Production Costs Calculation Model in Crushing and Screening

Using a technical-economic approach tool for finding the optimal production costs when comparing technical and economical solutions

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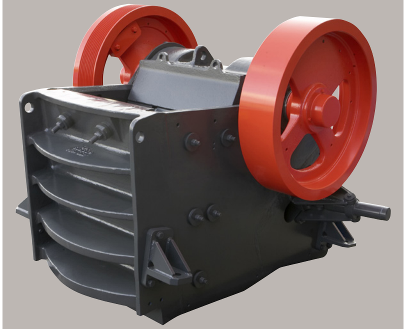

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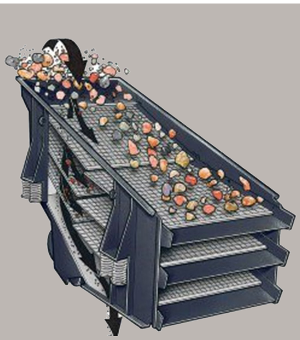

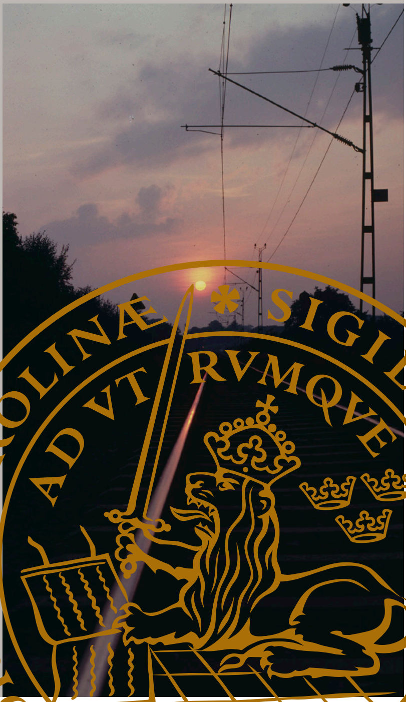

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Per Hedvall

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The mining and quarrying industries represent a highly important sector of the Swedish economy. The mining industry operates globally, whereas the quarrying industry operates on a regional/local basis. Demands for metal and construction aggregates have increased over the last decade, and almost 80 billion tons of solid minerals and rocks are extracted from the earth’s crust each year. Construction aggregates are the largest part of this extraction. Most of the metals in the crust are in mineral form, with one or more elements in chemical compounds. To extract the metals, the rock must first be reduced to fine or very fine particles, so creating the right properties for mineral beneficiation and metal extraction.

Construction aggregate is used as ballast in concrete and in asphalt or by itself in road building and other infrastructure, dams, protection, and padding. Construction aggregate ranges in sizes from large boulders to very fine sand, but normally the construction aggregate sizes are in the range of 1–100 mm. Railway aggregates are in the upper part of this range, aggregates used for asphalt and concrete in the middle, and sand in the lower part.

Crushing and screening are among the common size reducers and size sorters in the mining and quarrying industries. The crushers are machines for breaking rocks or other minerals into smaller particles/fragments. The screens are the size-sorting machines for separating coarser particles from finer particles. Technical process simulation and equipment selection for crushing and screening (C&S) plants are well established for mining and quarrying plants.

In this dissertation I develop a product cost calculation model (PCCM) that adds one more dimension to the area of process simulation, providing guidelines for calculating product costs within C&S plants and finding the process alternative with the lowest product cost for a C&S plant process application.

The PCCM calculates the product costs using, process uptime costs, process downtime costs, salary costs and auxiliary costs. The process uptime and downtime costs include capital costs and dynamic process costs such as wear parts, spares, tools, and power consumption.

The conformity, CF (calculated costs divided by actual costs) is in the range of 0.9–1.2 for the seven C&S plants tested. The application mining C&S plant gave the product cost allocation shown below:

Costs	Distribution (%)
Capital	30–50
Dynamic	30–40
Salary	10–20

Two examples demonstrate how the PCCM can be used:

1. In an existing C&S plant to calculate the product costs.
2. In a future C&S plant to calculate the production costs before the plant is built.

Key words crushing, screening, C&S processes and plants, product cost calculations, mining, construction and quarrying.

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Abstract

The mining and quarrying industries represent a highly important sector of the Swedish economy. The mining industry operates globally, whereas the quarrying industry operates on a regional/local basis. Demands for metal and construction aggregates have increased over the last decade, and almost 80 billion tons of solid minerals and rocks are extracted from the earth's crust each year. Construction aggregates are the largest part of this extraction. Most of the metals in the crust are in mineral form, with one or more elements in chemical compounds. To extract the metals, one must first reduce the rock to fine or very fine particles, so creating the right properties for mineral beneficiation and metal extraction.

Construction aggregates are used as ballast in concrete and in asphalt or by itself in road building and other infrastructure, such as dams, protection, filling, and landscaping. Construction aggregate ranges in sizes from large boulders to very fine sand, but normally the construction aggregate sizes are in the range of 1–100 mm. Where the railway aggregates are in the coarser part of this range, the aggregates used for asphalt and concrete in the middle part, and the sand in the finer part.

Crushing and screening are among the common size reducers and size sorters in the mining and quarrying industries. The crushers are machines for breaking rocks or other minerals into smaller particles/fragments. The screens are the size-sorting machines for separating coarser particles from finer particles. Technical process simulation and equipment selection for crushing and screening (C&S) plants are well established today for mining and quarrying plants.

PCCM is a calculation model for production costs that has given an additional dimension to the field of process simulation. By gaining knowledge of costs and the distribution of costs within C & S facilities, new conditions are given for finding the process alternative that gives the lowest product cost under the current circumstances and at the same time being able to show ways how the raw material, i.e. available mineral, can be used in the best way.

The PCCM calculates the product costs using process uptime costs, process downtime costs, salary costs and auxiliary costs. The process uptime and downtime costs include capital costs and dynamic process costs such as wear parts, spares, tools, and power consumption.

The conformity, CF (calculated costs divided with by actual costs) is in the range of 0.9–1.2 for the seven C&S plants tested.

Costs	**Distribution (%)**
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Two examples in this dissertation demonstrate how the PCCM can be used:

1. In existing C&S plant to calculate the product costs.
2. In a future C&S plant to calculate the production costs before the plant is built.

Keywords: crushing, screening, C&S processes and plants, product cost calculations, mining, construction and quarrying.

Sammanfattning

Gruv- och ballastindustrin utgör en mycket viktig sektor i den svenska ekonomin. Där gruvindustrin är verksam på den globala marknaden medan ballastindustrin finns oftast på en regional eller lokal marknad. Efterfrågan av metaller- och byggnadsmaterial har ökat under det senaste decenniet och mängden fasta mineraler och stenar som tas ut ur jordskorpan är nästan 80 miljarder ton per år, med ballast som den största delen.

De flesta metallerna i jordskorpan finns i mineraler med en eller flera grundämnen i kemiska föreningar. För att utvinna metallerna, måste man först storleks minska stenen till fina eller mycket fina partiklar. Det för att skapa rätt egenskaper för mineralförädling och metallutvinning.

Ballast används i betong och i asfalt eller direkt i vägbyggnad och / eller andra infrastrukturer som t.ex. dammar, skydd, utfyllnad och landskapsarkitektur mm. Ballast storlekarna sträcker sig från stora stenblock till mycket fin sand. Huvuddelen av ballaststorlekarna ligger i intervallet 1 − 100 mm. Där järnvägsballast finns i det grövre sortimentet, ballast i asfalt och betong i mitten av sortimentet och sand i den finare delen.

Krossning och siktning är en av det vanligaste sättet att reducera stenars eller mineralens dimension till önskad storlek. Krossar finns av olika typer och utgör en central utrustning för att bryta sönder stenar eller annan mineral till mindre enheter. Siktar är benämningen på en grupp av maskiner för att kunna separata ut grövre material eller enheter från ett givet materialflöde.

Teknisk process simulering inklusive val av optimal utrustning avseende kross- och sorteringsmaskiner är idag väletablerade hjälpmedel inom berörda branscher.

PCCM är en beräkningsmodell för produktionskostnader som gett en ytterligare dimension till området processimulering. Genom att få kännedom om kostnader och kostnadsfördelningen inom C&S-anläggningar ges nya förutsättningar för att finna det processalternativ som ger den lägsta produktkostnaden under rådande omständigheter och samtidigt kunna visa vägar hur råvaran, d.v.s. tillgänglig mineral kan användas på bästa sätt bl.a. med avseende på ekonomi och hållbarhet.

