from maintenance, disposal, personnel needed and energy consumed.

Even as the basis of these costs is set according to the purchasing decision, these costs can, of course, be further managed also in later stages during the life cycle. This can be done, for example, by optimising the maintenance strategy or the way the product is used (Lindholm & Suomala 2007). For CLIC project the most obvious example of these kinds of costs would be systems that are subcontracted in their totality, for example, ventilation and safety systems.

Additionally to potential for cost decreases, benefits from DFM include, for example, decrease in product development projects cycle time, increase in quality and reduction in maintainability efforts [Winner et al. 1988]. The quality increase and maintainability efforts are discussed more closely under the term reliability in chapter 4.3. Concerning projects cycle time Anderson (2013) gives an example on how DFM together with concurrent engineering affected the cycle time at Lexmark. This is illustrated in Figure 4.2.

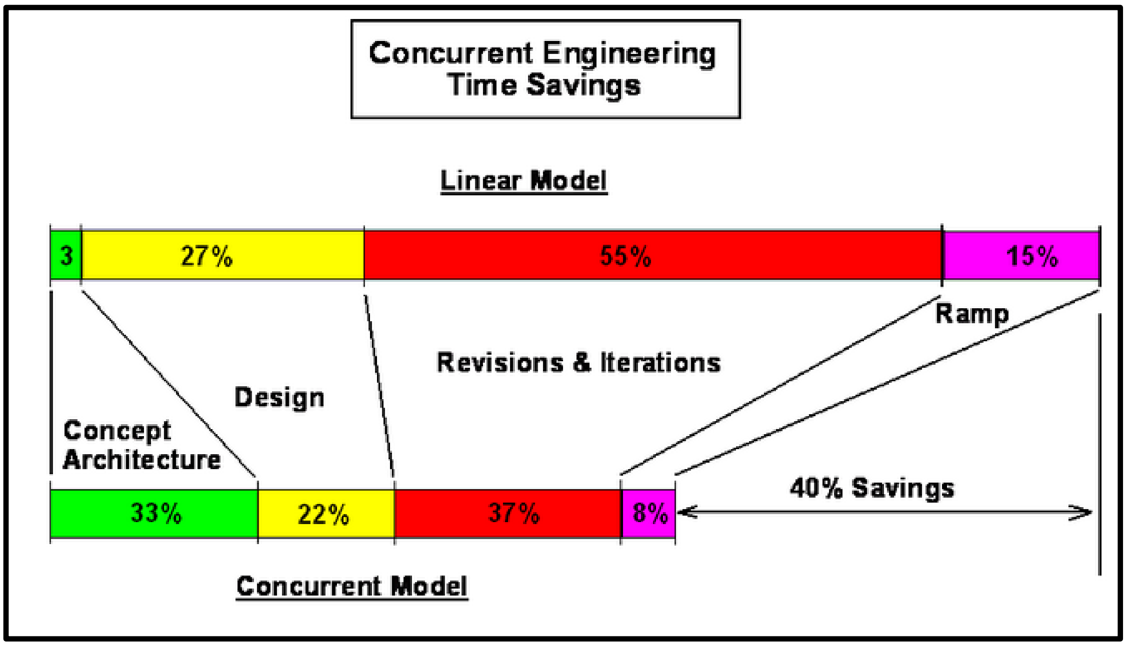


Figure 4.2. *Time savings achieved at Lexmark following implementation of DFM and concurrent engineering (Anderson 2013).*

One can note that the proportion of time used to concept architecture increases heavily when compared to the linear model and that the proportion of revisions and iterations decreases notably. The improvement of cycle time due to implementation of DFM is greatly based on decrease of changes and iteration in the start-up phase of production resulting from early concept architecture optimization. The total time for revisions, iterations and ramp-up phases decrease from nearly 75 % to less than 50 %.

In DFM it is desirable to keep the quantity of parts required to a minimum. This can be achieved, for instance, by combining actions carried out by separate components into a single component. (Aquilano et al. 1995) Minimizing the quantity of components is especially favourable for assembly operations and thus can be described by another term encompassed within DFM, design for assembly (DFA), which aims specifically at reducing the time, effort and cost of assembly operations in the product. (Miles 1989) DFA can be considered also a separate element from DFM, but as Swift (1989) remarks, in this field several techniques do overlap and their results are often similar.

Albeit DFM is usually clearly beneficial, designers face the problem of extensive knowledge requirements. When optimal functionality and economical manufacturing are considered simultaneously, extensive knowledge is required from several fields such as materials, manufacturing and assembly technologies. This can take years to accumulate. To an extent this issue can be combatted by co-operation between experts of different topics, but this may not be easy due to, for example, organisational structures such as separate locations of manufacturing and engineering design departments. (Swift 1989) Conradson et. al (1988) also present some drawbacks of DFM tools. For example, the DFM tools might not take into account many manufacturing capabilities or tolerancing considerations. Also, their accuracy may not be sufficient to provide useful information when products with low profit margin are considered. Bancroft (1988) adds that while DFM suggest combining components of the assembly so that one component can incorporate many functions, sometimes it is easier to add several simple manufacturing steps than one complicated one. When the importance of design is emphasized DFM also leads to shift in decision-making power within the organisation. It gives manufacturing a notable influence over product designer and conversely the designer is given a great influence over the choosing of the manufacturing method. Therefore Bancroft (1988) concludes that if applied incorrectly DFM has the potential to hurt the company instead of benefiting it.

4.3. Reliability

When complex machines are designed reliability is always a factor to be considered. It affects, for example, the design of the components, the quantity of the components and the upkeeping maintenance of the machine. (Marseguerra & Zio 2000)

The complete modelling of reliability and availability of a complex machine is likely to require huge effort. One needs to take into account, for instance, the dependencies of component failures, the different failure modes of components and systems as well as the seasonal variation in mean time between failures (MTBF), which leads to complicated modelling. (Marquez et al. 2005) For instance, in the case of the seasonal variation the MTBF tends to be larger at the start up after maintenance or upgrade break, declining as the time passes and starting to increase again just before the next scheduled maintenance. This is commonly referred to as bathtub distribution within the reliability engineering branch (e.g. Gurgenci & Guan 2001, Farrero et al. 2002) due to its form when described in time-failure rate –chart. The bathtub curve is presented in Figure 4.3.

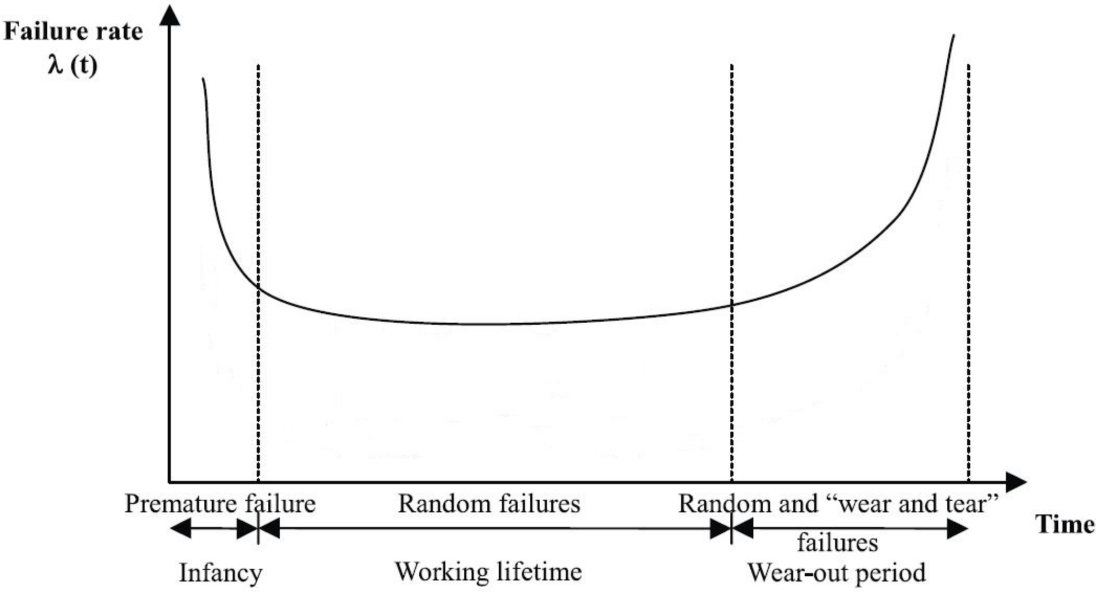


Figure 4.3. The bathtub curve (Modified from Farrero et al. 2002).

The curve is basically a combined distribution of three different Weibull distributions, with different parameters, one for each phase. On top of seasonal variation, a lot of data for different component breakdown rates might be insufficient or not available (Marquez et al. 2005). Despite extensive testing, this is especially relevant to CLIC as it employs novel technology.

Reliability can be analysed by several analytical models, such as k-out-of-n, component repair priorities and redundancies. To avoid restrictive, and probably misleading, assumptions needed to place in analytical models Monte Carlo analysis can as well used. (Marquez et al. 2005)

When examining a simple case where each component is crucial, i.e. unavailability of one component leads to unavailability of the whole machine, and assuming that design change does not affect the failure rates of the components, the fewer components are used the better the total reliability of the machine. The operating rate as a function of component quantity in this case is presented in Figure 4.4.

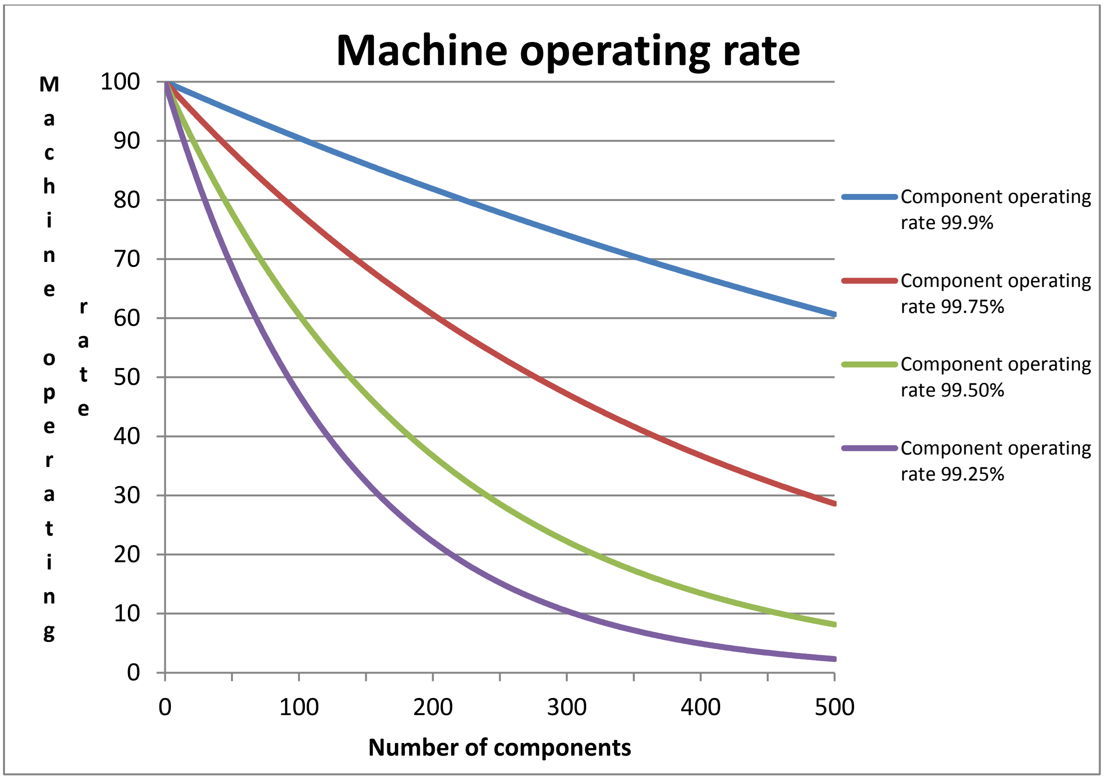


Figure 4.4. *Operating rate of a machine as a function of component quantity when all components are deemed crucial.*

For example, a system consisting of 100 components with failure rate of 0.25 % for each has an operating rate Q_s of:

$$Q_s = {Q_p}^n = (1 - 0.0025)^{100} \sim 77.86\ \% \qquad (4.1)$$

, where Q_p is operating rate of one component. If the number of components is decreased by 10 % to 90 the systems operating rate increases to 79.83 % and the greater the failure rate the greater is the improvement achieved by decreasing the component quantity. This leads to decrease in corrective maintenance (i.e. on-failure repair) cost as mean time between failures increases.

In some cases it is possible to carry on corrective maintenance while machine is operational and some systems are designed to tolerate a certain component failure rate before the efficiency is compromised beyond acceptable level. In this case the operational rate Q_s can be calculated with k-out-of-n method:

$$Q_s = \sum_{i=k}^{n} \binom{n}{i} p^i q^{n-i} \qquad (4.2)$$

, where n is the number of components, k is the number of components that are required to work for the system to work, p is the reliability of one component and q is the unreliability of one component. A k-out-of-n case with p=0.95 and k=0.9*n is illustrated in Figure 4.5.

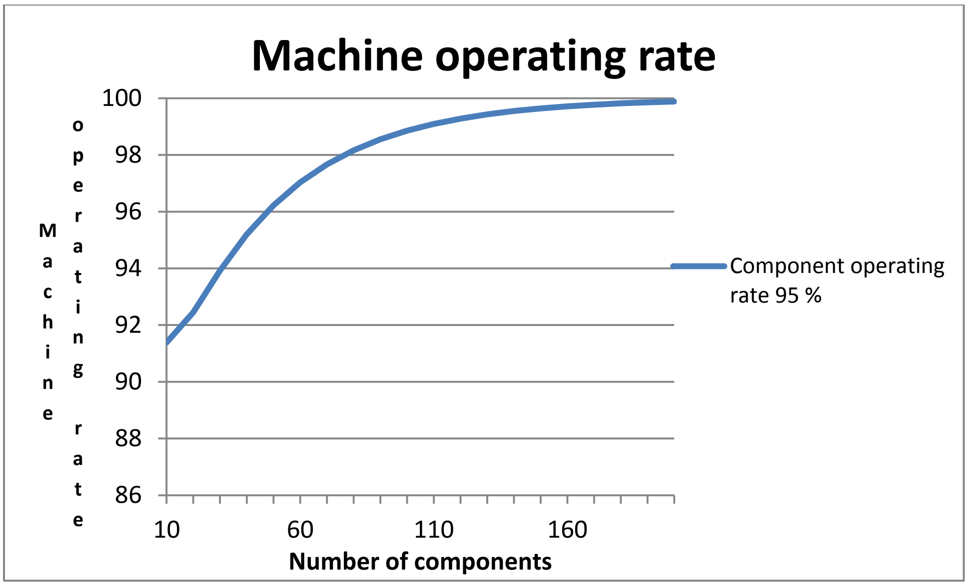


Figure 4.5. Operating rate of a machine as a function of component quantity when 95 % of components need to function in order to machine to be operational.

In this case the reliability of the machine improves when the quantity of components increases if the proportion of working components stays constant. With large number of components having high reliability the effect of component quantity in k-out-of-n case is reduced. For example, in case illustrated in Figure 4.5., if component reliability is increased to 99 % from 95 % the machine operating rate of 99.95 % is achieved already at 40 components.

The total reliability of CLIC depends on the reliability of its systems. Breakdown in any of the crucial systems (e.g. injector system, damping rings etc.) leads, in most cases, to seize of operation but in certain cases systems endure certain component failure rate during operation. Improved reliability results the availability of the machine to improve. Similarly to LHC, also for CLIC the lost operational day due to unavailability increases the cost-to-completion of the machine, i.e. the date when the machine has served its purpose and will retire gets postponed which results various costs to increase. Albeit being able to continue operation, unintentional breakdown also leads to loss of integrated luminosity leading to decrease in quality of the statistics of the physics measurements. (Petterson & Martel 2005)

4.4. Learning factors

Essential concept in the cost estimation for CLIC two-beam modules is application of the learning curves to the production. Learning curve is a function describing how the labour hours, or alternatively labour costs, decline as a result of improved efficiency when the cumulative production quantity increases. When labour costs are considered issues like inflation and changes in exchange rates have to be taken into account and these effects should be removed from examination when using learning curves (Day & Montgomery 1982). It should be noted that while the terms learning curve and improvement curve are often used interchangeably, learning curve can be used to refer only improvement due to learning of the operator, whereas term improvement curve includes also improvement resulting from, for example, organisational efficiency and improved tooling. (Zandin 2001a) Additionally there exists term experience curve which encloses also administrative costs, like marketing and distribution (Bhimani et al. 2008), albeit Argote and Epple (1990) make a note that this term, as well as terms progress curve and learning by doing, can also be used synonymously to learning curve . In this thesis the terms learning and learning curve are used to refer to all improvements caused by repetitive actions in manufacturing of large series of components.

Learning curves can be used to create a projection of costs when large unit quantities are produced. Adversely the theory can be used to set cost targets. In some cases it has been shown that learning effect does not occur if it is not expected and demanded by the management. (Howell 1981)

The concept of learning curves has been criticized for its similarity to the concept of economies of scale and it has even been proposed that the two concepts are essentially the same. Undoubtedly, the two terms do bear similarities but the approaches are initially different. According to learning theory, economies are achieved by optimising the manufacturing process following to experience gained from repeated actions in production over a period of time (i.e. accumulated production) when economies of scale are assumed to arise from the sheer volume of the production per time period (i.e. production rate). (Spence 1981) In principle both can exist simultaneously which makes their differentiation difficult. An example of this would be when company decreases its production rate the unit cost increases according to the theory of economies of scale, but the unit cost would still be inferior to first produced units as experience has been gained in production according to the learning curve theory which is not dependent on current production rate.

The learning curve theory was originally proposed by Wright (1936) after observing that the unit cost of airplanes decreased as more airplanes were produced. The percentage of cost reduction experienced always when the quantity of airplanes produced was doubled could be approximated to be constant. In Wrights study this percentage of remaining cost after doubling the cumulative production was 80 % (e.g. Anzanello 2011, Zandin 2001a, Argote 1990).

Wright’s model, also called log-linear model, due to the learning curve being linear in logarithmic coordinates, can be written:

$$y = C_1 \mathrm{x}^{\mathrm{b}} \qquad (4.3)$$

, where average cost of units y is determined by total number of units produced x and the cost to produce the first unit C_1. The learning effect is illustrated by parameter b ($-1<b<0$), where the learning is the greater the closer the value of b is to -1. (e.g. Yelle 1979)

Problem with parameter b is that it is not intuitive. Therefore parameter a, so called percentage slope or, as it is referred to in this thesis, learning factor is more commonly used. The relationship between b and a is:

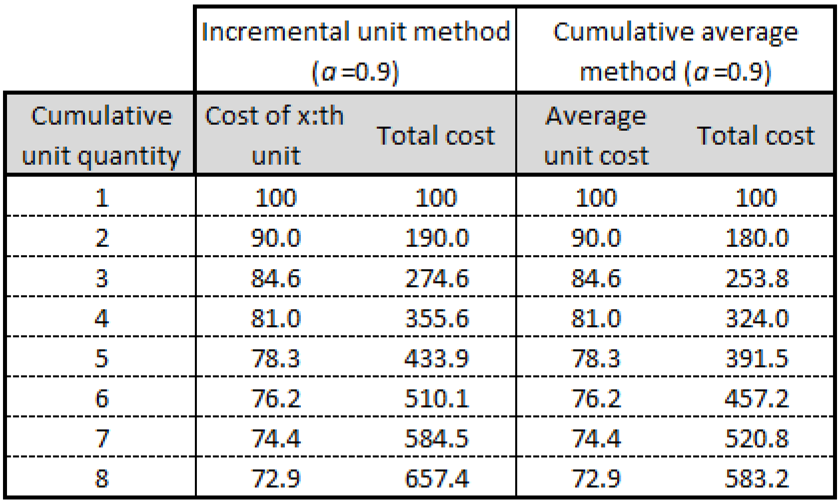
$$a = \frac{10^{b\,log_2+2}}{100}, \qquad (4.4)$$

,where figure a represents the portion of cost left when the cumulative production quantity is doubled. (Stump 2002) For example, if the first unit would cost 100 euros to produce and a=0.9 the average cost to produce two units would be 0.9*100 euros, the average unit cost for four units would be 0.9^2*100 euros and so on.

After Wright's initial model several different learning models have been developed. These can be roughly divided into two categories: log-linear and non-log-linear models. In log-linear models there are simple log-linear models and continuous log-linear model, where learning is considered to happen during the whole manufacturing process, not only after a unit is produced. The continuous model is also called mid-unit learning curve model. As simple log-linear model is used in this study they are described in greater detail later. Non-log-linear learning models include hybrid, or dog-leg, learning curves, which incorporate the possibility of learning factor changing during the production into the model and are thus basically combinations of two or more log-linear curves. Learning curves with plateau effect assumes that after a start-up phase of production the productivity improvements become negligible and the learning curve evens out. S-shaped curve provides possibility to fit log-concave and log-convex data and convex-asymptotic learning curves project a convergence to steady-state as production quantity increases. Also concave-asymptotic learning curves have been proposed. (Smunt 1999)

The two main types of simple log-linear learning models are the cumulative average learning model, or Wright model, originally proposed by Wright (1936) and a variation of this called incremental unit learning model or Crawford model (E.g. Fessia et al. 2007, Jensen 1991, Delionback 1987). Both of the models use the same formula 4.3. but they differ in their interpretation of the output y. When incremental unit model interprets y as the cost of x:th unit, the cumulative average model considers y to be the average cost of units when x units are produced. Being based on the same formula, both models implement the concept of learning percentage, but it is crucial to note that using the same factor leads to different results depending on the model used. This is illustrated in Table 4.1.

Table 4.1. *Comparison of the two learning models.*



	Incremental unit method (a =0.9)		Cumulative average method (a =0.9)	
Cumulative unit quantity	Cost of x:th unit	Total cost	Average unit cost	Total cost
1	100	100	100	100
2	90.0	190.0	90.0	180.0
3	84.6	274.6	84.6	253.8
4	81.0	355.6	81.0	324.0
5	78.3	433.9	78.3	391.5
6	76.2	510.1	76.2	457.2
7	74.4	584.5	74.4	520.8
8	72.9	657.4	72.9	583.2

It is clearly seen that the difference in total production cost when same learning factor (0.9) is used for the two different learning models is notable. The mathematics behind this difference is simple: total cost for individual unit method is the sum of unit costs whereas the total for cumulative average method is the cumulative average unit cost multiplied by unit quantity. The basis for both methods being the same, by converting the learning factor from one system to another, the same result can be achieved.

Intuitively it is clear that the precision of learning effect is reduced notably due to random variation when production quantities are small and that the precision increases with the number of units produced. Choosing wrong value as first unit cost will also result deviation from the cost forecasted by learning theory. As the production quantities increase, both of these phenomena have less influence and thus the theory can be assumed more accurate.

Choosing the right learning factor is crucial in order achieve valid estimation. The importance derives from great effect to the total cost of the product examined. The effect of learning factor (LF) a to average unit cost when incremental unit model is used is illustrated in Figure 4.6.

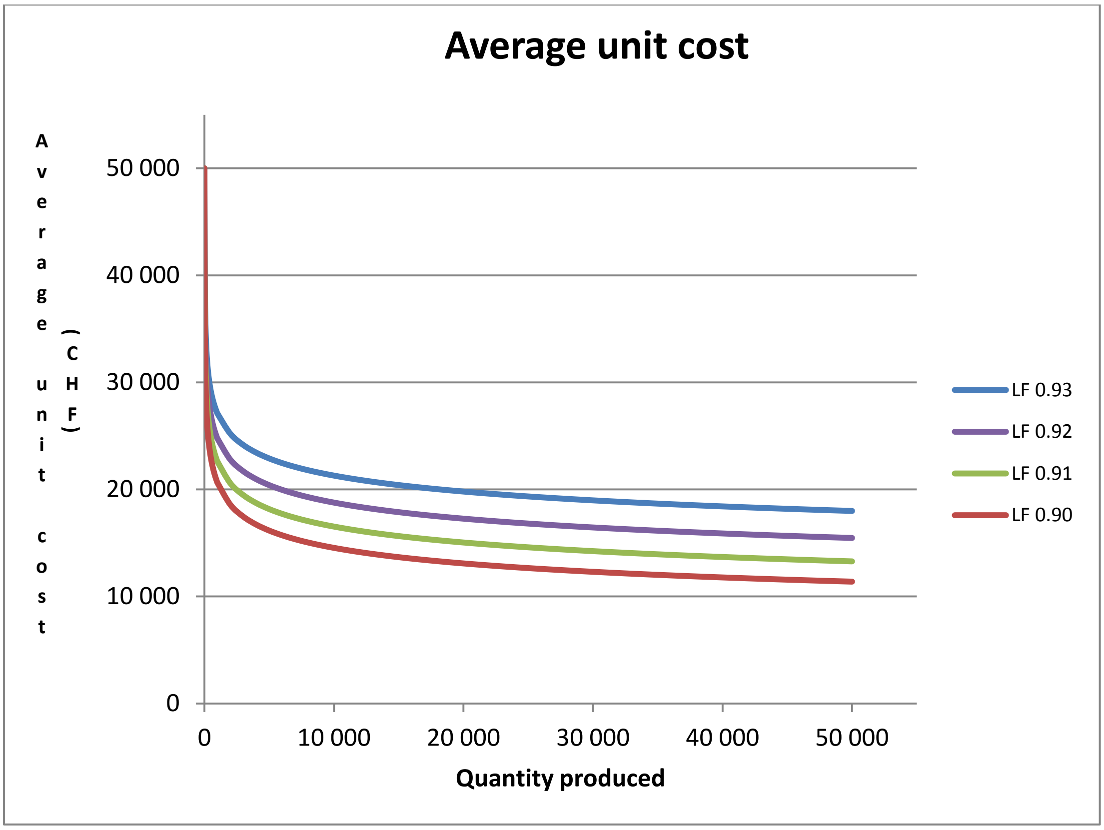


Figure 4.6. *Average unit cost as a function of production quantity for different learning factor values using incremental unit learning model.*

In the figure the development of average unit cost when the first unit cost is 50 000 CHF is displayed as a function of number of units produced. It can be clearly seen that even a change of just 0.01 in learning factor results notable variation in the average unit cost. The sensitivity is far greater than with prototype cost. For example, the average price of 50 000 units with a=0.92 and prototype cost of 50 000 CHF is the same as if prototype cost would be 42 985 CHF (14 % less than 50 000) and learning factor a=0.93 (just 1.1 % more than 0.92). Even when the learning factor can be based on previous production of similar units the margin of error when choosing a learning factor is considerable.

In the industry learning factor a usually gets values from 0.7 to 1 (Stump 2002), albeit these figures vary greatly. Argote and Epple (1990) collected realised learning factors from 108 studies and the range of factors was from 0.55 to 1.08 over 90 % of them receiving values between 0.7 and 1. Here is also seen that so called forgetting can happen. This can happen, for example, because of interruptions in the performance of tasks (Smunt 1999) and leads learning factor to be superior to 1 which means that latter units produced are more expensive than previous ones.

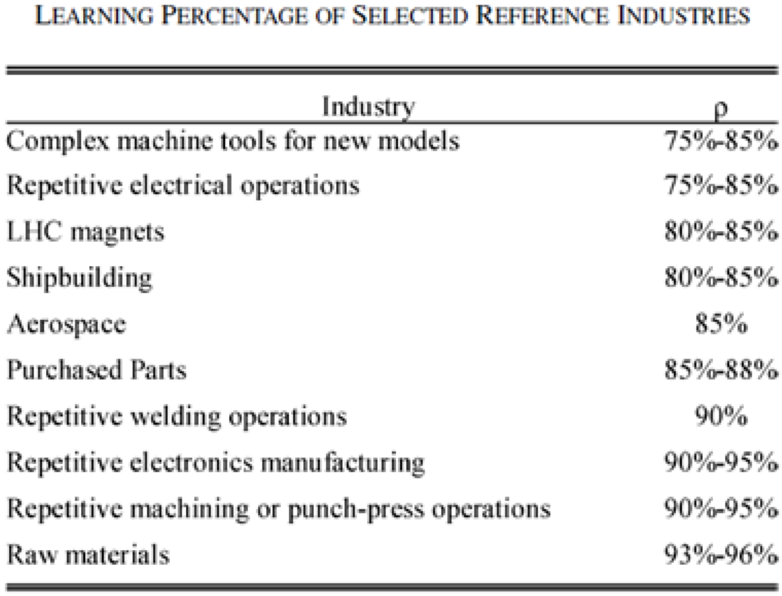
A rule of thumb is that the more the work includes automation the less there is possibilities to exploit learning effect and the closer the value of a is to 1. Delionback

(1987) gives following approximates for work including different amounts of manual labour:

- 75% hand assembly/25% automated = 80 % slope (a=0.8)
- 50% hand assembly/50% automated = 85 % slope (a=0.85)
- 25% hand assembly/75% automated = 90 % slope (a=0.9)

When different industrial activities are considered, experience based baseline learning factors have been established. Some of these are shown in Table 4.2.

Table 4.2. *Learning factors for selected industries (Fessia et al. 2007).*



LEARNING PERCENTAGE OF SELECTED REFERENCE INDUSTRIES

Industry	ρ
Complex machine tools for new models	75%-85%
Repetitive electrical operations	75%-85%
LHC magnets	80%-85%
Shipbuilding	80%-85%
Aerospace	85%
Purchased Parts	85%-88%
Repetitive welding operations	90%
Repetitive electronics manufacturing	90%-95%
Repetitive machining or punch-press operations	90%-95%
Raw materials	93%-96%

It is imperative to understand that these values are rough averages and the variation of realised learning factors is great even within activities of similar nature. For example, historical data for US Army missile programs show learning percentages from 75.5 % to 95.8 %, and even if the projects are stratified by contractor, execution years of the project etc. the range is not narrowed considerably (Vickers 2001).

Learning can be considered as infinite or a saturation point can be assumed to be achieved after certain production quantity after which there is no longer learning and the unit price stays constant. If no saturation is considered the unit costs keep on reducing infinitely, although for any practical purposes after certain point the slope of cost reduction is so small it can be estimated to be flat (Howell 1981).

The learning in production, and learning factor describing it, does experience some fluctuation and they can be affected, for example, by improving documentation, knowledge transfer or inventory flow of the production (Macher & Mowery 2003). Because the concept of learning factors already takes into account that at least some of these measures will be executed during the production run, it is hard to determine how much learning factors could be improved with these actions.

Albeit means of improving learning are recognised, managing learning factors is not easy. Firstly, cause-effect relationships are rarely clear. There might also exist equally possible contradicting explanations of a situation, for example, the differentiation between learning and economies of scale can be complicated. The amount of variables in the production system can also be so great that understanding the production system completely might be overwhelming. The complete understanding of input variables effect to the output of the model can also be lacking. As a result beliefs based on subjective, or even false, views that are hard to over-turn may become established within organization making managing of learning factors challenging (Lapré & Van Wassenhove 2003)

As several components of CLIC, for example AS disks and PETS bars, are manufactured in very large quantities, applying the learning effect is justified for cost estimating. Choosing the right learning factor to be used in the estimate is challenging as similar structures with corresponding accuracy requirements have not previously been produced in such a large scale.

In cost estimation for CLIC the incremental unit method has been used previously and to be able to easily use the learning factors in the previous estimates as well as to maintain coherency this study uses the same method. The learning factor estimates are considered to take into account also factors with which the learning could be improved and therefore learning factors are considered to have fixed values in this thesis.

To facilitate the calculation of total cost in large series production, the following equation is used for approximation of the total cost in the cost estimation:

$$\mathrm{C} = \mathrm{C}_1 \times \frac{\mathrm{n}^{(1+\log_2 \mathrm{a})}}{1+\log_2 \mathrm{a}} \tag{4.5}$$

,where C_1 is the cost of first unit produced, *n* is the quantity of units produced and *a* is the learning factor (0-1).

This formula gives a good approximation of the total costs for mass production. The larger the quantity produced the smaller is the relative error of the approximation produced by the formula. For very small series this approximation is poor, giving too large values and should not be used. As calculating the total cost analytically is simple when the quantity of terms is limited, analytical calculations should be used instead.

4.5. Quantity of production lines

Feasibility of different manufacturing strategies can be assessed with product-process matrix. This concept presented by Hayes and Wheelwright (1979) is shown in Figure 4.7.