PCCM beräknar produktkostnaderna genom att summera processens drifts-kostnader, processens stilleståndskostnader, lönekostnader etc. I drifts- och stille-ståndskostnader ingår kapitalkostnader och dynamiska processkostnader som innefattar kostnader för slitdelar, reservdelar, verktyg och energi i olika former. Under senare tid har elkostnader spelat en allt större roll för flera tillverknings-processer och är också en viktig kostnadsdrivare även för C&S-anläggningar.

Konformiteten, CF definierat som beräknade kostnader dividerat med i efterhand fastställda verkliga kostnader ligger i intervallet 0.9 – 1.2 för de sju genomförda fallstudierna knutna till aktuella C&S-anläggningar.

Exempelvis kostnadsfördelningen beräknas för en tilltänkt eller planerad C&S-anläggning beräknas beroende på olika scenarier t.ex. utvecklingen av energikostnad, löner etc.

Kostnadsslag	Fördelning (%)
Kapitalkostnad	30–50
Dynamiska kostnader	30–40
Lönekostnader	10–20

Övergripande kan utvecklad PCCM användas för kostnadsanalys av:

1. Befintlig C&S-anläggning för att beräkna produktkostnader och dess fördelning samt inflytanden från olika kostnadsdrivare.
2. En planerad eller potentiell C&S-anläggning i syfte att bedöma förväntade produktkostnader och dess fördelning samt inflytanden från olika kostnadsdrivare. Inom detta användningsområde kan flera alternativa C&S-anläggningar ekonomiskt bedömas utifrån sina specifika förutsättningar.

Nyckelord: Krossning, siktning, kross, sortering, processer, anläggningar, produkter, kostnad, beräkningar, gruvindustri, entreprenadindustri, och ballastindustri.

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Special thanks to the owners of the C&S plants, their plant managers, and their employees who approved and made it possible for me to perform full-scale verification tests of my PCCM. I appreciate all the help and advice I received during those tests. All this has given me a much broader insight into the secrets of C&S processes.

I would like to thank Per Svedensten, former at Sandvik, for his suggestions, comments, and support during my early PhD work. A big thank-you to my co-supervisor Christina Windmark, LTH, for her assistance during the whole production of this dissertation. It has been more valuable than gold!

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I would like to pay big tribute to Professor Emeritus Bodil Jönsson. It was her pamphlet “Seniordoktrander – Ett förslag vid midsommartid 2012” (Senior PhD students – A proposal at midsummer time 2012), that opened my eyes and convinced me to start going for a PhD.

Finally, I would like to thank my beloved family and especially my wife Eva, for their full support and encouragement throughout my PhD student work.

Lund, 9th of August 2022

Per Hedvall

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Selected definitions

Item	Specification - designation
MTPH / MTPY	Metric tons per hour / Metric tons per year
Throughput	The quantity of something which is processed, as MTPH.
Capacity	Maximum momentary throughput, as MTPH
Production	Annual throughput as MTPY
Operating time	Total production time per year, as hours
Working time	Net production time per year when the equipment is producing, that is, after deducting unproductive items, such as unplanned stops, or lost material, as hours.
Load	Actual throughput compared to capacity
Utilization	Ratio of load/maximum load
Availability	Ratio of working time/operating time
C&S plant production	Capacity x operating time x utilization, as MTPY
	Capacity x working time, as MTPY
Wear parts	WP
Spare parts	SP
Tools	TO
Maintenance & services	MS
Crushing and screening	C&S
Production Cost Calculation Model	PCCM
Native metal	Pure in its metallic form in nature
Metal minerals	Normally chemical compounds with at least one metal and one other element. Native metals are also grouped with the metal minerals.
Solid energy minerals	Solid rocks that contain coal of different types, and oil sands.
Ore	A naturally occurring deposit containing a valuable constituent, such as metal, gems, or solid energy minerals.
Sand, gravel, stone, and rock	Solid material from the earth's crust, in different sizes, where sand is the finest and rock is the mountain material.
Construction aggregate	A broad category of coarse, medium and fine-grained particulate material, used in construction, as unbound/bound masses/lots in building and infrastructure projects.
Conformity	Concordance between actual and calculated value as the ratio Calculated costs/Actual identified costs

List of selected symbols

Symbol	Explanation
i	Product i
j	Machine/equipment j
L_0	Quantity of feed material to plant, as MTPH
L_{0j}	Quantity of feed material to machine/equipment j, as MTPH
L_{2j}	Quantity of recirculated amount of material from machine or equipment j, as MTPH
P_i	Quantity of product i, as MTPH
pf_i	Proportion of product i
PF_i	Proportion of product i at the end of the process
WP	Wear parts
SP	Spare parts
TO	Tools
MS	Maintenance and service
T_{plan}	Operating time per year
n_j	Technical lifetime of machine/equipment j
n	Number of years
n_p	Number of products
K_{0i}	Basic invest for machine/equipment i, at year 0
k_i	Total production costs for product i
k_{WPj}	Annual cost of WP (Wear Parts) for machine/equipment j
k_{SPj}	Annual cost of SP (Spear Parts) for machine/equipment j
k_{TOj}	Annual cost of TO (Tools) for machine/equipment j
k_{wph}	Cost per kWh
k_{enj}	Max power consumption of machine/equipment j, per hour
n_D	Number of operators in the plant
k_D	Salary cost of one operator
k_{iD}	Salary cost for product i
k_{cpdyn}	Sum of all dynamic costs for the plant
k_{cpi}	Cost of process uptime for product i
k_{csi}	Cost of process downtime for product i
k_{renj}	Average renovation costs for machine/equipment j
k_{renkj}	Renovation costs for machine/equipment j

D_j	Balancing lost machine/equipment j
$1\text{-}D_j$	Load of machine /equipment j
MT_{php}	Maximum capacity of the C&S plant
MT_{phi}	Maximum capacity of product i
MT_{phj}	Maximum capacity of machine/equipment j
U_{RP}	Utilization of an equipment, line, or plant
SD	Solid (compact) density as t/m^3
BD	Bulk density, as t/m^3
AK_{ji}	Allocation key for explicit costs of machine/equipment j to product i
AKgi	Allocation key for general costs of product i
AV	Annuity value
NPV	Net present value
$NPVf_j$	Net present value factor for machine/equipment j
$EACC_j$	Equivalent annual capital cost for machine/equipment j
R_{nj}	Residual value of machine/equipment at year n
R_{0j}	Residual value of machine/equipment at year 0, according to NPV
r	Residual value as % of original investment at year n

1. Introduction

The chapter begins with an account of the background of the research presented in the dissertation. Thereafter, it presents the conceptual approach taken, the objectives, the research questions posed, and the scope and the limitations of this project.

1.1 Background

Industries that use natural resources such as sunlight, fresh water, air, minerals, stones, timber, and fertilizers can be categorized into segments such as mining, construction/quarrying, energy, and forestry. The mining and quarrying industries are very energy-intensive. Globally, mining accounts for some 7 % of the world's total energy consumption [1]. The turnover is large, and the market price of some minerals/metals has more than quadrupled over the last two decades. The price of gold, for example, increased from $300 an ounce at the beginning of 2000 to almost $1900 an ounce in 2011, a six-fold increase [2]. The recent downturn in the economy caused metal prices to fall again, so that in January 2020 gold was trading just below $1600 an ounce [2]. This decline stimulated competition to improve efficiency and productivity in the mining and quarrying industries. The prices of other metals also fell in early 2020. The biggest declines were in copper and zinc, which are particularly associated with global economic activity. Metal prices were projected to drop 13 % overall in 2020 as slowing demand and the shutdown of key industries weighed heavily on the market. Industrial metals would be affected the most by the global economic slowdown, particularly in China, which accounts for approximated half of global metals demand [4]. The global COVID pandemic caused metal prices to fall even more than expected [3]. However, since the beginning of 2022 the metal prices have increased due to the war in Ukraine and the following boycott of metals coming from Russia by EU and USA [84].