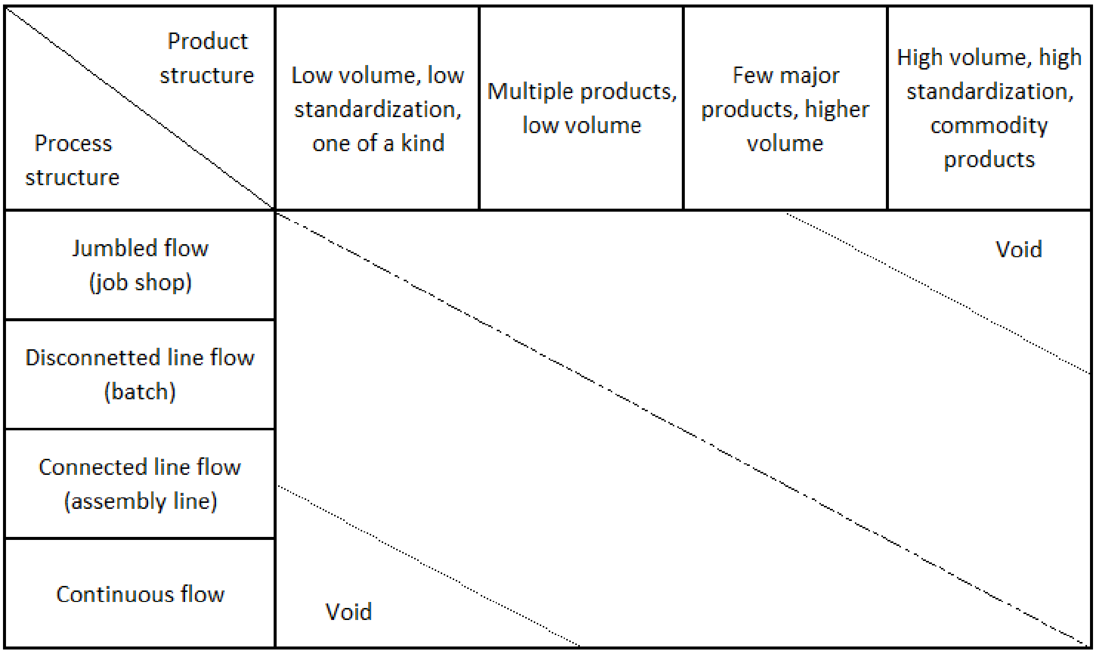


Figure 4.7. *Product-Process Matrix (According to Hayes & Wheelwright 1979).*

The central idea of this framework is that the optimised strategy is found at, or close to, the diagonal of the matrix. According to this scheme an assembly line is the preferred production strategy for high volume, low variation products. Good examples of such products are the components of CLIC RF unit.

Production line can be determined as a typically high volume manufacturing entity consisting of fixed sequence of production stages that consist of one or several work stations and/or machines. More broad definition of production lines includes flow lines for manufacturing and assembly as well as the potential buffers included. (Zandin 2001b) As the production quantities of components for RF unit of CLIC are generally large, production lines will be used in their fabrication. Production lines also promote uniformity of quality in the production through highly standardised work phases. This is especially important for CLIC as the components have high requirements for accuracy and one needs to be able to rely on that all the produced components fulfil these requirements.

In CLIC cost estimate, and therefore also in this thesis, a broad definition of production line is used. Therefore the term production line does not necessarily mean that a production line layout is used – a functional layout, or most likely a hybrid one, can as well be used. The decision on which layout to use, as well as optimisation of production, is to be done in co-operation with the contractors responsible for production.

Production lines can be optimised, for example, by choosing the right layout for the production in question, varying the levels of intermediary buffer storages between production stages and balancing the workload of the different phases so that idle times are minimised (Rekiek et al. 2002). Optimising and modelling of production lines is a vast field that has also been comprehensively covered in literature (Spinellis et al. 2000). Due to this vastness an in-depth examination will not be conducted here. Furthermore, as CERN does outsource the production, these decision are mainly concern of the contractors and as such not of major interest in this thesis. Instead the focus is on quantity of production lines used in production of components.

When the number of components to be produced is fixed, the fewer production lines are used the more components are produced per production line. As described in previous chapter 4.4. this affects the learning effect experienced in the production if no interchange learning is assumed to happen, that is each production line is assumed to be its own entity when learning effect is estimated and the cumulative unit quantity is calculated per production line not the total production of all the production lines. Therefore the total cost of the component increases when more production lines are used. If interchange learning, completely or partially, does occur the effect of quantity of production lines to cost diminishes. The change of cumulative cost of a component as a factor of production lines is illustrated in Figure 4.8.

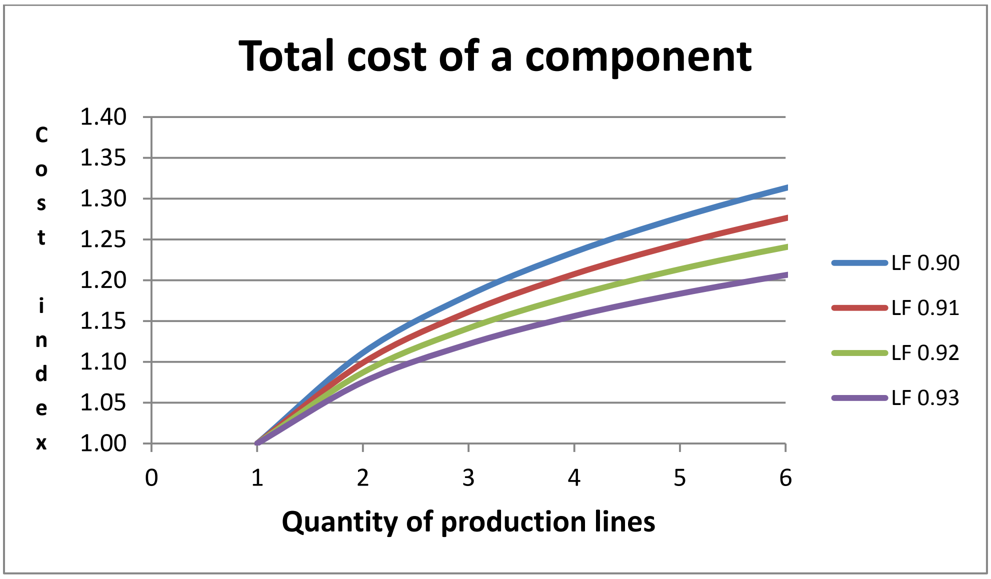


Figure 4.8. *Production cost as a function of production line quantity with different learning factor values.*

The figure shows the increase of total cost as the quantity of production lines is increased due to reduced benefits from the learning effect. Different lines illustrate the development with different learning factors: the larger the learning factor, the smaller the effect of quantity of production lines to the total cost is. By decreasing the quantity of production lines the quantity of components produced per production line increases leading to better exploitation of the learning effect and thus lower cost.

The critical need for consistent quality further emphasises using few suppliers (Aquilano et al. 1995). Naturally this leads to the fact that choosing suppliers is a very important task as close relationship with the supplier is likely to last for a long time. Points to be considered in the selection include, for example, capability (can the requirements be matched), quality assurance, financial capability ("financial health" of the firm), cost structure (having visibility to suppliers costs e.g. materials, direct labour, overhead and profits) and production scheduling (how our product fits in suppliers schedule). (Aquilano et al. 1995)

Berger et al. (2004) further point out some drawbacks of having larger supplier base. Dealing with several suppliers requires more resources for managing the more complex supply chains than when there are only few suppliers. Each supplier is also required to maintain the necessary technology, machinery, expertise and quality of production. The point of supplier requirements is especially relevant in cases where high standards are required from the contractors, such as state-of-the-art ultra-precision manufacturing needed for manufacturing CLIC RF unit components.

On the other hand, when the quantity of production lines or suppliers is reduced the robustness of production will suffer. Thus sharing the production can be justified from risk management's point of view. Risks that can interrupt the production of a plant or production line include, for example, natural disasters (e.g. flooding), accidents (fire) and financial risks (bankruptcy) (Berger et al. 2004). If one supplier has problems in deliveries the impact on total production is reduced if there are several suppliers that continue to deliver the components as agreed. In best case scenario they might even be able to compensate some of the production losses due to problems of one supplier by increasing their production. Especially when the requirements for production are high, validating an alternative supplier outside the current supplier base or increasing the production with current ones, is likely to take a lot of time.

As CERN is the final customer of the products provided by the suppliers the delivery schedule is relatively flexible in contrast to, for example, consumer electronics such as mobile phones where a delay of one to two months may result in huge losses as the device is no longer state-of-the-art when arriving to the markets. This being the case, the weak robustness of production of the components can still cause shortage of components in, for example, assembly of subsystems and therefore cause disturbance throughout the supply chain.

Additionally the political nature of CERN funding also promotes using several suppliers. To allocate the money spent by CERN more fairly among the member states contributing to CERN budget a return coefficients are set for supply contracts (Unnervik 2011). Dividing the production to several member states promotes these goals.

The quantity of production lines to be used is purely deterministic. The choice on how many lines to use can be clearly determined and thus no possible error needs to be considered after the decision has been made. If risk of interruption is not considered, decreasing the production lines quantity is only subject to the production capacity of the suppliers and scheduling of the production. If fewer suppliers can provide the needed components in acceptable time frame, there is nothing preventing using fewer suppliers. Increasing the number of suppliers might prove to be more challenging as several components require extremely tight machining tolerances not many suppliers are likely to be able to match. Additionally the requirement of mass production capability further limits the possible suppliers.

One drawback of subcontractors providing the components for CLIC is that investments are needed for their production facilities and after the production of CLIC components is finished, it might be difficult to adapt the facilities to different kind of production. This is not directly an issue to CERN, but naturally limits the interest of subcontractors to participate in the project and likely increases the price of the components they offer. On the other hand, as Rekiek et al. (2002) state, often modern production systems are characterised by short life-cycle-times of products and production systems and high investment costs, so in this aspect production of CLIC components only takes this trend a little further.

5. EVALUATING THE UNCERTAINTY

There exist several methods for evaluating the uncertainty depending on, for example, the application, variables and desired use of the result of the evaluation. For example, breakeven analysis can be used to evaluate the feasibility of two options. In this, one seeks out a breakeven point of an uncertain factor in which both alternatives are equally feasible and then estimate the likely value of this factor and compare it to this breakeven point. Another example is best case-worst case estimation (also optimistic-pessimistic estimation) where one gives uncertain variables their best and worst case values. If the outcome of even the worst case is positive, the alternative is desirable and vice versa if the outcome of best case is negative. When using this method, in normal case managerial judgment is required to make the final go-no go -decision. (DeGarmo et al. 1989) In this thesis two methods are used in evaluation of the uncertainty, namely sensitivity analysis and probability functions, the latter more specifically in the form of Monte Carlo simulation.

5.1. Sensitivity analysis

Sensitivity analysis is used in several fields where mathematical modelling is present to gain insight to e.g. engineering, social, physical and economic phenomena. (Hamby 1994) When conducting cost estimate in early product development stage numerous assumptions has to be made (Kellogg et al. 2010). Almost all of the parameter values and assumptions of every parametric model include some error and are subject to change. Many of the possible changes have negligible impact on the outcome of the estimate while others might cause considerable variations (Kellogg et al. 2010). Sensitivity analysis can be broadly defined as studying these errors and changes and the resulting impact on the outcome of the model (Pannell 1997). Saltelli (2002) gives a definition that illustrates well the usage of sensitivity analysis in this thesis: “Sensitivity analysis is the study of how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input”.

Because organisations have limited resources for reducing uncertainty it is important to know how to allocate these resources. Sensitivity analysis provides one way of directing the resources as efficiently as possible.

Sensitivity analysis can be conducted for a number of reasons such as:

- which parameters require additional research to acquire more knowledge and thus reducing output uncertainty
- which parameters are insignificant and can be eliminated from the model
- which inputs contribute the most to output variability
- which parameters are most correlated with the output (once model is in production use)
- what consequence results from changing an input parameter. (Hamby 1994)

Sensitivity analysis can provide information of robustness of the optimal solution for different parameter changes, the circumstances under which the optimal solution would change, how the optimal solution changes when circumstances change and would ignoring the changing circumstances affect notably the outcome, especially in a negative manner. By observing the changes of the outcome following the parameter changes the riskiness of the scenario can also be estimated (Pannell 1997). For example, if changing some input parameter would, according to the model used, seem to result only limited improvement in the output it may be beneficial to preserve the original parameter value nonetheless as applying the change might result in unforeseen change costs.

Most often sensitivity analysis is used to determine which parameters have the most influence on the output of the model which makes it possible to eliminate unimportant parameters. Further research can also be focused to those parameters that have the most effect on the output in order to decrease their uncertainty and thus improve the model. Albeit sensitivity analysis methods produce a ranking for sensitivities, its importance is usually limited. Instead it is important to find the top parameters to which the model is sensitive. (Hamby 1994)

One typical use of sensitivity analysis is to compare alternatives whose outcomes are close to each other. In these cases the alternative which is notably less sensitive to possible estimated changes is likely to be chosen over the other one. (Riggs 1977)

When conducting sensitivity analysis the ranges of parameter changes need to be estimated. Following this, it needs to be decided shall the parameters be varied one at a time while keeping the other ones constant, shall the examination concentrate on simultaneous changes of combination of parameters or shall simultaneous changes of all the parameters be considered. (Pannell 1997) Simplest of these approaches is the one-at-a-time method where one the parameters is modified while keeping rest of the parameters constant (Hamby 1994). This concept, also referred to as local sensitivity analysis, is applicable to deterministic models but rarely used with probabilistic analysis. It can be used to identify the most important inputs or to prioritize the need for further data collection. (Frey & Patil 2002) For models having dozens of parameters it can be inconvenient and subjective analysis may be needed to reduce the parameter quantity by eliminating the less important ones. (Hamby 1994)

The correlation of the parameters should also be assessed. (Pannell 1997) Say, for example, a production facility uses crude oil in its production process which also requires electrical power. The prices of these are likely to correlate so that if there is a rise in the price of crude the price of electricity will be elevated to some extent as well. This correlation should be built into the model.

Sensitivity index is a value used to assess the relative sensitivity of the model's parameters. For calculation of this index there exist several methods that are disparate with each other and thus their results cannot be compared with each other. These methods include, for instance, differential sensitivity analysis, the Smirnov test and Pearson's r method (Hamby 1994).

The data requirements vary for different sensitivity analysis methods. Several of these calculation methods are relatively complex, and the more complex models usually require more information, for example, equations for the input distributions and the formulation of output. (Hamby 1994)

According to Hamby's (1995) comparison of several different sensitivity indices the simple sensitivity index proposed by Hoffman and Gardner (1983) is generally the best performing when compared against a composite sensitivity index calculated on the basis of ten different sensitivity indices. Hoffman's and Gardner's index is calculated:

$$Sensitivity\ index = \frac{D_{max}-D_{min}}{D_{max}} \tag{5.1}$$

,where D_{max} is the maximum value of the output using the determined range of parameter input and D_{min} is the minimum value of the output using the same range. As well as reduced effort in calculating the index, from managerial point of view, this simple index does not require extensive familiarizing with the method used to be understandable. As "an analysis which is not understood is unlikely to be believed", (Pannell 1997) the conclusions from results achieved using simple sensitivity index are more easily justified to the decision makers.

5.2. Monte Carlo analysis

Total cost distribution can be estimated either analytically by combining the distributions of elements of the work breakdown structure (WBS) or by using Monte Carlo process (Kellogg et al. 2010). Monte Carlo process is an experimental probabilistic method that can be used to solve deterministic problems. It is usually used for modelling events that have considerable uncertainty in their inputs. Fields of use include, for example, finance (e.g. Glasserman 2004), biology and computer science (e.g. Liu 2008).

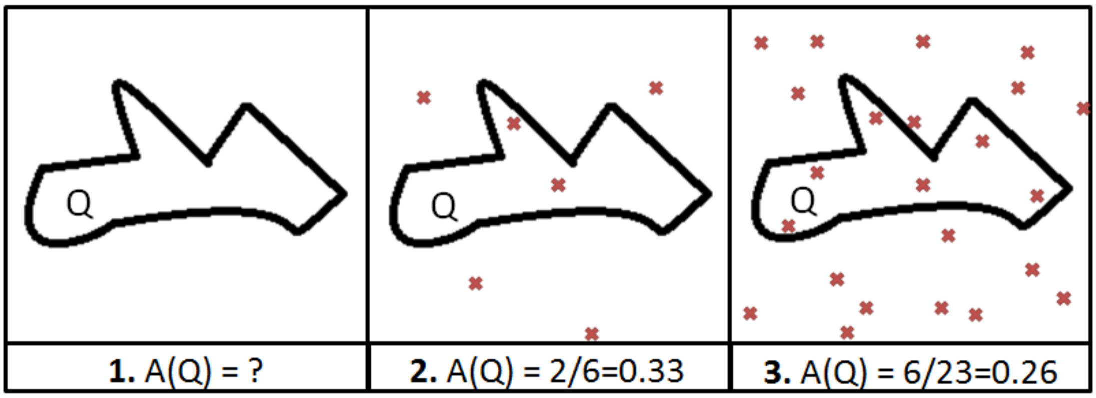
The term Monte Carlo refers to the famous casino area in Monaco. It is said that the term was first used for stochastic simulations conducted for the Manhattan project during the Second World War, albeit the technique itself has been used a lot earlier.

In pre-computerized era conducting a comprehensive Monte Carlo analysis was extremely time intensive. During the last decades the use of the method has been emphasised by the development of computers giving all more people access to devices capable of simulating large number of experimental trials with random outcomes within reasonable time frames (Papadopoulos & Yeung 2001) albeit Marseguerra & Zio (2000) noted a few years ago that the weak point of extensive Monte Carlo simulation is still the computing time.

Monte Carlo process uses randomness and repetition in order to determine the outcome of the model or as Moshman (1967) states it is “use of stochastic techniques to solve a deterministic problem”. In practise this means that in Monte Carlo process each variable is drawn randomly from a specified range of the variable. For example, in uncertainty estimation random numbers are used to sample input parameters’ uncertainty range (Papadopoulos & Yeung 2001). Despite the determination of this range can at times be challenging, conducting the estimation analytically gets very complicated as the complexity of the WBS increases, resulting Monte Carlo to be the preferred method.

Basil and Jamieson (1998) further describe some advantages of Monte Carlo simulation. With Monte Carlo large, as well as small, number and uncertainties of inputs can be dealt with. Same is true for untypical input or output distributions. One can also avoid complex second order partial differentiations

A simple example illustrating the function of the Monte Carlo technique is estimating the area of irregular two-dimensional shape Q. This is illustrated in Figure 5.1.



1. A(Q) = ?

2. A(Q) = 2/6=0.33

3. A(Q) = 6/23=0.26

Figure 5.1. *Estimating the area of two dimensional shape Q with Monte Carlo technique.*

Here the shape Q is placed inside a square, for which the area can easily be calculated by determining the sides of the square. Sides of the square are chosen as coordinate axes and then numbers are drawn randomly to correspond coordinate points inside the square. An approximation of the area of Q is the percentage of the randomly generated points that fall within Q times the area of the square. The more points are generated the better is the estimation of the area of Q. For example, in Figure 5.1 the estimation of area of Q after 6 iterations is 0.33 but after 23 iterations it is improved to 0.26. With enough iterations the approximation can be considered to have negligible error.

To begin Monte Carlo simulation random numbers need to be sampled. This can be done with several different methods. Simple random sampling, as the name suggests, works simply by generating a random number and applying it to the probability distribution of the variable parameter. With appropriate scaling the distribution for parameter's values is achieved. (Macdonald 2009) Possible issue with this method is that because random numbers are picked always from the total range, the random numbers might not be evenly distributed. To confront possible error caused by this, larger number of random numbers can be generated which leads to greater statistical accuracy but has an evident downside of requiring more computational effort.

Alternatively stratified sampling can be used. In this method the random numbers are forced to be drawn from certain places of the distribution. (Macdonald 2009) For example, the method can draw random numbers from 10 different ranges each corresponding to 10 percentile of the total range.

One further alternative is to use latin hypercube sampling which is a further evolution of stratified sampling. The input is divided into strata and then samples are generated so that the value generated for each parameter comes from a different stratum (Helton & Davies 2003).

The latter methods result in less variance when the number of simulation runs is the same (Macdonald 2009). Still, no matter how the random numbers are sampled the determining parameter for accuracy of Monte Carlo analysis is the number of iterations used i.e. how many times the random numbers are generated and results calculated based on these. Therefore using simple random sampling with more iterations can be more accurate than stratified or latin hypercube sampling with fewer iterations.

Summing up, Sawilowsky (2003) gives a simple list of conditions that need to be met in order to provide a useful simulation with Monte Carlo:

- The pseudo-number generator produces values that pass the test for randomness
- The number of iterations of the experiment is large enough to ensure required accuracy
- The proper sampling technique is used
- The algorithm used is valid taken account what is being modelled
- The study simulates the phenomenon in question

The output of Monte Carlo analysis is a possibility distribution from which, for example, mean and variance can be extracted. When the distribution is illustrated as probability density function it also gives an intuitive illustration of the uncertainty in question.

6. CONFIGURATION OF RF UNITS

In the CLIC Conceptual Design Report an outlook for the next phase of the project, Technical Design Report –phase, is presented. Regarding the cost optimization of the project, one of the main areas regarding the two-beam modules to be investigated in TDR -phase was “number of components: longer RF structures, aiming at a reduction in the overall number of components” (Schmickler et al. 2012). Based on this demand, a parametric study of the cost reduction opportunities obtained by modifying the length of RF units is supplied in this thesis.

Reduction of total quantity of components will self explanatorily decrease the total cost if the design of the components remain unchanged. In case the design of component changes when RF units are made longer the cost effect needs closer examination. Additionally, when the quantity of RF units decreases, assuming that the design of two-beam modules stays otherwise the same and thus their quantity decrease as well, savings can be achieved in installation costs as fewer modules need to be installed. Also installation time can be assumed to decrease.

In this chapter the baseline configuration of the RF unit and the considered modified configurations of longer RF units are presented.

6.1. Baseline configuration

The configuration of CLIC RF unit, according to the current plans as presented in the CLIC Conceptual Design Report, is used as a baseline scenario for this study. In this design one PETS, that consist of copper bars of nominal length of 242.1 mm (34 cavities) extracts energy from the drive beam and feeds it through the RF network to two accelerating structures, both having a length of 29 accelerating disks. Illustration of the baseline configuration is presented in Figure 6.1.

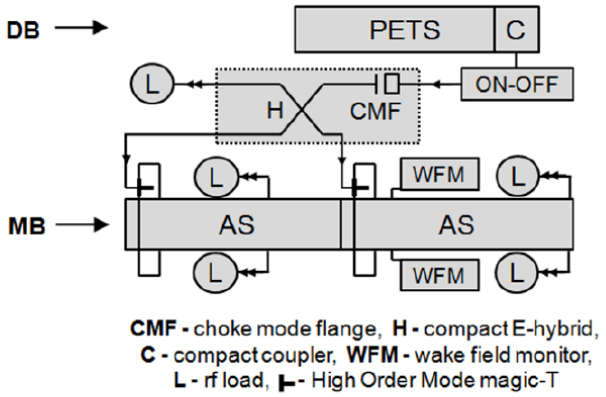


Figure 6.1. *The baseline configuration of CLIC RF unit (Schmickler et al 2012).*

The considered modifications to this baseline modification are presented in following subchapters.

6.2. Configuration A

In configuration A the RF unit's length can be increased stepwise. Accelerating structures can be lengthened one disk at a time – that is two disks per S-AS and RF unit. PETSs are lengthened correspondingly so that they can extract more energy from the drive beam to be fed to main beam. The RF network connecting the two remains unchanged from the baseline configuration seen in Figure 6.1.

The main advantage of this configuration is that length can be adjusted by small steps and thus the possible limitations of e.g. machining of the components can more easily be evaded. Another clear advantage is that there is no modification to the design of RF network, so no additional engineering effort is needed there. A simplified illustration of configuration A, highlighting the changes when compared to the baseline configuration, is presented in Figure 6.2.

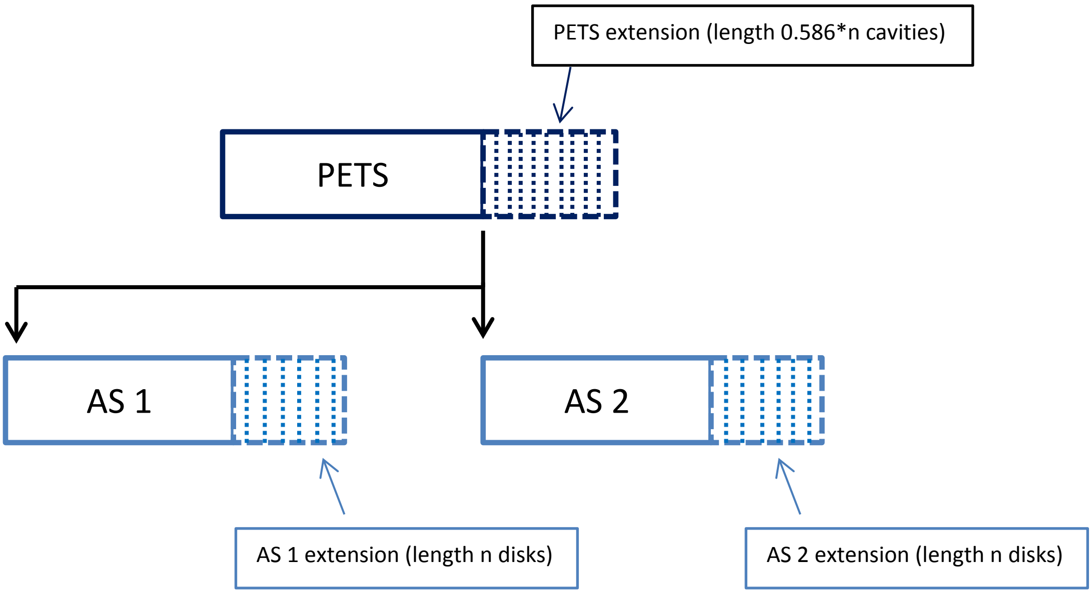


Figure 6.2. *Simplified illustration of configuration A for lengthening the RF units.*

Different length structures have already been produced for needs of different experiments. For example, accelerating structure of 72 cells, which is considerably longer than the baseline CLIC accelerating structures, has been produced for FERMI FEL facility (Dehler et al. 2012). Similarly, a longer PETS has been manufactured for test purposes.

6.3. Configuration B

In configuration B the RF unit is lengthened by adding two additional accelerating structures to the structure. The length of PETS is doubled to respond the increased energy requirements of having more accelerating structures. In this configuration the RF network undergoes minor design changes to be able to deliver RF power to every accelerating structure. In this study a simple method of adding one splitter to RF network is considered. The length of waveguides per RF unit is also increased to correspond to the need to transfer RF power to 4 AS instead of 2.

This configurations advantage is that the manufacturing process of accelerating structures can be kept exactly the same as in baseline configuration. Simplified illustration of this configuration is shown in Figure 6.3.

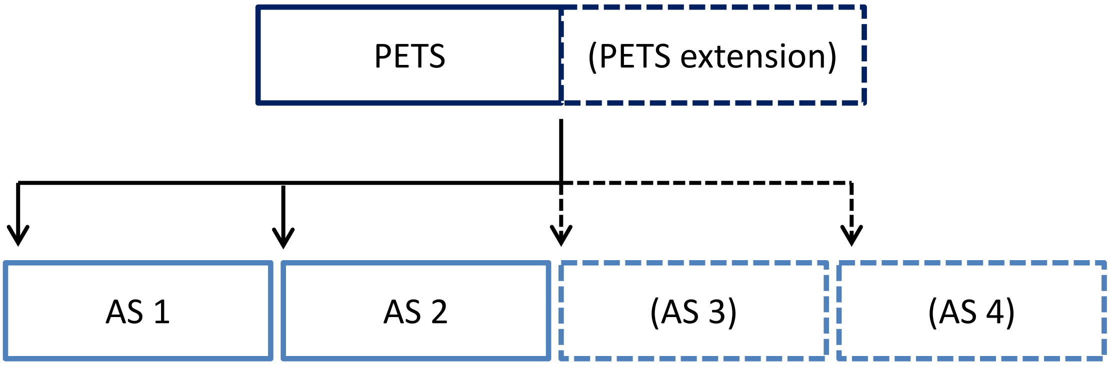


Figure 6.3. *Simplified illustration of configuration B for lengthening the RF unit.*

6.4. Configuration C

At the very end of the study when the results of this study were presented, an expert on physics of acceleration structures pinpointed feasibility issue in configurations A and B. Namely this considered the function of RF network with greater power levels extracted by longer PETS. As a result a third layout configuration was proposed and calculations were conducted also for this layout. The added configuration, configuration C, is largely based on configuration A with the difference that the lengths of PETS subassemblies are considered to be kept constant and only accelerating structures are assumed to be lengthened. This is demonstrated in Figure 6.4.

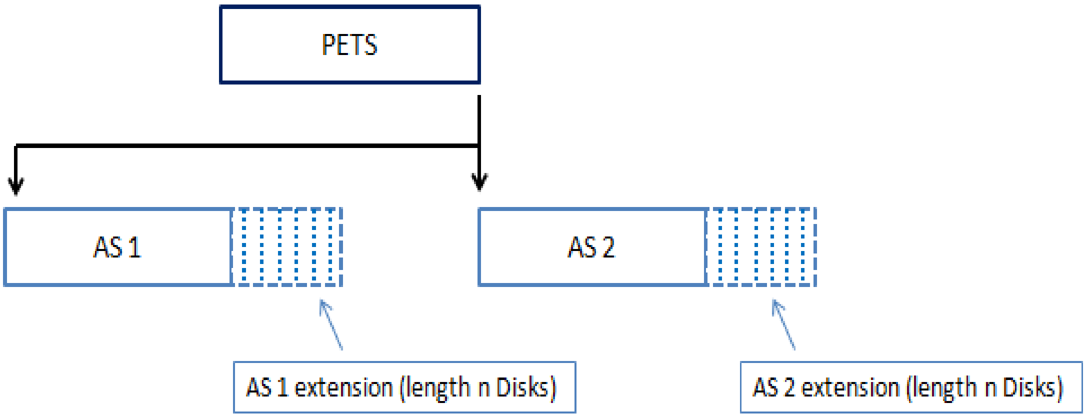


Figure 6.4. *Simplified illustration of configuration C for lengthening the RF unit.*

Naturally in this scenario the unit cost of PETS stays constant and potential cost reductions result from possible decrease in overall quantity of RF units leading to fewer operations required in their manufacturing and assembly. This possibility is based on that when the accelerating structures are prolonged keeping the length of PETS constant the operating efficiency of acceleration is improved because of fewer energy losses when the energy is transferred to the main beam. This allows the reduction of RF unit quantity. When total lifetime costs of CLIC are considered the reduced energy consumption resulting from this should also be taken into account. This study concentrates on the procurement cost of RF units and thus does not take these possible savings into consideration.

7. COST ESTIMATE MODEL

In this chapter the basis for the cost estimate conducted is presented. Parameters used in uncertainty estimate are also described.

7.1. Method

The basis for initial cost estimate uses engineering approach for cost evaluation. This is an analytical technique, where the cost of each component is evaluated as a sum of its parts based on their engineering design (Cavalieri et al. 2004). The method is time consuming but necessary due to lack of previous data. In engineering approach the specifications for manufacturing a product are analysed in order to determine the cost of the product. This method is often used for materials, at times for direct labour costs but for overhead costs its use is not preferred. (Moriarity & Allen 1991) To complement the results of engineering approach, survey approach is used. That is, for most components there exist internal cost estimates as well as estimates from possible industrial contractors. The current cost estimate used as a baseline in this study is formulated from these estimates using expert evaluation.

The cost estimate of this thesis was conducted as parametric study in which the cost is derived from analytical function of a set of variable (Cavalieri et al. 2004). Parametric modelling is most often used in earlier phases of projects but it is sometimes used even during detailed design, production and operational phases (Hamaker 1987). A model including all the parameters considered was created for each of the structure modifications considered. These models include the major components of the RF unit with their relevant cost information.

For configuration A there is a possibility to lengthen the structure by adding a single disk to accelerating structure. As RF unit incorporates two accelerating structures two disks will be added at one time. The PETS is lengthened correspondingly by increasing the number of cavities in the PETS bars, keeping the original ratio of disks in accelerating structure per cavities in PETS bar constant. Similarly following components are lengthened, when disks are added to the accelerating structure: PETS minitank, damping material within PETS, AS vacuum manifods and damping materials. The changes of length of these components are based on the drawings of the components so that length changes are relative to length of accelerating disks stack or length of PETS bars. For example, length of minitank will increase by as many millimetres that is the increase of length of PETS bars so that it is capable of encapsulating longer PETS. The changes in length and resulting changes in first unit cost of each component are incorporated in the model.