One way of surviving in this challenging situation is to use technical-economical optimization of mining and quarrying operations. Doing so requires accurate tools to evaluate projects and estimate the operational and total costs of product(s), both in terms of the cost for each product in each machine and of the total production cost of the whole process. But developing such tools is difficult because mining and construction processes involve a number of complex operations [4], making it difficult to calculate accurate and reliable product costs for each process in the crushing and screening plant.

Since the dawn of humanity, the natural resources of stones and rocks have been used as tools, equipment, and construction materials. At first, these resources were used in the form nature provided them. However, humans soon started improving the properties of stones and rocks by reducing their size and grinding, sharpening, and polishing them to create better tools for use in daily life. Ancient stone tools found on the shores of Lake Turkana in Kenya in 2011 have been dated to approximately three million years ago [5].

Metals came into use later than stones, although native metals like gold and copper metals also have a very long history. Gold would have been one of the first metals to be used, as it is found in nature in the form of eye-catching, shiny, yellow nuggets that can easily be worked without being heated. We do not know when the first human picked up a gold nugget, but flakes of gold have been found in Paleolithic (Old Stone Age) caves in Spain, dating back as far as 40,000 B.C. [6]. Copper also occurs in nature in a directly usable metallic form, and was used by humans in several regions by approximately 9000 B.C. For example, a copper pendant found in Iraq is dated to 8700 B.C. [7]. One of the oldest known mines is the Lion Cave in Eswatini (Swaziland) in Africa. This cave (tunnel) was cut into a cliff face and was 2 m wide, 9 m deep and 6 m high. The activity in the Lion Cave has been dated to 41,000 B.C. by carbon-14 dating. The miners were extracting red ochre (hematite iron), a pigment used by early humans as body paint during their rituals. The amount of material mined and moved from the Lion Cave is estimated to be at least 50 tons [8]. The major step in obtaining metals was when early humans discovered how to extract metals from metal minerals (chemical compounds of several elements). One of the first evidences of metal extraction metallurgy (Copper) comes from present-day Serbia and dates from the sixth millennium B.C. [9]. Metals have been essential to the development of human society since the Bronze Age, some 5000 years ago [10].

Over the centuries, the use of stone and rock resources has evolved from using natural stones to the extraction of metals and industrial minerals and the production of construction aggregates. Today metals are extracted in mining industries while aggregates are produced in construction industries. Stones and rocks are and will continue to be an important resource for humanity because the earth’s crust consists of stones and rocks in almost unlimited quantities [4].

In this time of recession and a global pandemic, construction industries have suffered and construction sites in many countries have shut down. But the Pandemic has hit different for different counties for example in UK the Construction went down 7 % first pandemic year and then drop 20 % more the second pandemic year [11] while in Sweden the business maintains almost on equal level as before [12]. Those that have remained open have faced disrupted supply chains and operational restrictions. This disruption has been reflected in financial indexes: since February 2020, public engineering, construction, and building materials (ECB) companies have decreased in value significantly more than other companies [13]. The US construction was hit by the Corona due to that US imports about 30 % of its building materials from China, with a further 20 % each coming in from Canada and Mexico [85]. The global impact of the coronavirus pandemic made the building materials supply chain difficult i.e. for example this supply chain drop 20 % in cargo volumes at American ports in the 1st quarter of 2020 [85].

From building hospitals in just a few days to donating lifesaving equipment, the industry has played a critical role in responding to the crisis and in the recovery from it.

The mining and construction industry accounts for around 13% of global GDP [4] and could contribute to the economic recovery from the pandemic effects, while also meeting our urgently contained construction-related needs [14].

Stones and rocks are normally too large to be properly handled for direct use. They need to be reduced to fine fragments for more effective handling and treatment. Crushing plays an important role in this size reduction process chain. To date, few papers have been published on how to calculate the production cost in crushing and screening for mineral fractions per ton produced. The attempts that have been made have often foundered on the difficulty of adequately accounting for all the input data [15]. The focus has then shifted to user friendliness.

1.2 World production of solid minerals and rocks

Geological surveys are vital for locating the supply of ores and rocks that are essential for mining and construction. The amount of solids extracted from the earth's crust is around 80 billion tons per year. As **Figure 1.1** shows, construction aggregates are by far the greatest part of these solids.

The construction aggregates segment includes sand, gravel, ripped rock, blasted rock, and recycled debris. The limestone segment includes limestone, marble, shell, fly ash, and clay for producing cement. The coal segment is mainly brown (lignite) coal, black (bituminous) coal, anthracite, and graphite. The ores segment includes metal minerals and diamonds. The last segment, others, includes such things as landfill (landscaping) and quality industrial minerals (for example, clay for the porcelain industry). Most of the quarrying products (construction aggregates) are sold in local markets, while most of the mining products (metals) are sold on the distant global market [4].

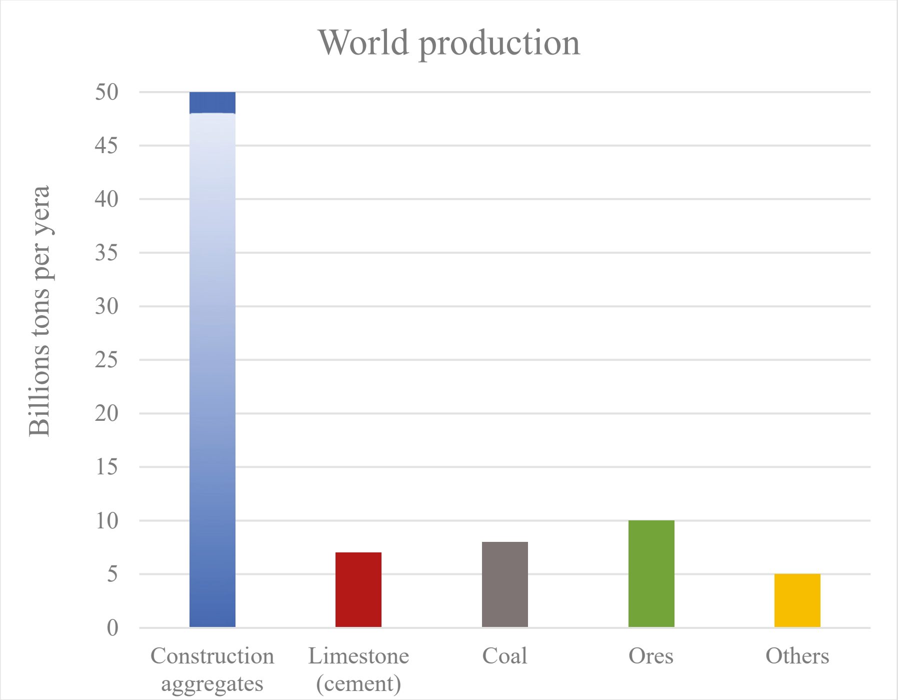

Figure 1.1 *World production of solid minerals, stones, and rocks [4, 16, 17, 18, 19, 20, 21].*

1.3 Mining industries

Mining industries are a segment of the metals and minerals business. Mining today is the extraction of valuable minerals or other geological materials from the earth's crust, usually from an ore body/deposit. These deposits form a mineralized package that is of economic interest to the miner [4]. Mining is normally divided into metal, energy minerals, and gemstone mining. Ores recovered by mining include metals, coal, oil shale, and gemstones.

Metal mining means the ore excavation and enrichment of metal minerals such as magnetite (iron), and chalcocite (copper). Energy mining means ore mining and extraction of solid energy minerals/rocks such as black coal and lignite. Gemstone mining means ore mining, beneficiation, and extraction of precious gemstones such as diamonds, emeralds, and opals.

Metal mining consists of several processes, of which the major ones are drilling and blasting (D&B), loading and hauling (L&H), coarse crushing (CC), crushing and screening (C&S), grinding and classifying (G&C) and mineral beneficiation (MB), see

Figure 1.2. Mining's main end products are normally fine-grained ore concentrate, where the costs of CC and C&S are in the range of 5–10 % of the total production costs in mining [4, 22].

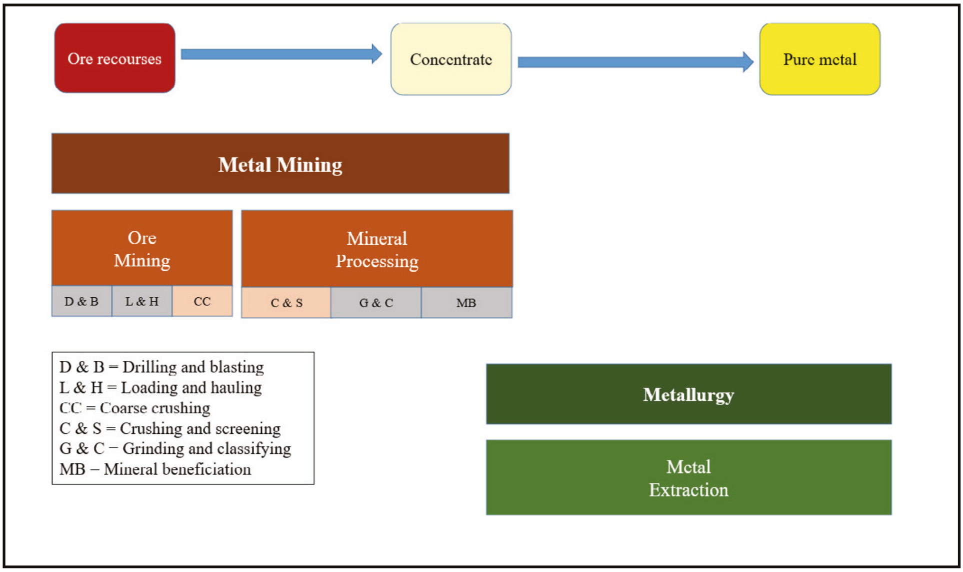

Figure 1.2 Overview of metal mining and metallurgy [4].

The main task of metal mining is to produce and supply other industries with metals for further use in producing parts or complete products such as equipment, machines, and building materials. The process chain from ore to finished product is shown in **Figure 1.3**.

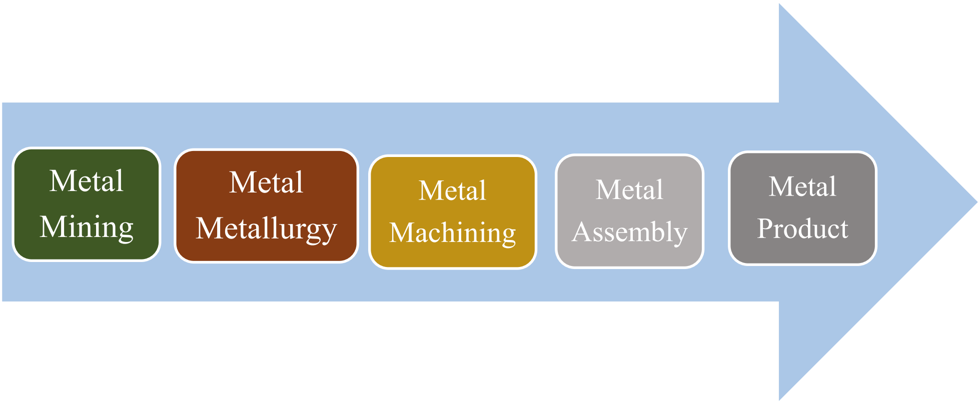

Figure 1.3 The metal process chain, from ore to finished product [4].

1.4 Construction industries

Construction industries are divided into two main subsections, quarrying and civil engineering. The quarrying industries produce the construction aggregates/stones for roads and the cement to make concrete. Civil engineering is designing, creating, and building infrastructure, see **Figure 1.4**.

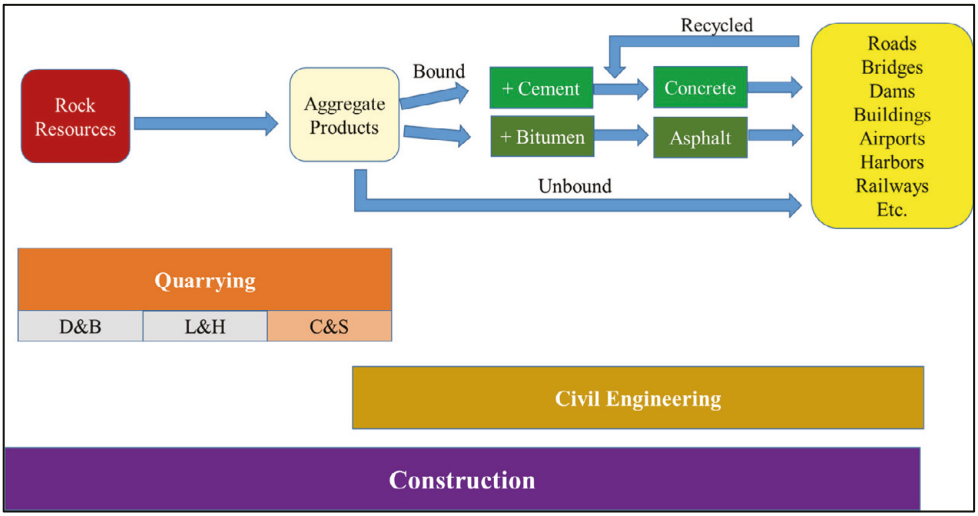

Figure 1.4 *Overview of construction industries [4].*

Quarrying is normally divided into three main streams, depending on the deposit:

- Alluvial rock, for example, sand, gravel, and moraine
- Solid rock, for example, ripped rock and blasted rock
- Reuse and recycling of construction and demolition debris and waste

The end products of quarrying are usually discrete fine to medium particle sizes of narrow fractions with different quality and shape properties. These end products are used as ballast in concrete and road construction. Normal concrete contains fine to medium particle size aggregates up to 75 % by weight, with cement, water, and reinforcement making up the remaining 25 %. In road construction, asphalt normally contains 90 % by weight of aggregates. The rest of the road structure is different particle sizes of rocks [4].

The costs of C&S constitute around 40–60 % of the total production costs in quarrying [4].

1.5 Crushing and screening (C&S)

A mineral processing plant is built up of several different processes and associated peripherals. The essential value creation takes place in crushing equipment, while the sorting equipment has the primary task of ensuring the quality of the product. Product that is larger than required is returned to the crushing equipment for further processing. Below is an overall description of a mineral processing plant.

C&S is consistently used as the acronym for the combined process of crushing and screening. It may be used as the name of an entire plant, including all other related equipment.

1.5.1 Crushing and screening plants

The main purpose of a C&S plant is to produce fine size rock particles from large rock particles in the right quantities, in the right particle size, and of the right quality for direct use or as feed for further processing like upgrading or extraction of the required rock properties [24]. A crushing plant can consist of a single crusher or a complex set of crushers, screens, and other equipment [4]. It may have various stations (primary, secondary, tertiary, . . .) where different crushing, selection and transport cycles are performed in order to obtain different stone sizes or the required granulometry. Due to limitations on the reduction ratio in a crusher, several stages are usually required to reduce the rock from lump size to the required product size. In a C&S plant this is done through several unit processes (process chain) [16], including

- Feeding
- Crushing
- Screening
- Transportation
- Blending/mixing
- Splitting/dividing
- De-dusting

A typical C&S plant is shown in **Figure 1.5**.

Figure 1.5 Typical C&S plant from above, and a side view of the secondary station in the plant.

C&S plants are of three main designs, see **Figure 1.6**:

- Fixed plants, which are stationary
- Mobile plants, normally on wheels or crawler tracks, to be moved often
- Portable plants on skids, which are rarely moved

Fixed plants are normally used when working with large deposits for several years. Mobile plants are preferable when working with small deposits for a short period, after which they are moved to the next location and operation. Portable plants are typically used in single projects, over a limited time period to minimize site preparation, for example, for dam projects [4].

***Figure 1.6** Typical stationary C&S plant (left) and a mobile C&S plant (right).*

1.5.2 Feeding and transportation

Feeding and transportation means that solid rock materials are transported from point A to point B through controlled flow (supply of material). Feeding is normally divided into three types: coarse, medium, and fine feeding, corresponding to the largest particle size of the rock materials. The most common type of feeders use vibration to force the solid rock materials forward, as in **Figure 1.7** (left). Feeders are used to feed the ore into the C&S machines or to feed a conveyor system. The transport of ore/rocks between machines in a C&S plant is usually carried out by a transport conveyor system, as shown in **Figure 1.7** (right). The conveyors move ore/rock materials from one place to another, over both short and long distances. Conveyors are especially useful in the transportation of heavy/bulky materials such as ore and rocks [4].