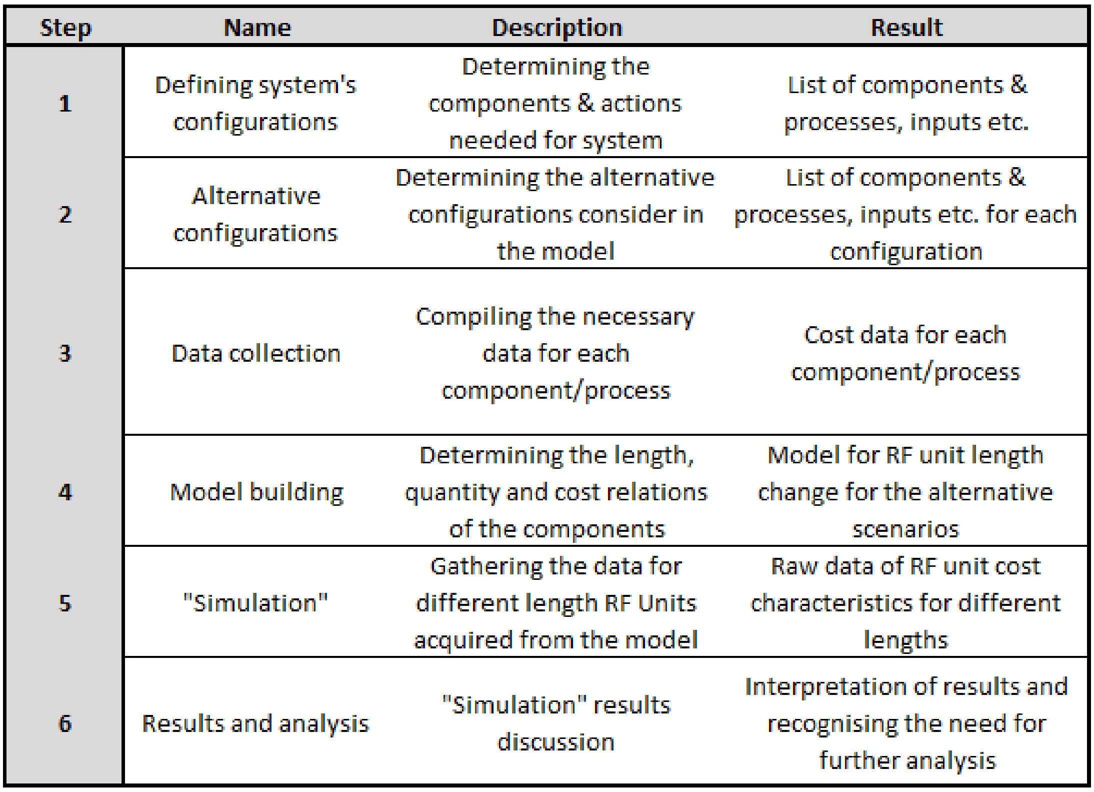
In configuration B the main modifications considered when the structure is lengthened is the increase of quantity of accelerating structures from 2 to 4 and lengthening the PETS correspondingly. The PETS components are prolonged similarly as in configuration A whereas the components of the accelerating structure keep their nominal length. Additionally RF network connecting PETS and accelerating structures is assessed to undergo small design changes in order to be able to feed two S-AS instead of one. As these changes fall upon simple components that contribute very small part of the cost, the changes were approximated without full account on technical details, as described in chapter 6.3.

For configuration C there are no changes from the baseline scenario in PETS or RF network. Only accelerating structures and its components are lengthened similarly as in configuration A described above.

As a base for scaling the increase of costs of components when they are lengthened quotes and/or realised orders for test structures having different length than the components in the baseline design were used. The quality of information varied from light breakdown of costs to lumped sum for the component in question. The increase of cost with length in case of machining was approximated to be linear albeit it was acknowledged that in reality the cost is likely to increase slightly stepwise as manufacturing processes are likely to undergo some changes when the length is increased considerably. When raw materials were considered, the cost increase was based on the cost per volume of the components and the increase of the volume with the design change. For few standard inventory components the basis used was cost per length unit.

Stepwise execution plan of the cost estimate is shown in Table 7.1.

Table 7.1. Execution plan for conducting the cost estimate for longer RF units.



Step	Name	Description	Result
1	Defining system's configurations	Determining the components & actions needed for system	List of components & processes, inputs etc.
2	Alternative configurations	Determining the alternative configurations consider in the model	List of components & processes, inputs etc. for each configuration
3	Data collection	Compiling the necessary data for each component/process	Cost data for each component/process
4	Model building	Determining the length, quantity and cost relations of the components	Model for RF unit length change for the alternative scenarios
5	"Simulation"	Gathering the data for different length RF Units acquired from the model	Raw data of RF unit cost characteristics for different lengths
6	Results and analysis	"Simulation" results discussion	Interpretation of results and recognising the need for further analysis

7.2. Parameters for uncertainty estimation

The values of parameters cannot, at this stage of the project, be taken as certain. To evaluate the effect the changes to these parameters could cause sensitivity analysis was conducted to classify the factors by their potential to influence the total cost if their values change. For evaluating the uncertainty Monte Carlo analysis was used.

For CDR phase of the study, the general uncertainty target of the cost estimate is +/- 30 %. In the CLIC cost estimate, that value is calculated based on experts judgement on components technical maturity, i.e. how likely the technological design is still to change and how much, and commercial procurement, i.e. how many valid offers are expected to be received from the industry for each component (Lebrun et al. 2012). In the current estimate the uncertainties for PETS and S-AS are estimated for the whole PETS and S-AS structures. As this thesis goes to more accurate levels of the product breakdown structure (PBS) and costing structure of RF unit than the current CLIC cost estimate a different method, described in this chapter, is used.

When uncertainty of the RF unit cost estimate is examined, some parameters are assumed to be change parameters instead of having constant values. The one parameter that is still taken as constant is the quantities of each component to be produced that are directly proportional to the quantity of the RF units. Due to the early stage of the project it is possible, even likely, that also the quantities will undergo slight changes as the design is optimised but evaluating the probability of these changes would be very difficult. As a result changing the unit quantity could cause decrease in the accuracy of the estimate as well as increase, and therefore this parameter is kept constant in this study. Also, the quantity of RF units in the baseline configuration does not influence the saving percentage achieved by prolonging of RF unit greatly, as the quantities of the components are dependent to each other. The stronger relative learning effect experienced with slightly smaller component quantities is not assumed to have major cost impact.

Change parameters for each component in the model are learning factors (see chapter 4.4.), production lines used in production (see chapter 4.5.) and first unit costs. For each of these a value used for calculating the cost estimate in this thesis was used as a baseline. To illustrate the uncertainty, ranges described next were considered for the parameters. For learning factors and prototype costs values were considered to be normally distributed within the ranges.

Normal distribution has the following characteristics:

- It is continuous and symmetrical
- Mean, median, midrange and mode have the same value and are situated at the centre
- The tails of the normal distribution extend indefinitely, therefore the distribution has range of –∞ to +∞ (Waller 2002)

Despite the latest point, the distribution can well be used to describe real world cases as values differing greatly from the mean are extremely rare. The width of the distribution can be assessed by z-distribution factor calculated,

$$z = \frac{x-\mu}{\sigma} \tag{7.1}$$

, where x is maximum value of the range, μ is the mean and σ is the standard deviation.

The z-distribution factor used for normal distributions in this study was 2.5757 resulting 99% of the generated values to be within the specified range. In case a different z-distribution needs to be considered it can easily be modified to the model. The effect of different z-factors to the distribution is illustrated in Figure 7.1, where the random variable is assumed to have a range from -100 to 100.

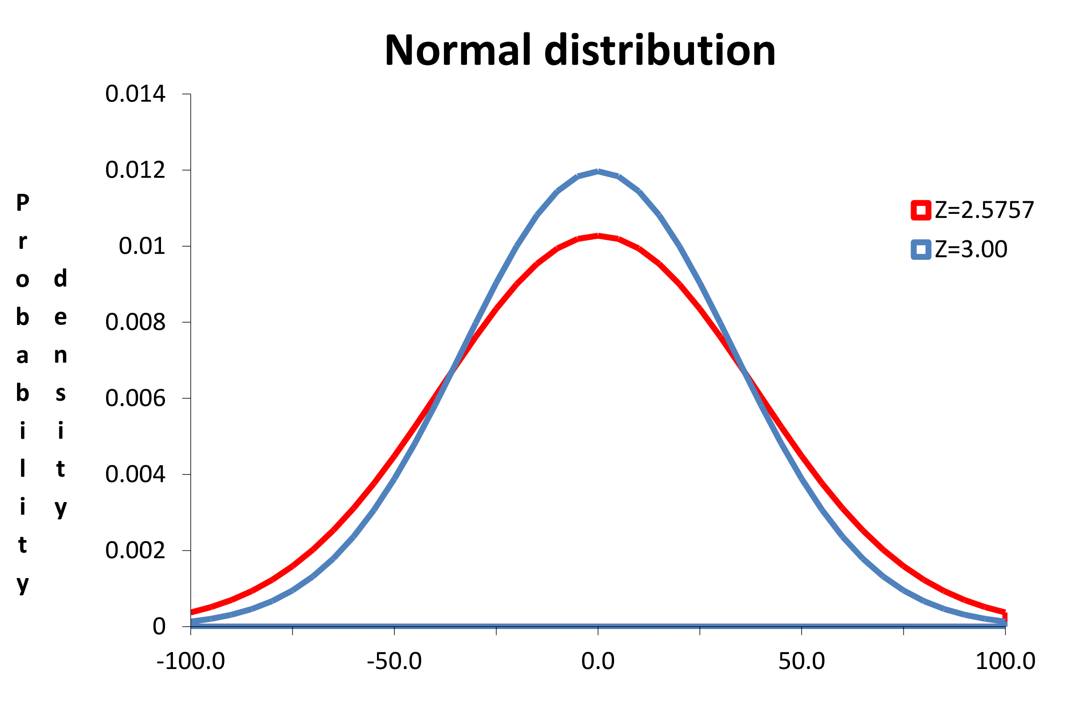


Figure 7.1. *Normal distribution for variable having the range -100 – 100 with different z-factor values.*

It is clearly seen that as z-factor is increased the distribution gets narrower. It is to be noted that with z=3.00 the integral over the curve in Figure 7.1 is 99.74 % instead of just 99.00 % with z=2.5757.

The baseline values for learning factors are a result of expert evaluation and albeit there does exist knowledge on similar type of production, as described in chapter 4.4., the variation can still be considerable. Because of this, learning factors can be assessed as the most uncertain of the parameters and thus several ranges were considered. The ranges studied were baseline value of learning factor +/- 0.01, +/- 0.02 and +/- 0.03. The probabilities of each of the values inside the ranges were considered to be normally distributed, the expected value always being the initial baseline value from the estimate.

For prototype costs a wide range of 50-150 % of the baseline cost was considered. The distribution was considered to be normal also for this parameter and the z-distribution factor the same, 2.5757, as with learning factors and similarly easily modified if needed.

The quantity of production lines was estimated to have a fluctuation of one production line more or one production line less than what has been estimated as production line quantity in the estimate for baseline configuration. A discrete probability distribution was used with the probabilities of;

$P_{BL-1} = 0.25$

$P_{BL} = 0.5$

$P_{BL+1} = 0.25$

, where $P_{(BL-1)}$ is the possibility of having one production line less, $P_{(BL)}$ the possibility of having equal amount and $P_{(BL+1)}$ possibility of having one production line more than in baseline case.

As stated by Pannell (1997) the correlation of the parameters should always be assessed. It is acknowledged that some correlation is likely to exist between prototype costs and learning factors in the way that the more prototypes are optimised and their cost reduced, the less there is room for improvement in the manufacturing process and thus the higher is the learning factor. This correlation is nonetheless assumed not to be of significant importance when total cost is considered. As estimating this correlation would also require further assumptions, all subject to errors, in this model it is assumed that there exists no correlation and all the parameters are independent of each other.

In the study both the one-at-a-time and simultaneous change of the change parameters were considered for different examinations of model uncertainty and sensitivity.

8. RESULTS

Light qualitative comparison of the alternative layouts was conducted. Based on this, the configuration A was found to be superior. This was mainly due to its modifiability as the lengths of either S-AS or PETS are not fixed and thus allow, for example, the machining and assembly to be optimised. Quantitative comparison was conducted in form of cost estimate for the alternative layouts and is presented in this chapter.

At the very final stages of this study the configuration B, as presented in chapter 6.3., was found out to be unfeasible due to too large energy extraction of double length PETS that would lead to RF network not functioning properly. Same could also be true for configuration A, at least in case where PETS is lengthened considerably. Therefore a third scenario, configuration C was proposed. As presented in chapter 6.4., this configuration features fixed length PETS to standardize the energy input to RF network. Accelerating structures are lengthened as in configuration A (see chapter 6.2.), leading to increased efficiency of extracted accelerating power and fewer assembly operations at the expense of total length of the machine. This configuration is presented in this paper alongside configurations A and B but its benefits need to be judged against the cost increase resulted by the longer machine and increase in certain component quantities, most notably the AS disks.

8.1. Cost of configuration A

When lengthening of RF unit is considered using configuration A, cost savings compared to baseline configuration are seen to be present. The most notable cost savings result from the RF network subsystem as the quantity of these systems needed is directly proportional to RF unit quantity and its design remains completely unchanged as lengthening is conducted. The cost as a function of length of RF unit is illustrated in Figure 8.1.

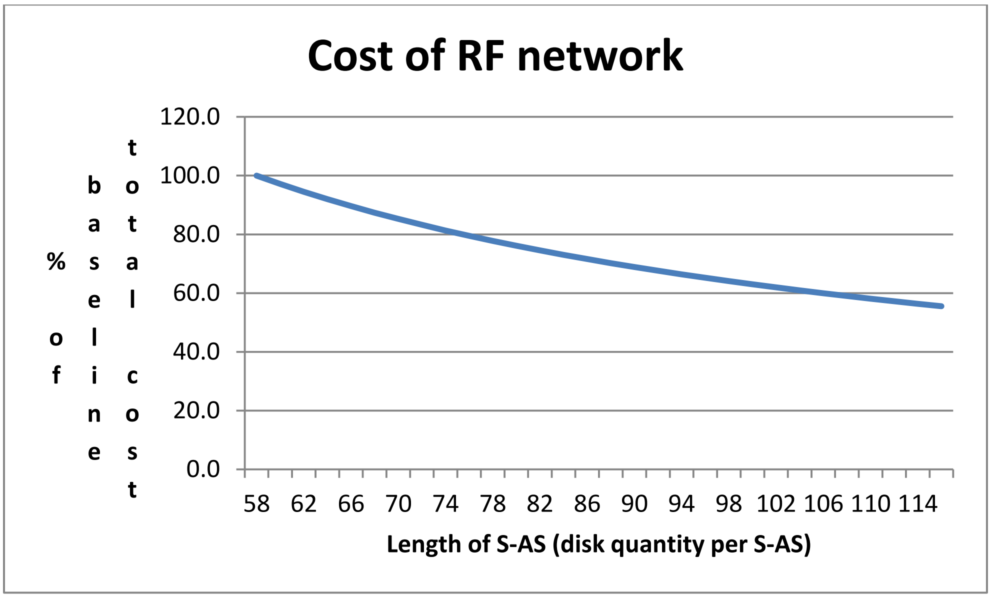


Figure 8.1. *Total cost of RF network subsystem as a function of S-AS length in configuration A.*

The cost is seen to decrease evenly. The application of learning theory in the model limits the cost reduction from following linear curve as learning effect is reduced when smaller quantities are produced or assembled resulting higher unit costs than in baseline configuration.

The cost of S-AS subsystem does not decrease notably when RF unit length is increased as seen in Figure 8.2.

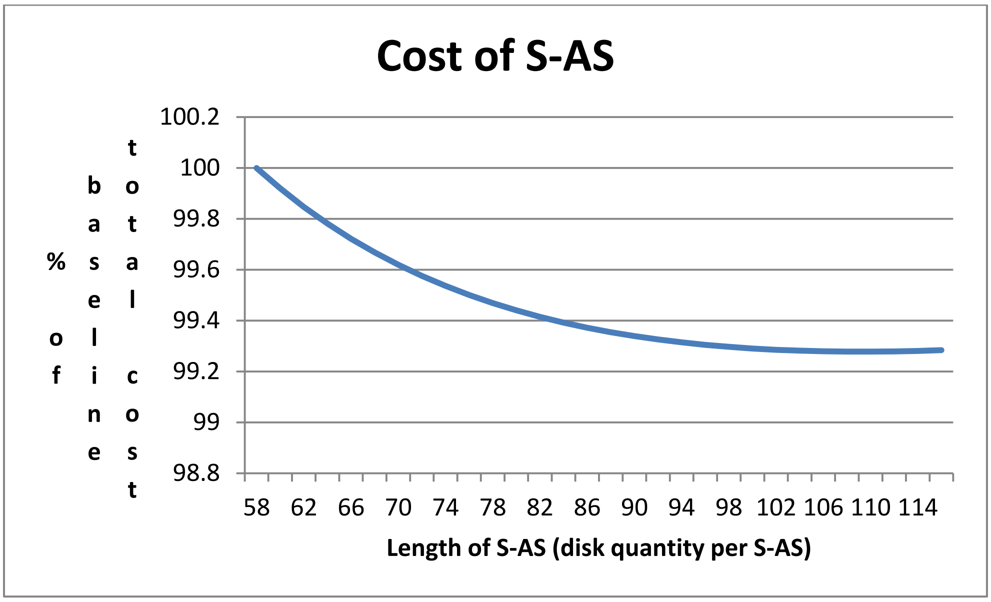


Figure 8.2. *Total cost of S-AS subsystem as a function of S-AS length in configuration A.*

This is mainly due to that cost of AS disks dominate the cost of this subsystem and their total quantity stays the same despite lengthening of the structure. In fact it is seen that the cost will not decrease after length of 110 disks per S-AS but starts increasing again. Nevertheless, the slope of the curve is small no matter is the cost decreasing or increasing so the effect is limited.