Figure 1.7 *Vibrating feeder with dust encapsulation (left), and conveyors (right).*

1.5.3 Crushing

Crushing is a size reduction technique for solid material [16], and a crusher is a heavy machine whose purpose is to break stones into small fragments. Coarse crushing is used when crushing raw run of mine (ROM) and run of quarry (ROQ) materials. With fine crushing, the crushed product is normally below 50 mm in size. Modern crushing technology started in the mid-nineteenth century with the invention of the Blake jaw crusher [23], see **Figure 1.8** (left).

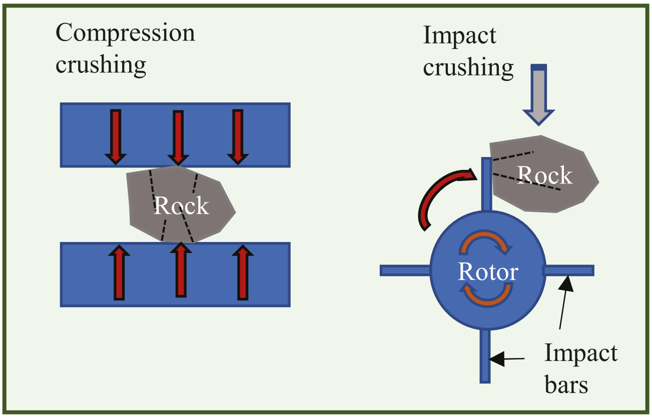

Figure 1.8 *The two main rock-crushing principles [4].*

More sophisticated crushing technologies such as cone crushers and vertical shaft impactors followed during the twentieth century. Today two main principles dominate the crushing of rocks, namely compression or impact. The working principle of compression crushing is forcing two surfaces toward each other in order to crush the rocks between them. Impact crushing can be described as rocks dropping into a fast rotor with impact bars that deal a smashing blow to the rocks, see **Figure 1.8** (right).

Figure 1.9 shows the most common compression crushers. Today the jaw crusher is the most common compression crusher in the world [4].

Figure 1.9 *Different types of compression crushers, gyratory, jaw, and cone [4].*

Due to the limitations in the reduction ratio for a crusher, several crushing stages are usually required to reduce a rock from the initial lump size to the desired product size. A compression crusher has a reduction ratio of 3–6, meaning that a rock of 900 mm will be reduced to 150–300 mm after crushing. An impact crusher can have a reduction ratio of 10–20 [24]. The use of impactors is limited by the toughness and abrasiveness of normal rocks (excluding limestone), because the production costs are too high compared with compression crushers [4].

1.5.4 Mechanical screening

Screening is used to sort solid material by size by separating coarser from finer particles. Products larger than 75 mm are considered coarse. Intermediate screening yields products between 20–75 mm, and fine screening yields products less than 20 mm [4, 16], 22]. Size sorting through screening is performed through the principle of stratification in the material bed of the screen, or through the principle of free-falling particles through the screen deck (**Figure 1.10**).

A screen consists of a drive that induces/creates the vibration, screen media that causes particle separation, and a deck that holds the screen media. The inclination of the screen decks can vary from horizontal to very steep.

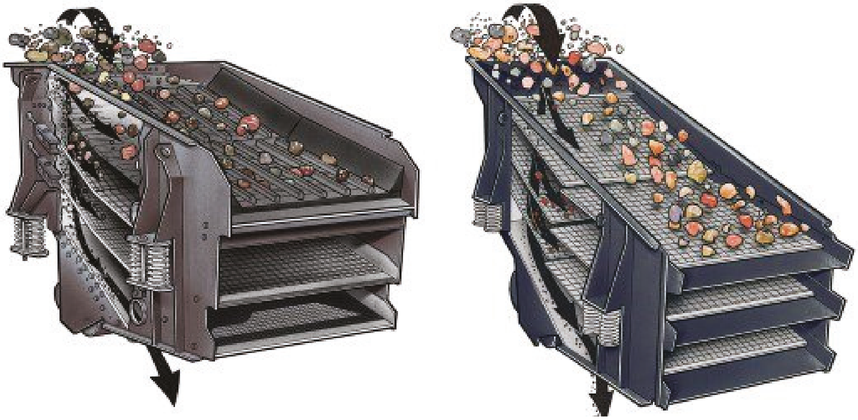

Figure 1.10 *The two main screening principles: right, screening through stratification, and left, screening through free-falling [4].*

Screening duties can be divided into:

- Scalping screening, roughly dividing into coarse and fine particles
- Closed circuit screening, taking out the desired size reduced product
- Final product screening, dividing the material flow into one or more narrow final fractions

The determination of screening accuracy is normally based on the proportion of correct particle sizes of the desired fraction in the screened product. The accuracy demanded is highest for final product screening and lowest for scalping screening. The most common screen machine type is a free-swinging circle motion screen type that uses stratification [4, 24]. Both the type of screening machine and the type of screening media influence the separation sharpness. Today there are several types of screen media, including bars, plates, wires, rubber, and polyurethane (**Figure 1.11**).

Different screening media will yield different screening results for the same type of screening machine. The same type of screening media can normally use different types of holes that also will give different screening results. There are several different hole types in screening media, such as square, round and elongated [4]. The most common type of hole opening used in mechanical screening is a square hole [4].

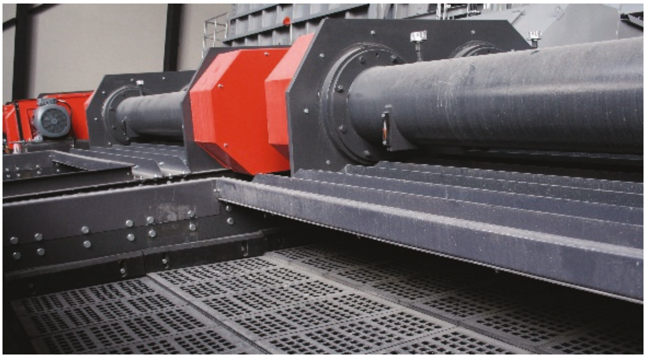

Figure 1.11 Screen deck with rubber screening media with square holes.

1.5.5 C&S circuits

The purpose of a C&S plant is to produce the right quantity and quality of product(s) by creating a chain of unit processes. Due to the limitation in the reduction ratio for a crusher, a C&S plant normally contains several crushing stations to reduce the rock from lump size to wanted product size [4]. The crushing circuit can be open or closed (**Figure 1.12**). The commonly used icons in flow diagrams and circuits can be seen in Appendix A.

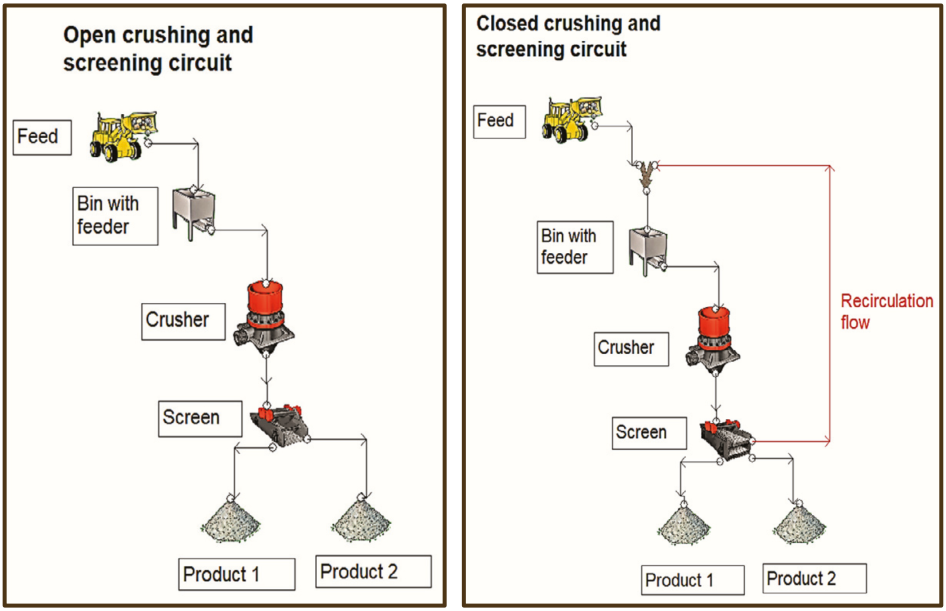

Figure 1.12 Typical open (left) and closed (right) crushing circuit with explanations.