PETS benefit prominent decrease in cost when RF unit is lengthened as seen in Figure 8.3.

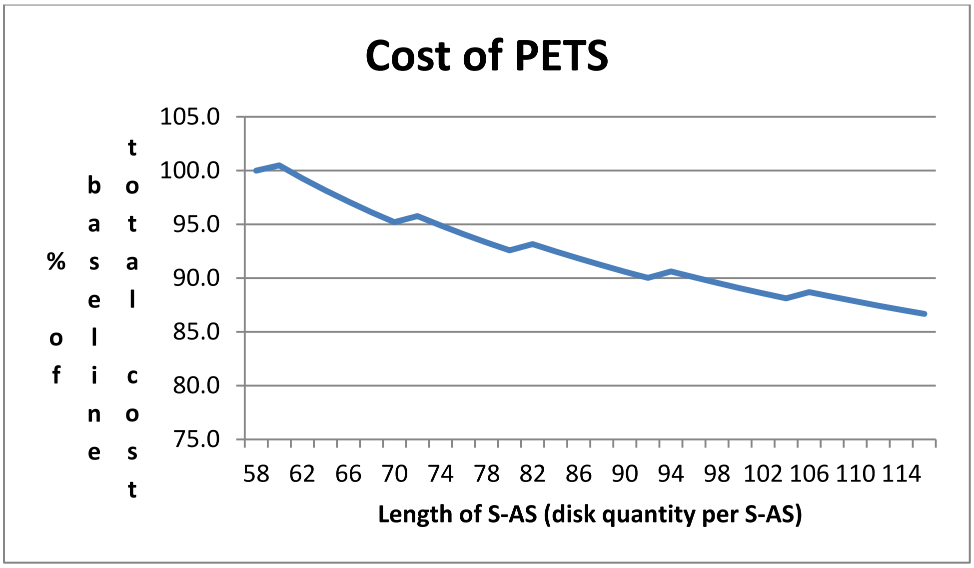


Figure 8.3. *Total cost of PETS subsystem as a function of S-AS length in configuration A.*

What is distinguishing for cost of PETS is the slight cost increase that happen every 10-12 accelerating disks added to the structure. This originates from the calculation method for PETS length. The ratio of PETS cavities to acceleration disks is kept constant at 0.586 PETS cavities per AS disk in RF unit, but as the length of PETS needs to be increased by discrete amount of cavities, rounding is applied. The occasional cost increase for PETS results from the increase of PETS length by two cavities instead of usual one due to this rounding.

The total cost of RF units when configuration A is applied is presented in Figure 8.4 and the corresponding marginal savings are illustrated in Figure 8.5.

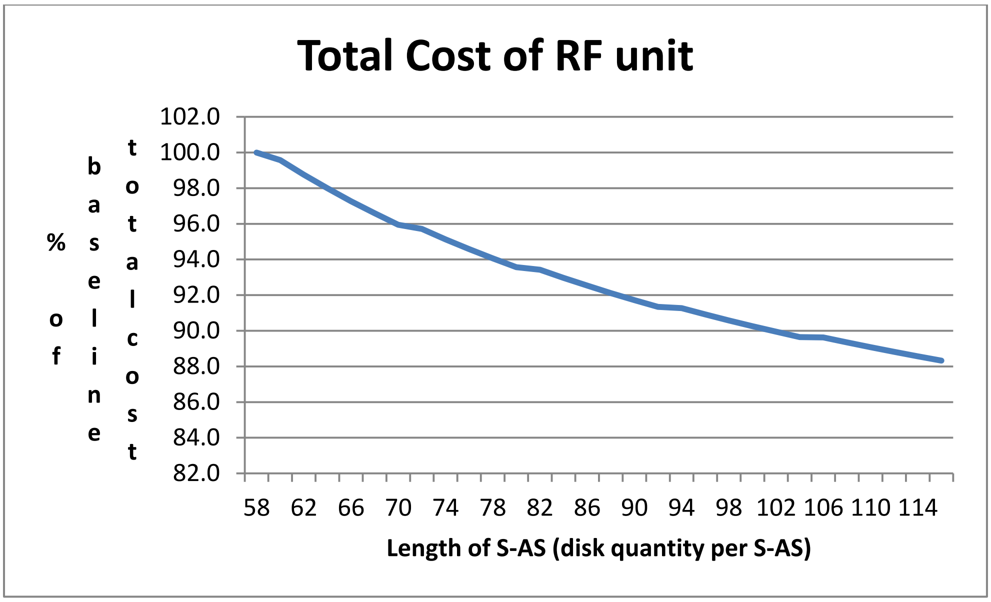


Figure 8.4. *Total cost of RF unit in configuration A.*

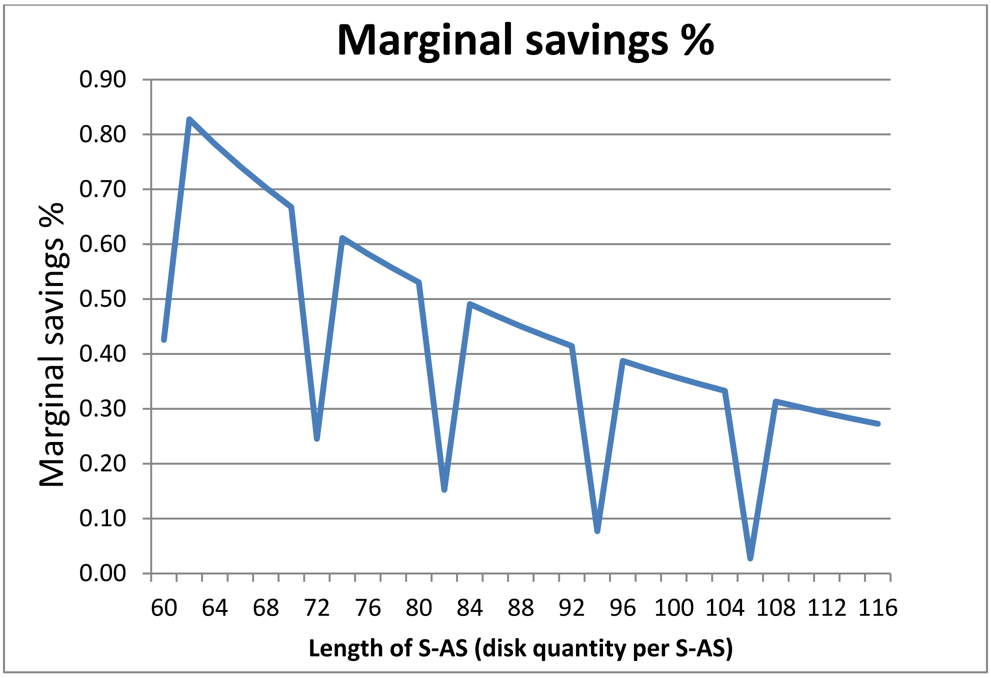


Figure 8.5. *Marginal cost savings as a function of disk quantity in configuration A.*

As seen in Figure 8.4 the cost savings achieved using configuration A are notable, on average approximately 0.5 % per 2 AS disks added. The periodic dramatic drop in marginal savings, seen in Figure 8.5, comes from cost of PETS and its origin is explained more thoroughly above (see Figure 8.3). Although the slope of marginal saving percentage does decrease quite rapidly, the absolute cost savings do accumulate well beyond the limit of 200 AS disks per S-AS.

8.2. Cost of configuration B

When lengthening is considered using configuration B the design and quantity of S-AS components are unchanged from baseline configuration and the cost of this subsystem is thus constant.

PETS is lengthened similarly as in configuration A, but only with the option of having 4 accelerating structures instead of 2, its length corresponding 116 disks per S-AS in configuration A. Therefore also the cost reduction is same as with configuration A of same length, illustrated in Figure 8.3, namely 13.3 %.

Because one PETS needs to feed energy to 4 accelerating structures instead of 2 as in baseline configuration and configuration A, the RF network needs to be modified accordingly as explained in chapter 6.3. Cost of RF unit and its subsystems as a function of AS quantity is illustrated in Figure 8.6.

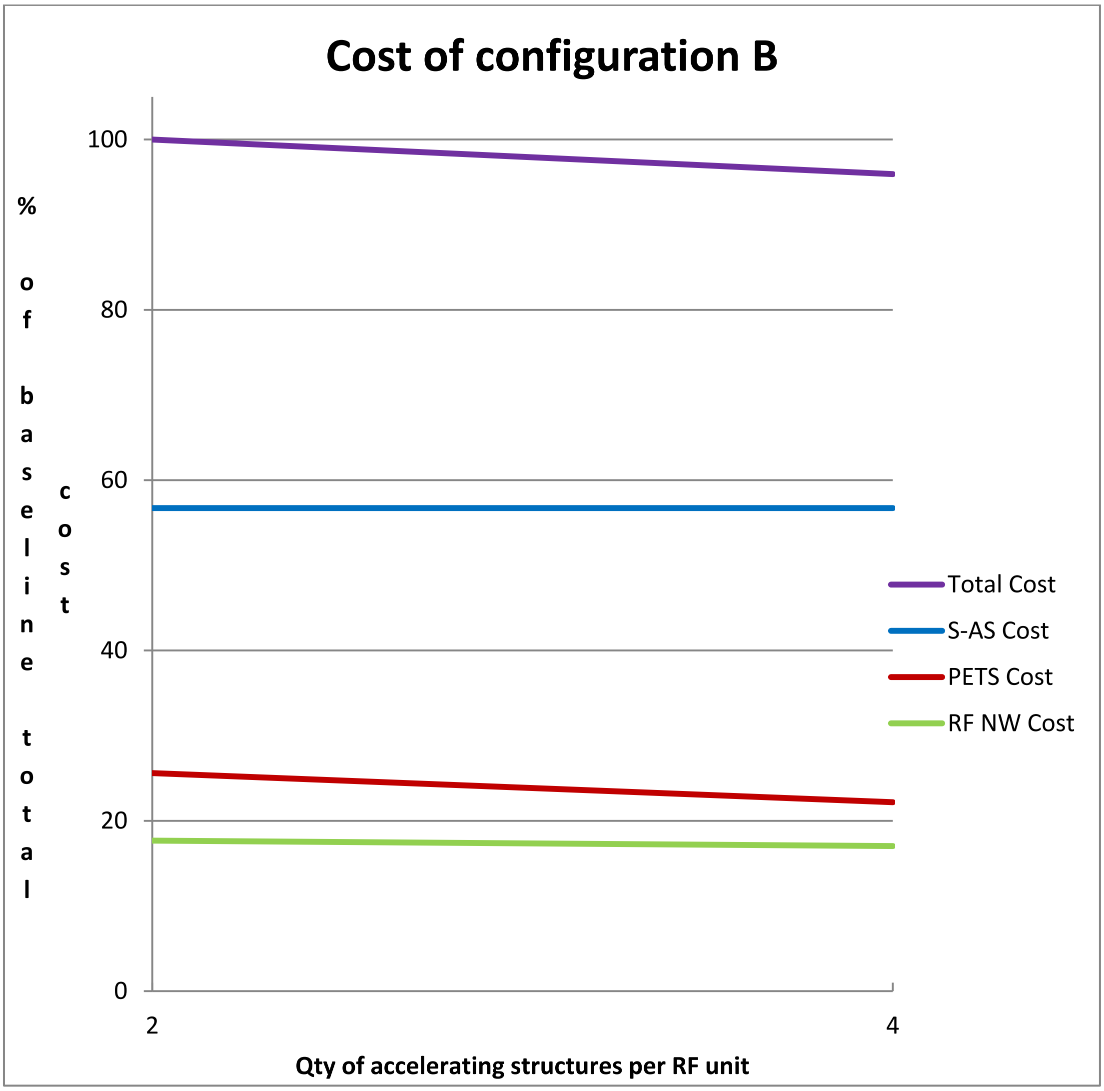


__Figure 8.6.__ Cost of RF unit and it’s subsystems in configuration B.

As seen the cost reduction is greatly inferior to the reduction of cost in configuration A. For the most part this is due to compact loads used to dump remaining RF energy after accelerating structures. These contribute almost 64 % of the cost of RF network in the baseline scenario. Because in configuration B the quantity of AS remains unchanged so does the quantity of these compact loads and one cannot benefit from the reduction of their costs as in configuration A. Therefore the cost savings of configuration B remain inferior to configuration A.

8.3. Cost of configuration C

In configuration C the length of PETS stays constant. Otherwise the configuration and costs of subsystems are equivalent to those of configuration A. Because the energy extracted from the drive beam is not scaled to the length of AS the PETS cavities per AS disks ratio diminishes and the energy transferred to the main beam per AS disk is inferior to configurations A and B. Albeit the efficiency ratio of extracted energy being input to main beam increases due to longer AS, this leads to need to increase the total number of AS disks in the CLIC machine which is considered to be constant in the other configurations. The exact number of AS disks needed to achieve the same maximum energy level of 3 TeV, as in configurations A and B, is dependent on the physics and further studies are needed to determine these quantities for different length configuration C RF units. When known, this number can easily be modified into the model used for the calculations to achieve comparable results with other configurations considered.

Taken into account the disclaimer mentioned above, to illustrate the effect of configuration C on cost, here are depicted the results when the quantity of accelerating disks in the CLIC machine is taken as constant, similarly as in configurations A and B. The cost of RF units in configuration C is shown in Figure 8.7.

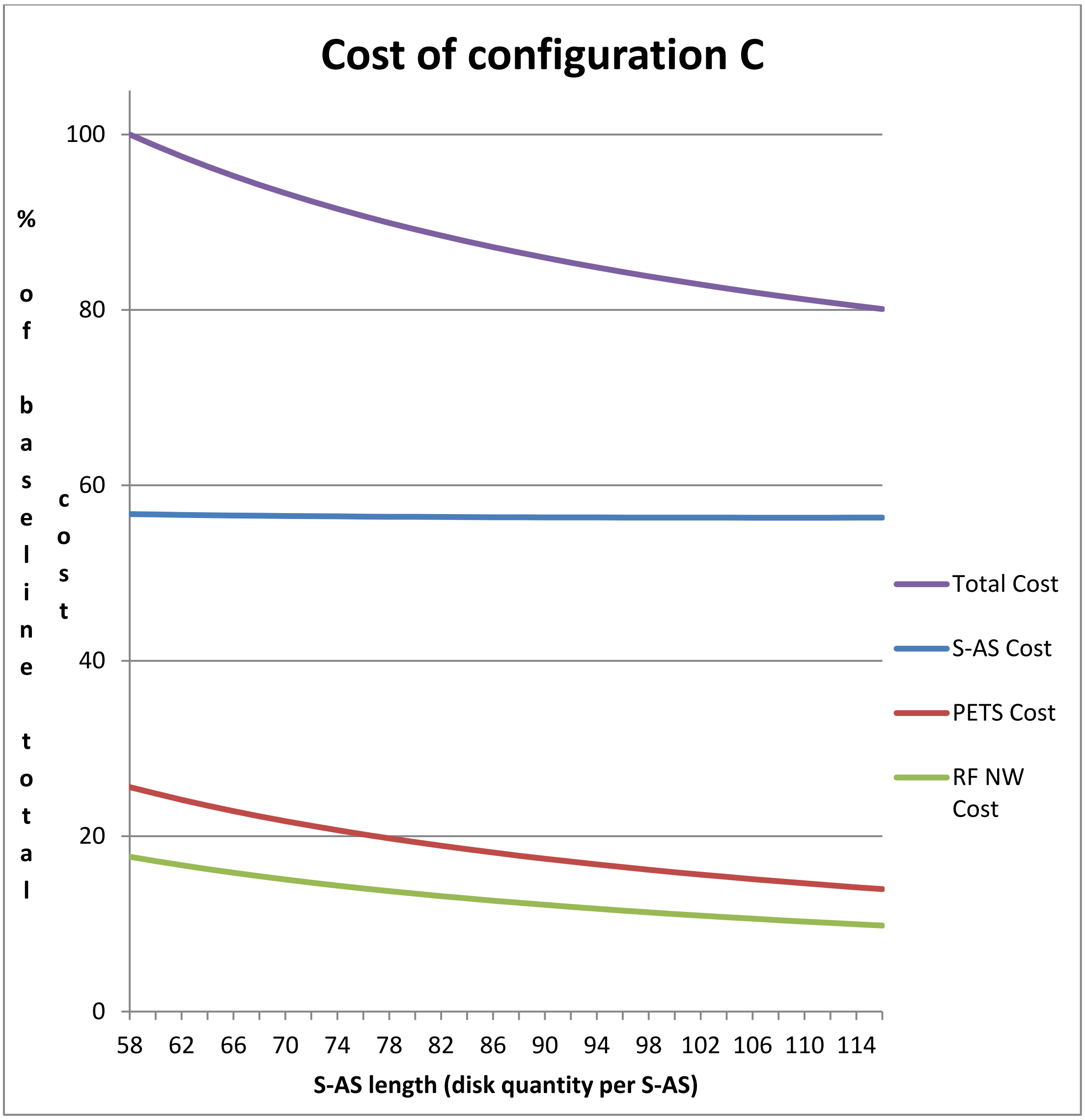


Figure 8.7. *Cost of RF unit and it's subsystems in configuration C.*

As mentioned the costs of S-AS and RF network are equivalent to those of configuration A. The cost of PETS subassembly decreases steeply because their quantity decreases as in configuration A but their unit cost does not rise because their length does not increase. The drop in PETS cost causes also the total cost to decrease heavily compared to configuration A.