When the circuit is open, the material flows in one direction. In closed circuits, oversize particles are recirculated and re-crushed, while particles that have reached correct product sizes or smaller are removed from the circuit.

1.5.6 Plant configurations and product qualities

When designing a C&S plant, the following main factors must be taken into consideration:

- What type of raw material will be processed, and are there any contaminants?
- How big is the feed and what end products will be processed?
- How much will be processed?
- When and where will the C&S plant be set up?
- Who is the customer?

Different types of materials have different crushability (toughness) and wear properties (abrasiveness). **Table 1.1** shows some examples of raw material and their crushing properties.

Table 1.1 *Examples of raw materials and their properties that strongly affect crushing [24].*

Type	Toughness	Abrasiveness
Basalt	Extremely hard	Intermediate
Granite & Gneiss	Hard	High
Limestone	Soft	Low
Quartzite	Hard	Extremely high
Iron (Magnetite)	Soft	Low
Iron ore (Hematite)	Hard	High

A C&S plant can have one, two, or several crushing and screening stages depending on the end product quantities and qualities, such as product sizes and priorities. As compression crushers have a maximum size reduction ratio, the number of crushing stages needed to obtain the right product sizes depends on the feed sizes. The reduction ratio is defined as the ratio Rr = feed size / product size = F80/P80 [24], see **Figure 1.13**. **Table 1.2** gives examples of reduction ratios for a few different crushing applications.

Reduction ratios also depend on the toughness of the rock bound for crushing. When soft rocks are crushed, the reduction ratio will be higher than when crushing hard rocks [24].

When crushing blasted granite rock o 0–600 mm (with F80 = 320 mm) can to 0–25 mm (with P80 =.20 mm)., this particular case, the reduction ratio Rr can be calculated as Rr = 320/20 = 16.

Table 1.2 *Nominal reduction ratios for compression type crushers [24].*

Compression type crushers	Normal reduction ratio
Jaw	2–4
Primary gyratory	3–5
Secondary gyratory	4–6
Cone	4–6

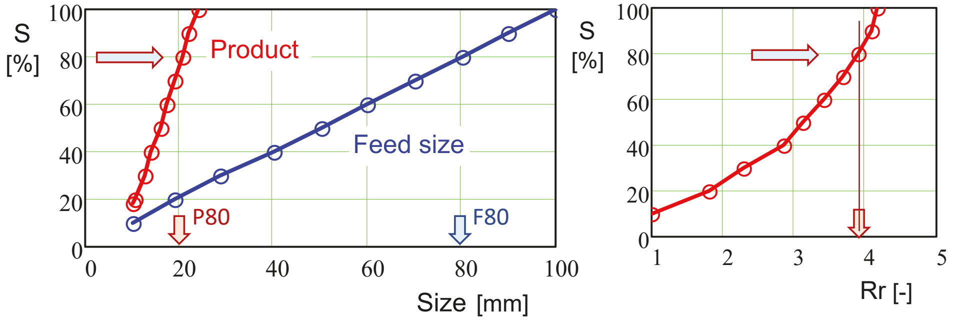

Figure 1.13 *Particle size distribution for a product (red) and a feed (blue) (left); and the related distribution for the reduction ratio Rr, modified based on [24].*

A jaw crusher normally has an $Rr_1 = 3$ followed by a cone crusher with normal $Rr_2 = 6$, could reach the total reduction ratio due to the product $Rr_{1\text{-}2} = 3 \cdot 6 = 18$, a little higher than the needed Rr = 16. The reduction ratio Rr provides a first insight into how many crusher stages are needed to reach the desired end product sizes. In addition, the product properties (size and quality) have a major influence on the creation of C&S plant flows. Choosing one large machine or parallel small machines usually depends on who the customers are [25].

The end product sizes are normally tested through laboratory sieves with square or round holes [4, 24]. Square holes and round holes of equal size will not give the same particle size distribution (PSD) [24].

Table 1.3 *Guideline for reduction ratio with required number of crushing stages [4].*

Reduction ratio (x)	Number of crushing stages	Remarks
2–6	1	The maximum reduction ratio only when crushing soft rock
5–15	2	The maximum reduction ratio only when crushing soft rock
15–45	3	The maximum reduction ratio only when crushing soft rock

(x) = Compression crushing

Especially in construction aggregates, quality properties (such as fraction purity and shape) are required before they can be used in asphalt and concrete [4]. Different counties and different regions have different norms that stipulate the way to analyze the end products. These affect the design of the C&S plant [4].

Fraction purity normally means how many misplaced particles (oversize and/or undersize) are allowed in the fraction. A requirement for lower percentages of misplaced particles in the fraction mean it is more difficult to screen the fraction [4].

Earlier demand related to shape in the fraction requires a more gentle crushing force using, for example, a lower reduction ratio (which means more crushing stages) but today the processes go towards higher crushing pressure and long fractions, with normal close circuits to create good shape [16].

All the above facilities and restrictions must be incorporated if a new C&S plant is to be able to meet the stipulated requirements for the end products, [4].

1.6 Objective

As technical simulation programs of the C&S plant process have become common and powerful tools, it is now possible to technically optimize C&S plant processes in the design phase. There is, however, almost no program or method today to calculate the full cost of production in C&S and to identify equivalent process alternatives that give the lowest possible end product cost using flowsheets created by the technical simulation from C&S process programs.

This thesis aims to develop a full-scale platform or setup for studying product costs in a C&S plant under actual conditions or for future applications. The objective for the platform is then to find the minimum product costs for selected process setups. The work carried out can be formulated as both a scientific and an industrial challenge.

Scientific challenge: To be able to identify and select sufficient input data set to find the most important cost-drivers, which then enable prediction of product cost within 10 % accuracy in the manufacturing process involving mineral crushing and screening in open and closed systems for one or several products.

Meeting this challenge will contribute new knowledge that can serve as a basis for competence development within academia and industry.

Industrial challenge: To be able to implement, in appropriate cases, in both an engineering and an industrial context, theoretical models and principles of the platform based on empirical results obtained under full-scale conditions. The technical implementation should strive for reducing manufacturing costs and increasing the competitiveness of a C&S plant.

A C&S system works under complex, changing process conditions including altered crushability of the raw/feed material due to multiple mineral contents with different compositions, changed particle size distributions in the feed and changes in the moisture content in the feed material depending on weather conditions.

This work also aims to highlight the important links between technology and the economy. It aims to provide a basis for future research that will enable producers to identify the optimal use of a given mineral quarry as regards the choice of product mix through increased precision in cost calculations. Furthermore, future developments also require high-precision cost models to make sustainable and robust analyses of environmental economic considerations.

1.7 Research questions

To meet the above objectives, this thesis addresses two research questions. The first deals with what information/data is needed to be able to perform trustworthy final product(s) cost calculations in C&S plants.

RQ1: How should the necessary information and data be incorporated to perform reliable final product cost analyses in a complete C&S plant?

The second research question deals with how to make the end product cost calculations. Due to the complexity of C&S processes, two sub questions were required to accommodate different C&S systems.

RQ2A: How to design and populate the product cost calculation platform for the case of an open C&S circuit?

and

RQ2B: How to design and populate the product cost calculation platform for the case of a closed C&S circuit?

A C&S system consists of one or more open or closed circuits. So RQ2A and RQ2B, individually or together, form the basis for product cost calculations of a C&S system. To be able to calculate the product costs in complex C&S systems, several RQ2A and RQ2B are needed that relate to the process solution in the C&S system.

The research questions are formulated in such a way that both scientific and industrial goals are included. The author sees no advantage to separating the two research questions, since doing so could reduce the quality of the study.

1.8 Scope and limitations

The scope is to develop a new production cost model for crushing and screening processes. The model aims to present more accurate results when calculating the production costs and to serve as a tool for calculating the product costs for selected process alternatives. The aim is to be able to find the lowest product cost for different C&S process alternatives. The model is intended to be implemented in both existing C&S plants and in future C&S plants and needs to be able to consider C&S processes with different feed materials.

The following limitations have been imposed on the scope of work: Only jaw and cone crushers have been considered, using compression for size reduction. Mechanical screening is limited to using free-swinging motion as a basic principle. The plants that were studied were limited to C&S used in metal mining and mineral quarrying.

As correct initial data is extremely important for satisfactory results, considerable effort was taken to validate the input data, except for the actual adaptation of the production-economic model to a current application where I have reported all real financial and process technical facts from the customers for the test C&S plants as they have presented to me, I made at least three equivalent full-scale test runs at each test plant to create higher confidence in the input data. This was to ensure that that the tests showed similar results. When this was not the case, I performed more tests. Only costs directly associated with the C&S are included. None of the indirect costs for the overheads necessary for the company to function are included in this dissertation.

1.9 Selected definitions

Table 1.4 gives the definitions used throughout this thesis.

The thesis is based on two important equations that define the production capacity of a C&S plant:

- C&S plant production = Capacity x operating time x utilization
- C&S plant production = Capacity x working time

Table 1.4 *Selected definitions.*

Item	Definition
Throughput	The rate at which something is processed
MTPH / MTPY	Metric tons per hour / Metric tons per year
Capacity	Maximum momentary throughput, as MTPH
Production	Annual throughput as MTPY
Operating time	Total production time per year, as hours
Working time	Sum of all net production times per year, as hours
Load	Actual throughput compared with capacity
Availability	Ratio of the sum of all working times to operation time
Utilization	Ratio of load/maximum load
Simulated C&S plant	Calculated and designed C&S plant that has not yet been built
Existing C&S plant	C&S plant built and running
Steady state	The throughput and the PSD from the machine/plant are constant over a certain period of time and has reached steady stable operating conditions.
Feed	Material entering the plant or machine/equipment
Product	Materials leaving machine/equipment
End product(s)	Material(s) leaving the C&S plant
PSD	Particle size distribution as cumulative percent passing

1.10 Outline of the thesis

The thesis is structured as follows:

Chapter 1, Introduction: This chapter introduces the research topics and the basic research objectives, the concept approach taken, and the concrete research questions posed.

Chapter 2, Review of Product Cost Calculations in C&S: This chapter describes earlier research in the area of product cost calculations and models in C&S. Several of these documents deal only with operating costs and do not take the cost of capital into consideration.

Chapter 3, Research Methodology: This chapter explains the research approach taken and introduces the research methodology employed in obtaining the results reported in the thesis.

Chapter 4, Basic PCCM Model for C&S: This chapter provides a brief introduction to the field of research involved and describes the contributions made by the author to the work presented. The initial version of the models from the first case study is presented.

Chapter 5 Model Refining for Several Products:

Shows the development of the models to the final version, through new and more accurate information and cost equations, and developments from the second case study.

Chapter 6 Model Verification: This chapter describes testing of the models in three existing C&S plants and in one application C&S plant.

Chapter 7 Discussions and Conclusions: This chapter discusses the results as a whole and summarizes the most important conclusions arrived at on the basis of the results presented. Finally, the results are related to the research questions posed.

Chapter 8 Future Research: The thesis ends with proposals for future research to incorporate impact crushers and grinding mills.

This dissertation is based on the publications and presentations in Appendix E.

Appendixes:

A. Flowchart icons
B. Simulation models and programs
C. Spreadsheet
D. Performance guarantee
E. Contribution to published paper
F. Case study of full-scale plants
G. Environment, health, and safety
H. Production analysis, input sheet
I. Analyses of simulation results

2. Review of Product Cost Calculations

This chapter reviews previous work in cost modeling related to crushing and screening plants. The available models found in scientific literature and in other reference works are reported. However, little has been published in this specific field. The chapter results in a compilation of the most important published works. The compilation includes each model's level of detail.

2.1 Introduction to product cost calculations

C&S plants were once thought of as merely raw material processors. A change in perception started with the MinBaS (Swedish Minerals, Ballast, Aggregates, and Stones) project driven by MinFo (Swedish Mineral Processing Research Association), SBMI (Swedish Aggregates Producers Association) and SFI (Swedish Stone Industries Association), in cooperation with the Chalmers Technical University and Lulea Technical University and sponsors from the private industries such as LKAB, Boliden, Jehanders, NCC, and Sandvik.

The MinBaS project showed that the complexity of production in C&S plants can be compared with that of normal industrial production plants [26] and opened the possibility of researching C&S plants from a scientific point of view. Influential ideas about cost calculations in C&S that influenced this dissertation also come from Svedensten [15] and Bengtsson et al. [27] and how they handled C&S processes.

By using their work and Ståhl's standard cost equation [28, 29], a new concept for production/product cost calculations opened up for size reduction plants and especially for C&S process plants. This thesis is based on this revised way of looking at C&S plants as industrial production plants and further develops production/products cost calculations to create a new cost evaluation tool for C&S plants and processes. Its topic may therefore be seen as related to production and product costs specifically in C&S processes. Production cost calculations in manufacturing of one or several end/final products are essential in all businesses that produce goods to establish the costs that the business must carry to achieve profit. These production costs are also the basis for deciding on the selling price for the manufactured goods. No matter what type of product you sell, the price must cover costs and some profits [30].

Normally production costs are divided into two main steams, fixed costs and variable costs. Fixed costs are expenses that remain unaffected by changes in production volume. Fixed costs normally consist of items like rent, utilities, and overheads. Variable costs are costs that change with the manufacturing volume of the product(s). Normally variable costs are direct labor, direct material, and supplies consumed to make the manufactured product [31].

Once all the production costs are calculated, the total production cost is divided by the number of units produced to obtain the cost per unit manufactured. Manufacturing costs refer to the variable costs, meaning that the manufacturing cost per unit is stable when the number of manufactured units changes [31].

The production cost includes both the fixed and the variable cost, meaning that if the number of items increases the production cost/unit will decrease, or if the production number decreases then the product cost/unit will increase [32]. A production cost model must include all the costs of all machines and equipment in production and related operations. The aim is to calculate the hourly production cost [32]. Production cost evaluations are normally used by producers and suppliers to obtain the unit costs (product costs) for goods and services. In this case, the unit cost is the total cost of a given production run, divided by the number of units produced. Alternatively, buyers and owners can use the total cost of ownership (TCO) as an economic estimation to determine the direct and indirect costs of a product or system [33].

This chapter examines several published calculation methods for production costs in mineral/rock processing C&S plants. A summary and conclusions in regard to these methods is given in section 2.5.

2.2 General product/production cost calculations

Companies that manufacture and sell products must be able to calculate their product costs with good accuracy. If a company produces more than one product, the company must be able to track and allocate all direct and indirect product costs sensibly.

Ståhl shows that connecting economy and technology is the most important factor in achieving efficiency and competitiveness in a discrete part manufacturing system [28] and in the development of manufacturing systems [29]. The basic form of the standard cost model according to Ståhl [28] is shown in Equation 2.1. This cost model does not take into account indirect costs that can be related to, for example, management, sales, or purchases. The model is available in various extended versions that include such things as maintenance, storage and handling, and transportation.

There are four main subcost groups in the generic standard cost model, designated a–d. These are costs for tools and tooling systems (a), raw material costs (b), production costs uptime (c1), production costs downtime (c2), and labor costs (d).

$$\begin{aligned}
k = & \left.\frac{K_A}{N_0 \cdot n_b \cdot n_{part}}\right|_a + \frac{k_B}{N_0}\left[\frac{N_0}{(1-q_Q)\cdot(1-q_B)}\right]_b + \\
& \frac{k_{CP}}{60N_0}\left[\frac{t_0 \cdot N_0}{(1-q_Q)(1-q_P)}\right]_{c1} + \\
& \frac{k_{CS}}{60N_0}\left[\frac{t_0 \cdot N_0}{(1-q_Q)(1-q_P)} \cdot \frac{q_S}{(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb}\right]_{c2} + \\
& \frac{n_{op} \cdot k_D}{60N_0}\left[\frac{t_0 \cdot N_0}{(1-q_Q)(1-q_S)(1-q_P)} + T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb}\right]_d
\end{aligned} \tag{Equation 2.1}$$

The designations of the cost subgroups (a–d) are related to process controlling factor groups that strongly influence the performance or outcome (result parameters) of all production that can be linked to raw material processing [35]. The equation according to Ståhl [35] also uses indices related to the factor groups, and to the result parameters in terms of quality (Q), disturbances and stops (S), and production rate (P). The relationships between factor groups and performance parameters are reported and described in a production performance matrix (PPM). A production follow-up based on a PPM is referred to as a systematic production analysis (SPA) [35].