Because the costs of configuration C presented in Figure 8.7 are based on baseline amount of AS disks, but in reality the quantity of these disks in configuration C needs to be superior to baseline quantity to preserve accelerating power, these costs cannot be directly compared to the other configurations, including the baseline configuration. Therefore it is worth looking into the critical point when the total number of AS disks in CLIC is increased in configuration C. This point, defining the maximum quantity of RF units that can be used in order their cost being still inferior to the cost of baseline configuration, is shown in Figure 8.8.

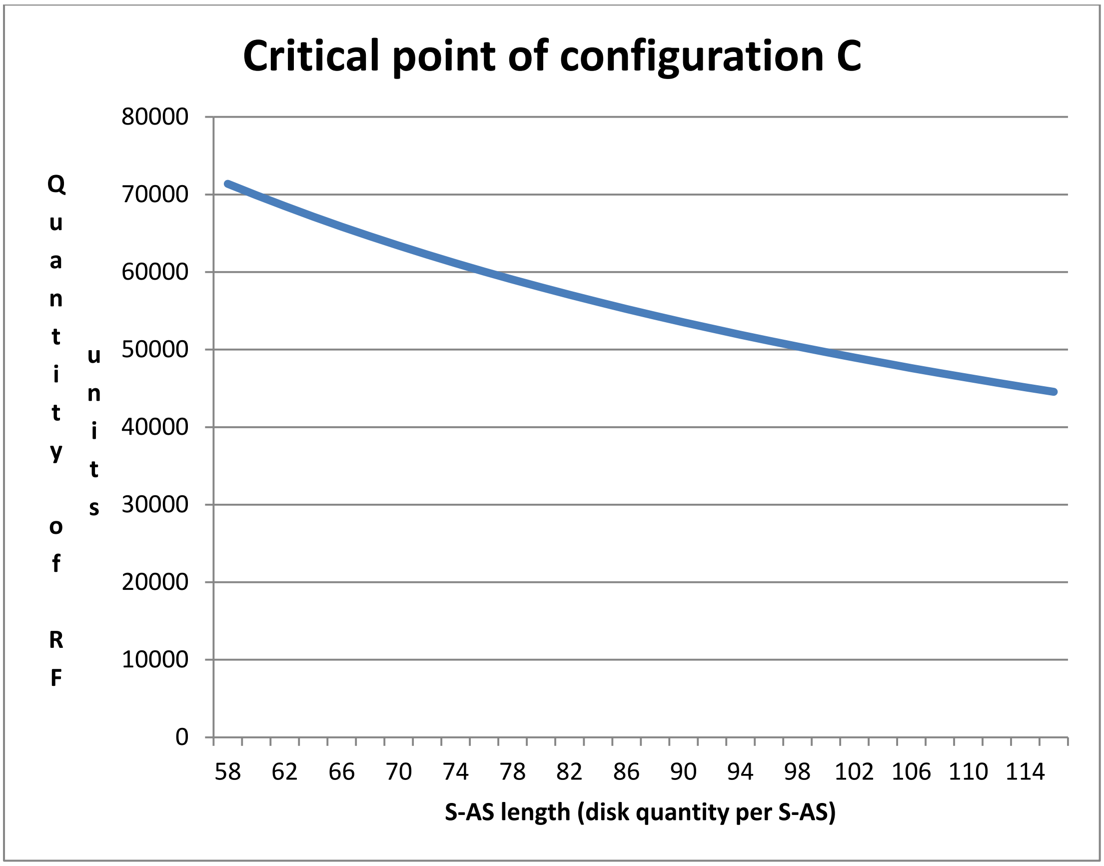


Figure 8.8. *The critical point of configuration C.*

For example, for double length S-AS (116 AS disks) lengthening the RF units following configuration C renders total cost of RF units inferior to baseline configuration if the number of RF units does not exceed 44 557. For comparison, in configuration A the quantity of RF units at this length is 35 690 units and the baseline configuration's RF unit quantity, for nominal length of 58 AS disks, is 71 380 units.

8.4. Sensitivity checks

Sensitivity of the cost estimate model was examined for the different components as well as for each change parameter. Sensitivity index described in chapter 5.1. was used.

The sensitivity index was unsurprisingly the greatest with the components that contributed most to the total cost of the RF unit. Therefore the sensitivity calculations for components and also for the change parameters in the baseline configuration offered little value.

The development of change parameters' sensitivities when RF unit was lengthened had more informational value. Change parameters' sensitivities were looked into on component, subsystem and RF unit -levels.

In Figure 8.9 is shown the development of sensitivity index of RF unit and it's subsystems in configuration A when learning factor range considered is +/- 0.02.

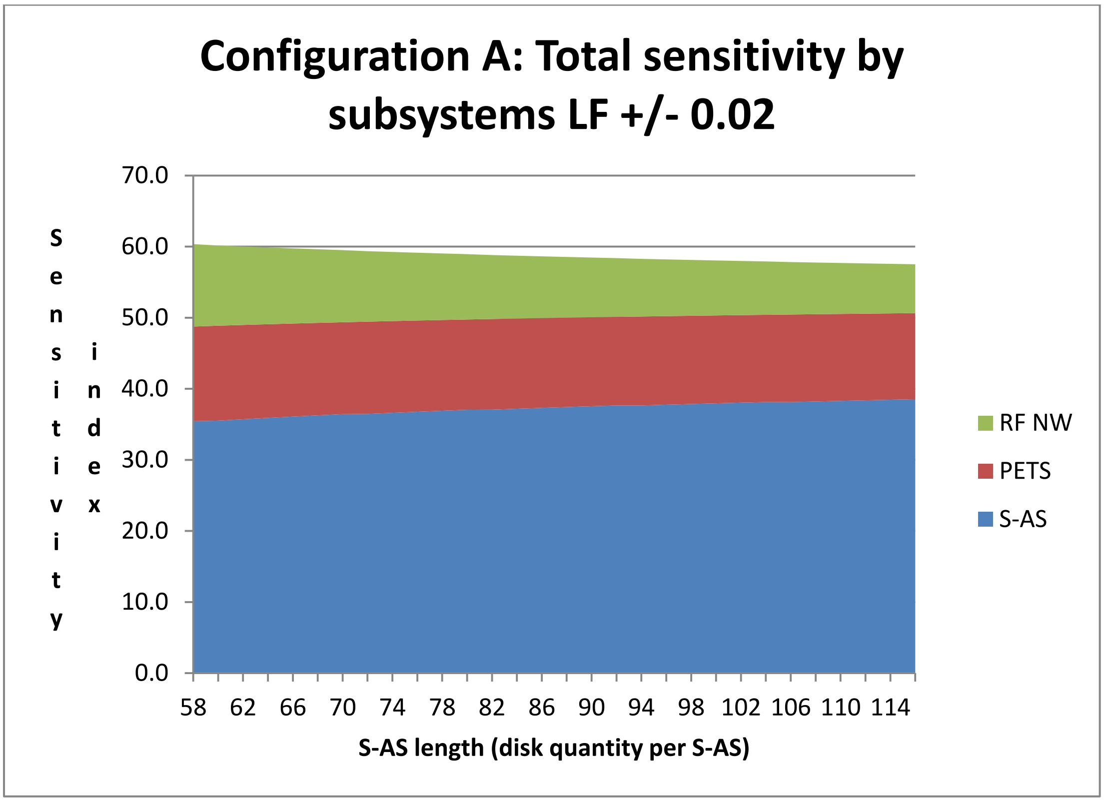


Figure 8.9. *Total sensitivity index of RF unit and its subsystems in configuration A when learning factor is considered to have a range of +/- 0.02.*

One can see that the total sensitivity index declines slightly, while the proportion of PETS declines slightly, the proportion of S-AS increases and the one of RF network declines. The proportions of sensitivities of the components (within subsystems) do not change considerably when RF units are lengthened, the greatest change coming from machining of PETS for which the sensitivity index stays approximately the same when RF units are lengthened leading its proportion to rise.

When configuration B is examined the changes in sensitivities are in the same vicinity as for configuration A for S-AS and PETS subassemblies. Conversely the sensitivity of RF network is considerably different as its sensitivity does not decrease but stays practically the same. This leads to total sensitivity being roughly constant in configuration B, as illustrated in Figure 8.10.

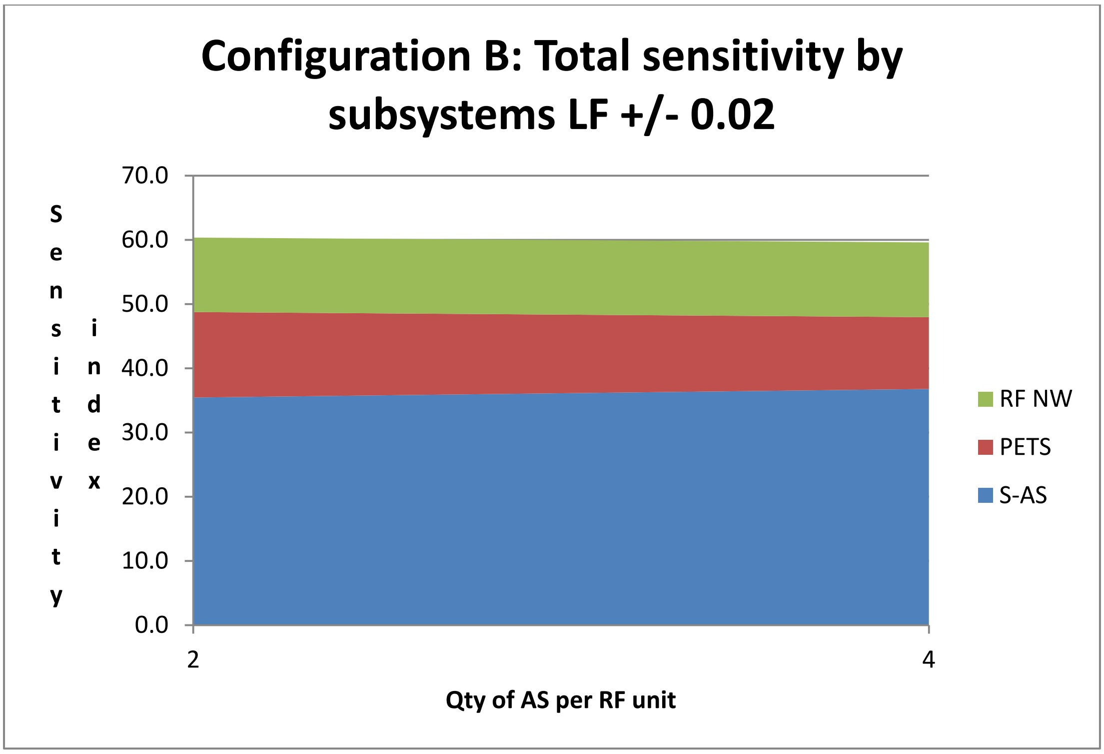


Figure 8.10. *Total sensitivity index of RF unit and its subsystems in configuration B when learning factor is considered to have a range of +/- 0.02.*

Results from corresponding configuration C sensitivity examination are seen in Figure 8.11.

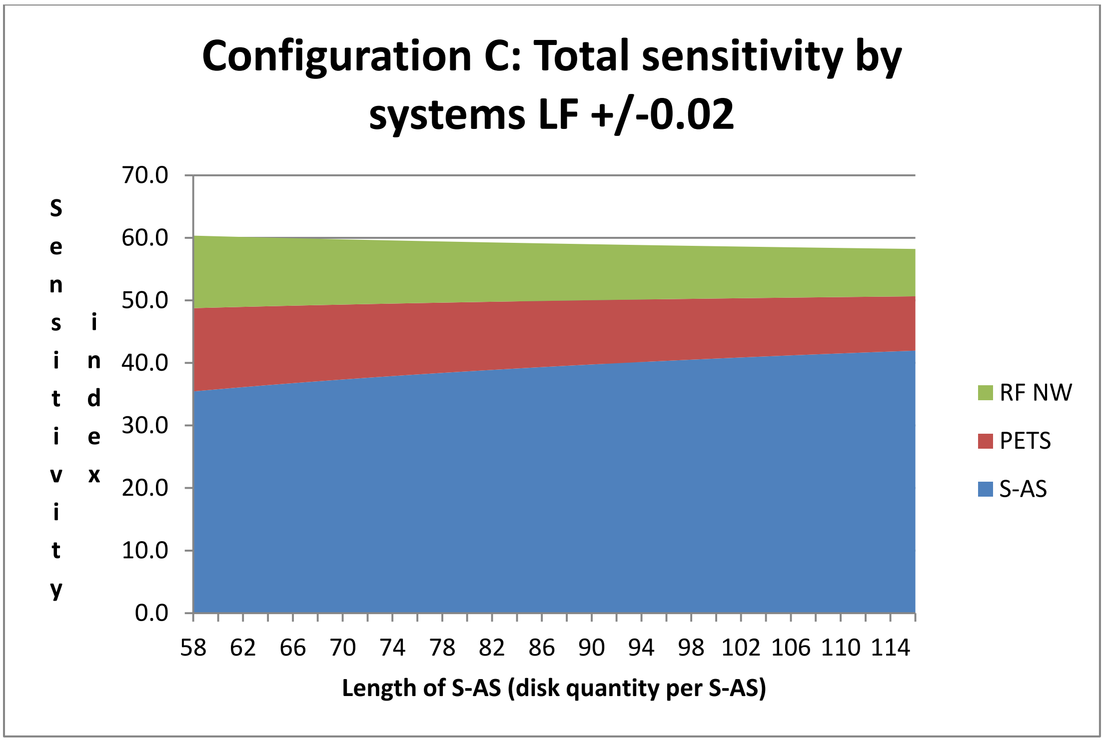
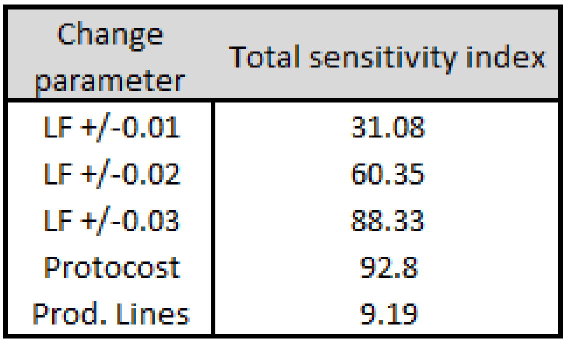


Figure 8.11. *Total sensitivity index of RF unit and its subsystems in configuration A when learning factor is considered to have a range of +/- 0.02.*

The vicinity of total sensitivity is still the same in configuration C, but in comparison to configuration A the sensitivity of RF network increases slightly more, S-AS sensitivity increases notably more and PETS sensitivity declines considerably more when the length is increased.

Above were illustrated the results only for the case where learning factor with range of +/- 0.02 was examined. Generally when subsystems are examined, regardless of the parameter modified, the change of sensitivity follows the same pattern and the total sensitivity of RF unit decreases when it is lengthened. The vicinities of the sensitivity index with different parameters, on the other hand, vary considerably as seen in Table 8.1.

Table 8.1. *Total sensitivity index for different change parameters in baseline configuration (length 58 AS disks).*



Change parameter	Total sensitivity index
LF +/-0.01	31.08
LF +/-0.02	60.35
LF +/-0.03	88.33
Protocost	92.8
Prod. Lines	9.19

One can see that, for example, the sensitivity index for production lines is approximately ten times inferior to first unit cost’s (protocost) sensitivity index. The sensitivity is also seen increasing heavily as the range of learning factor is increased.

8.5. Monte Carlo analysis

The uncertainty of the RF unit was also assessed using Monte Carlo analysis. With Monte Carlo also polyvariant parameter changes were examined. A simulation run of 30 000 samples was executed in order to achieve the goal of relative standard error which was set at 0.1 %. The change parameters were set to vary according to ranges and probabilities specified in chapter 7.2.

Charts illustrating the output probability density function were created by collecting the simulation results into 51 groups corresponding to 0.02 % of the mean cost in the case of univariate investigation where the range of the learning factor is +/- 0.01. The results from univariate investigation for the baseline length are presented in Figure 8.12.

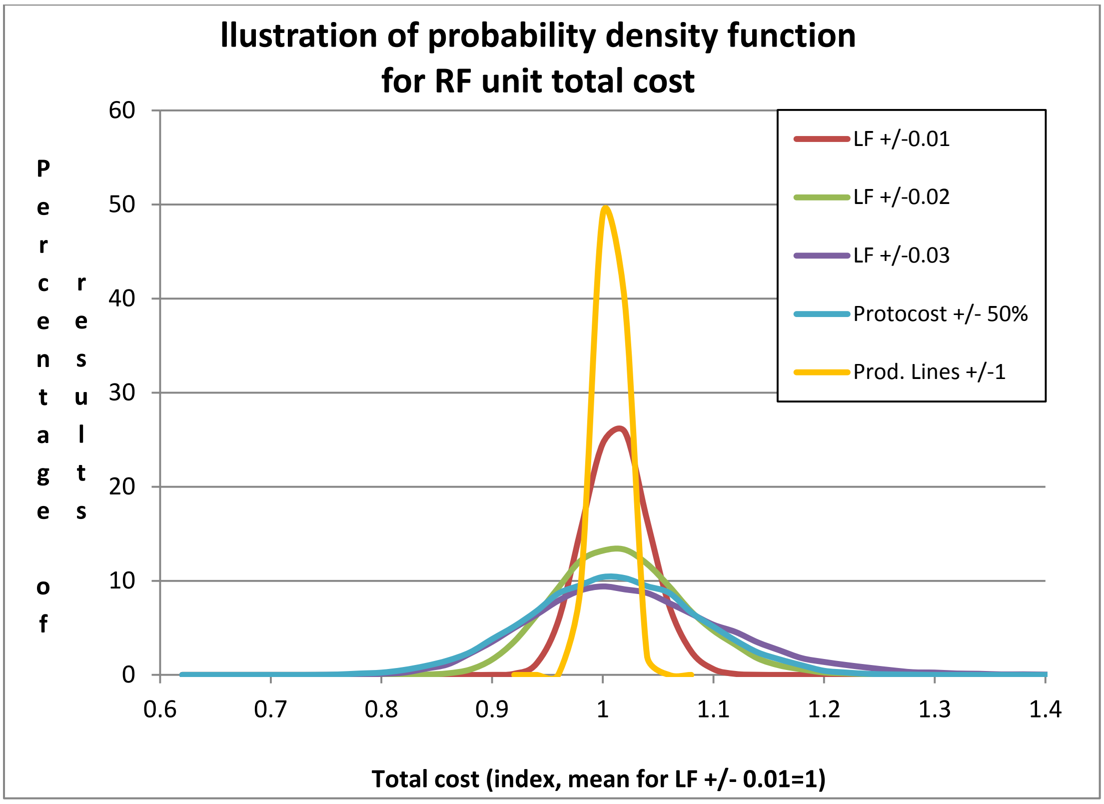


Figure 8.12. *Illustration of probability density function for total cost of RF units in baseline configuration (58 AS disks), univariate investigation.*

Different curves demonstrate the probability density function when one change parameter is modified. It is seen that the change in production line quantities has very little effect on the total cost resulting in a narrow distribution. Another observation is that the greater learning factor range is considered the more skewed the output distribution is so that distributions right-hand tail is longer than the left-hand one.

The length of the RF unit is effortlessly modified to the model to produce illustrations of probability density functions for different length structures following different configurations. To illustrate the effect of lengthening 90 % confidence intervals, i.e. the percentage interval of the expected value including 90 % of the results, for baseline configuration and double length RF unit for different configurations are tabulated in Table 8.2.

Table 8.2. *90 % confidence intervals for baseline configuration and double length RF unit for different configurations, univariate investigation.*

90 % confidence interval	Baseline	Double length for configuration A	Double length for configuration B	Double length for configuration C
ONLY LF +/-0.01	95.1-105.1	94.7-105.5	95.1-105.0	95.2-105.1
ONLY LF +/-0.02	90.5-110.5	89.8-111.8	90.5-110.7	90.6-110.4
ONLY LF +/-0.03	86.6-116.0	85.4-117.7	86.1-116.6	86.6-116.2
ONLY PROTOCOST +/- 50%	87.1-113.0	85.8-114.1	87.0-112.8	87.0-112.9
ONLY PROD.LINES +/- 1	97.8-102.0	97.8-102.0	97.8-102.0	97.9-102.0

As seen here, the relative confidence intervals do stay rather stable when RF unit is lengthened. The only more considerable changes from the baseline configuration are seen in configuration A (LF +/- 0.02, LF +/-0.03 and protocost) and configuration B (LF +/- 0.03), where the confidence interval widens slightly.

Similarly the probability density functions were illustrated based on Monte Carlo simulation for polyvariant examination where all change parameters are modified simultaneously. The results are presented in Figure 8.13.

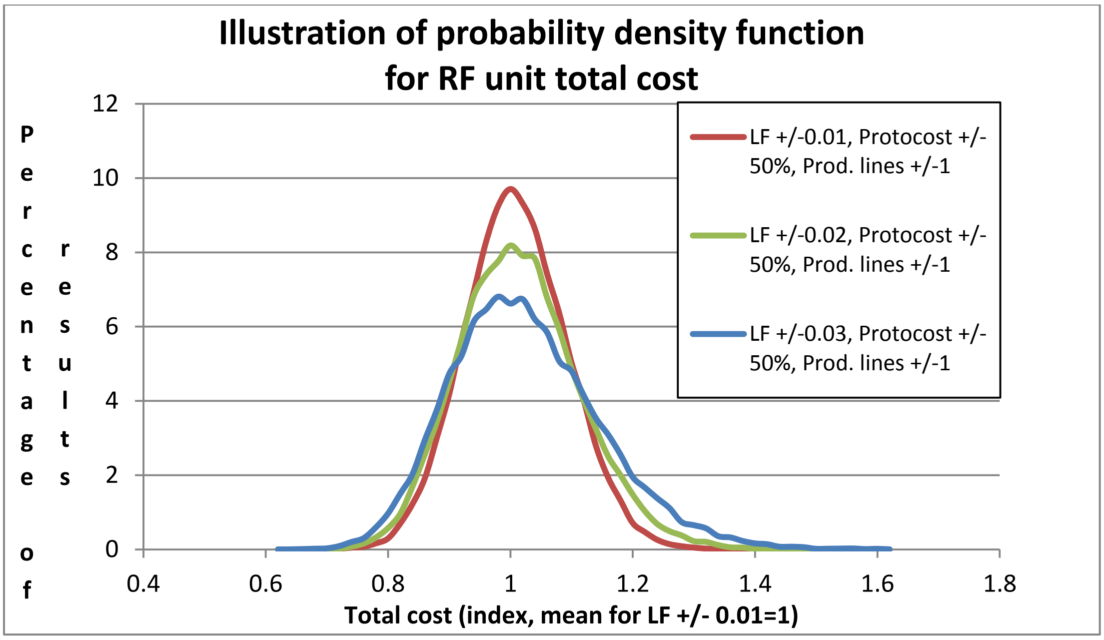
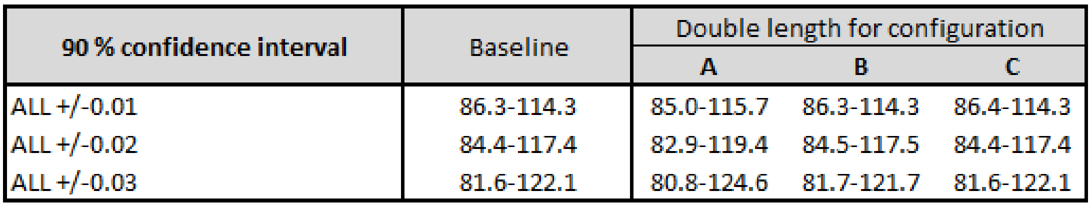


Figure 8.13. *Illustration of probability density function for total cost of RF units in baseline scenario (58 AS disks), polyvariant investigation.*

Here is seen similar the skewing of the distribution when the range for learning factor change is increased as with only learning factors in univariate examination.

Again, the length of the RF units is effortlessly modified to produce distributions for different length structures and different configurations. The 90 % confidence intervals for the baseline configuration and double length RF unit following different configurations are tabulated in Table 8.3.

Table 8.3. *90 % confidence intervals for baseline configuration and double length RF unit for different configurations, polyvariant investigation.*



90 % confidence interval	Baseline	Double length for configuration		
		A	**B**	**C**
ALL +/-0.01	86.3-114.3	85.0-115.7	86.3-114.3	86.4-114.3
ALL +/-0.02	84.4-117.4	82.9-119.4	84.5-117.5	84.4-117.4
ALL +/-0.03	81.6-122.1	80.8-124.6	81.7-121.7	81.6-122.1

When configurations B and C are considered the variation in 90 % confidence interval when RF unit is lengthened is minuscule. Instead for configuration A the confidence interval widens slightly.

9. CONCLUSIONS

Cost estimation for lengthening the RF units of CLIC was conducted. The RF unit consist of three major subsystems; accelerating structures, power extraction and transfer structures, and RF network. Manufacturing each of these requires several components and manufacturing phases. RF units contribute approximately 20 % of the total cost of CLIC and as such, limiting the number of RF units through lengthening was seen as potential way of reducing the cost of CLIC.

The large quantity of RF units and its components means mass production will be applied in their manufacturing. Wright’s (1936) theory of learning curves was applied to emphasise the improvement in manufacturing and assembly as the processes are repeated thousands, even millions of times.

The cost estimate models created give a tool for conducting a cost estimate for RF units of different length following three different configurations and provide a look on the uncertainty included in these estimates. For the three scenarios considered the configuration C was found out to be the preferred one as configurations A and B were deemed unfeasible at the end of the study. Following configuration C the total cost of RF units does experiences notable decrease, but as the total quantity of accelerating disks is kept constant as an assumption, the accelerating power diminishes in this configuration. Therefore to achieve the same accelerating power as in baseline configuration or in configurations A and B more accelerating disks need to be used. Thus the cost reduction capabilities and overall feasibility of configuration C is dependent on how the lengthening of the RF units will affect the total quantity of the accelerating disks, and therefore also the quantity of configuration C RF units, needed and how this would affect other systems of CLIC.

To give an idea of how lengthening of RF units would affect configuration C feasibility, the critical point for RF unit quantity for different length RF units was calculated. This number of RF units which, if exceeded, would render the total cost of RF units superior to baseline configuration was calculated and presented in Figure 8.8. Based on this major prolonging of RF units should not be considered as an increase of RF unit length by just 20 AS disks, to 78 AS disks per RF unit, would require the operating efficiency to increase by 17.3 % in order to RF unit quantity required to be inferior to critical point. As the baseline efficiency of RF units is approximately 84 % (Schmickler et al. 2012) this would be impossible to achieve.

When the other CLIC systems are considered, the main concern with lengthening the RF unit according to configuration C is the increase in machine length that leads to several cost increases. For example, tunnel length as well as the length of beam transport for both drive and main beams would increase. Therefore the critical point needs in reality to be beaten by some margin to keep the increase of machine length within acceptable limits and thus the cost of CLIC implementing longer RF units inferior to the baseline configuration.

This is regardless that, when longer RF units are used their quantity is inferior to RF units in the baseline configuration which affects the quantity of interval components between the units, which in turn might lead to limited decrease in overall length of the machine. Albeit this decrease is likely to be no more than few hundred meters in the best case scenario, with configuration C this effect would limit the increase of total length of CLIC that is expected to happen due to increased quantity of accelerating disks.

The values of learning factors, first unit costs and production line quantities, the main parameters used for conducting the cost estimate of RF units, are all subject to change before the production of the components is started, which is not foreseen until the end of the decade. In order to take this into account and gain insight on the most influential cost factors, a sensitivity and uncertainty analyses were conducted. The sensitivity of the parameters was evaluated and to estimate the uncertainty of the model, probability distributions for the total cost of RF units were created using Monte Carlo sampling.

The effect of production lines’ quantity to the total cost was found to be limited while learning factors and first unit cost have notably greater significance. Also, the overall uncertainty was found to be notable. The spread of closest 90 % simulation results to the expectation value, i.e. the 90 % confidence interval, had in most cases a width of at least 90 % - 110 % of the expectation value.

Additionally to examining the uncertainties of the model, the uncertainty of these key parameters affecting the cost estimate was taken account so that their values can be easily modified into the model. This is important shall further studies show them to be different than the ones used when calculations for this study were conducted. Also, the parameters used for scaling the costs of components for different lengths can be modified with limited effort if first unit costs of different length RF unit components turn out being considerably different than the ones used in cost estimation of this study.

Albeit configurations A and B were ultimately discarded as unfeasible for lengthening the RF units, when subsystems are examined the models created for them, especially for configuration A, can provide insight on their cost structure. This can be beneficial in case the RF units shall be considered to be modified in ways different from what was investigated in this thesis. One example of these findings would be the importance of RF network’s compact loads as the notable difference in cost estimates for configurations A and B was largely caused by difference in the quantities of this component. Decreasing the quantity of compact loads, for example, by combining the two compact loads after AS to a single one if possible, could thus result in notable cost savings.

The cost estimates conducted in this thesis cannot be taken as persistent. Parameters used have at the moment relatively high uncertainties which reflect as the wide confidence interval of the total cost of RF units. Therefore the model should be updated with the current information shall it later be used as a reference for further studies or decision making. Especially this concerns the first unit costs used for the components because their effect on total cost is far greater than the impact of production line quantity and with sufficient information they can be estimated with far less uncertainty than learning factors.

No specific error analysis was conducted in this thesis. It is recognised, however, that as well as the baseline cost estimate also the cost estimates for longer structures are subject of including some error due to uncertainties. Because these uncertain values are also used for scaling the costs for different length components of the RF unit, the scaling is expected to include error as well. In worst case, this error can be notable. For example, in case cost estimate for shorter (cheaper) component X is 20 per cent higher than the actual realised value and the cost estimate for longer (more expensive) component X is 20 % lower than the actual value, the error when calculating the cost increase per added length unit is high. Of course, the probability of estimates being considerably far from the actual value to opposite directions for shorter and longer unit is relatively small. The possibility exists, nevertheless, and to take this into account in uncertainty calculations the wide range of +/- 50 % was used for first unit costs.

This thesis concentrated on cost of the RF units and excluded the effects to other systems of CLIC that the design change of the RF units might cause. In some cases the changes to other systems might be preferential when cost is considered (e.g. smaller cooling system component quantity due to fewer RF units), but they may as well develop supplementary cost which may counter the cost reductions achieved from RF units and render the cost effect of lengthening the RF units negative (e.g. longer tunnel length). Therefore these effects to other systems need to be studied shall the lengthening be considered to be realised.

Crucially the exact effect that the lengthening of RF units has to the physics of the accelerator need to be investigated in order to confirm that the machine remains operable and the planned total efficiency of CLIC machine is preserved. This issue was clearly emphasised at the end of the study when configuration C was introduced to confront problems pinpointed in configurations A and B.

Looking back at the research process, the configurations considered should have been validated with physics specialists at latest after initial cost estimates for them were conducted. Now fine tuning the estimates and conducting sensitivity and uncertainty calculations for configurations A and B took a lot of effort that could only partially be capitalised when configuration C was added to the study and looked into. Even more importantly this led to an approach that was ultimately not the best one for examining configuration C, namely the assumption that the total quantity of AS disks in CLIC stays constant regardless of length of the RF units. With initial configurations A and B this approach allowed easy comparison of these configurations and the baseline configuration but as this does not apply to configuration C no unambiguous results nor recommendations of the effect of lengthening of the RF units to their total cost can be provided.

The need to examine alternative machining methods for the disks of the accelerating structures in order to limit their production costs has been observed previously (Turunen 2011, Schmikler et al. 2012) and remains to be realised. If RF units are prolonged, as in this study, the machining process of the disks does not change. On contrary, the manufacturability of longer components, most notably PETS bars and damping shims of accelerating structure should be examined closer. Different length components have been produced previously for test purposes and in this study the costs of these components of different lengths were used to scale the cost for different length structures. The cost was assumed to change linearly with respect to length of the component. This is just an approximation and in reality it is more likely that the cost of machining is not perfectly linear as there exist limits to component lengths where, for example, there is a need to change the way machining process is conducted or the equipment used in the machining process needs to be modified or changed. Mapping out these discontinuity points would help in optimising the length of RF units from manufacturing point of view.

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