In the model in Equation 2.1, k is the production cost per part. In order to obtain this cost, all four cost subgroups have to be calculated. k_B is the cost of raw material, k_{CP} is the cost of equipment during process uptime per hour, k_{CS} is the cost of equipment during downtime per hour, $n_{op} \cdot k_D$ is the cost for average salary for n_{op} number of operators per hour, N_0 (number of parts in a batch) and t_0 is the cycle time for each part (floor-to-floor time).

By dividing the quality yield (1-q_Q) or the time exchange (1-q_S), the actual number of components that must be manufactured is obtained, which also includes discarded parts. The extra time required to manufacture these parts due to downtime is obtained by dividing by the time exchange (1-q_S). Similarly, for the rate losses, divide by (1-q_P).

The loss parameters (q_Q, q_S, and q_P) are calculated as the ratio between the loss in question and the total value of the parameter. For example, if 10 components are discarded in a total of 100 manufactured components, the scrap rate $q_Q = 0.1$ (10/100). The other loss terms are defined and calculated in a similar way.

U_{RP} is the degree of utilization with respect to reduced production, and (1-$U_{RP)}$ is the degree of free capacity. This parameter U_{RP} is included in the standard cost model in order to allocate the cost of overcapacity to the produced volume of components, in relation to its share of total production. The costs of overcapacity are allocated in proportion to the time to produce a particular batch T_{pb}. In this model, large batches may carry a higher cost share for free capacity.

Setup time T_{su} is the time required to adapt and adjust the equipment from manufacturing component X_1 to manufacturing component X_2.

2.2.1 General cost models for customized applications

In many cases, the standard cost equation must be adapted to the current application area, such as adaptation to different manufacturing methods, operating steps, or specific operations [28]. The standard model for part cost calculation was basically developed for discrete batch production. What is common to all applications is that they contain a cost factor per unit of time for equipment and salaries. In the general cost equation, the machine hour cost is described by the factors k_{CP} and k_{CS}, the cost per hour during operation and at standstill. These cost factors can include both fixed and variable costs per unit of time.

What essentially distinguishes application-adapted cost models from the standard model is how the time that controls the rate is expressed for current production. In the standard equation, the cycle time t_0 expressed per unit (unit of time per unit, e.g., minutes per unit) is used to describe the time required per unit produced. The reciprocal value of time consumption per unit produced is the rate of production, that is, the number of units manufactured per unit of time.

In continuous processes or applications such as stone crushing, the time required is expressed as hours per ton and the rate as tons of crushed mineral per hour. The corresponding unit of time and rate for paper production, for example, would be hours per meter and meters of paper per hour, respectively. In general, the time variable below is denoted by Ψ_{Time} and the rate variable is denoted by Ψ_{Rate}. In cost calculations, either variable can be used as they are the reciprocal of each other, that is, $\Psi_{Time} = 1 / \Psi_{Rate}$.

The rate or time variable is included in several places in the general cost model due to the fact that several cost items are dependent on time consumption or rate. This relationship is exemplified below in Equation 2.2, which uses the rate variable instead of the time variable ($t_0 = \Psi_{Time}$).

$$
\begin{aligned}
k = {} & \left.\frac{K_A}{N_0 \cdot n_b \cdot n_{part}}\right|_a + \frac{k_B}{N_0}\left[\frac{N_0}{(1-q_Q)\cdot(1-q_B)}\right]_b + \\
& \frac{k_{CP}}{60N_0}\left[\frac{N_0}{\psi_{Rate}\cdot(1-q_Q)(1-q_P)}\right]_{c1} + \\
& \frac{k_{CS}}{60N_0}\left[\frac{N_0}{\psi_{Rate}\cdot(1-q_Q)(1-q_P)}\cdot\frac{q_S}{(1-q_S)} + T_{su} \right. \\
& \qquad \left. + \frac{1-U_{RP}}{U_{RP}}T_{pb}\right]_{c2} + \\
& \frac{n_{op}\cdot k_D}{60N_0}\left[\frac{N_0}{\psi_{Rate}\cdot(1-q_Q)(1-q_S)(1-q_P)} + T_{su} \right. \\
& \qquad \left. + \frac{1-U_{RP}}{U_{RP}}T_{pb}\right]_d
\end{aligned}
\qquad \textit{Equation 2.2}
$$

Each manufacturing process or application has different properties, which means that the cost equation must be modified in different ways.

Table 2.1 shows some examples of application processes using either time variables Ψ_{Time} or rate variables Ψ_{Rate}.

Table 2.1 *Examples of the use of custom cost models for different production-related applications based on Ståhl's standard cost model [28].*

No.	Application – process	Time consumption per unit, Ψ_{Time}	Production rate, Ψ_{Rate}	Reference
1.	General model	t_0, cycle time /unit [h/part].	R_p, number of units per hour [units/h].	[36, 37]
2.	Metal sheet forming	t_0, cycle time/part [h/part].	R_p, number of details per hour [details/h].	[34, 38, 39]
3.	Machining – metal cutting	t_0, cycle time/part [h/detail].	R_p, number of details per hour [details/h].	[28, 29, 40]
4.	Stone crushing and screening*	m_m, time/mass, or m_v, time/volume [h/ton] or [h/m^3].	R_{mt}, mass or volume per hour [ton/h] or [m^3/h].	**This thesis**
5.	Paper production or surface coating	m_h, time/unit length [h/m]	R_{mh}, unit length per hour [m/h]	[41, 42]

* The cost models for C&S are developed in chapter 4 and chapter 5 in this thesis.

Note: Ståhl's production cost model is a general production cost model that has been adapted to several application processes, but not explicitly for C&S production cost calculations. It is one of several cornerstone ideas in this thesis, see chapter 4 and chapter 5.

2.3 Absorption cost model

This cost calculation model represents the information regarding all expenses that are associated with the production process of a product or service [44]. Absorption costing is also called full costing, including the fixed overhead charges in the product costs. There are normally four steps in the absorption cost model.

A. Calculation of full production costs as per product including
   - Direct material cost
   - Direct labor cost
   - Fixed and variable production overhead costs.

B. Calculation of stock value and production.

C. Under/over absorbed fixed production overhead costs.
   - Relation between actual fixed production overhead costs and fixed production overhead costs.

D. Absorption costing profit calculation.
   - Gross profit.
   - Net profit.

Note: This type of model is useful when determining the sales price of products [44]. The model uses the fixed overhead costs and allocates them to overall units that are produced during the period, thus providing a cost per unit. Under absorption costing, companies handle all manufacturing costs, including both fixed and variable manufacturing costs.

The standard model for part cost calculation according to Equation 2.1 can be supplemented by so-called β-factors that take into account indirect costs if they are known in advance. These factors can also allow cost-based pricing to be made [44].

2.4 Product cost calculations in C&S plants

Few cost estimates related to C&S are reported in the literature, which justifies the present study. The reported models are based exclusively on purely empirical assumptions and experience. The assumptions are often very difficult to verify as they are based exclusively on more or less documented experience under different circumstances. Below are the most common models reported in the literature. The designations used have been adapted to a uniform nomenclature where possible.

2.4.1 Major mineral processing equipment costs

Mular [45] suggests and explains different ways of making approximate estimates of the equipment costs in a mineral processing plant. The main principles given are:

- Obtain the data for equipment with prices from the suppliers
- Use cost indices to upgrade earlier prices for equipment from suppliers

The praxis is that suppliers always give the nominal price from the latest pricelist. They will supply exact prices for the desired equipment, but with the restriction that prices are daily prices and thus have short durability.

The other way to determine equipment costs uses cost indices to adjust earlier prices for "identical" equipment and capacity ratio:

$$k_{C\_new} = K_{0old} \cdot \left(\frac{MT_{ph\_new}}{MT_{ph\_old}}\right)^{\kappa}$$

Equation 2.3

Where k_{C_new} is the new cost and $P_{\_old}$ is the known previous price for the established and well-known equipment. The ratio between MT_{ph_new} and MT_{ph_old} is a capacity index that is evaluated by using the exponent κ, where MT_{ph_new} is the maximum capacity for the new equipment and MT_{ph_old} is the maximum capacity for the old equipment.

The choice of exponent κ depends on experience of cost estimation for a particular industry and the degree of conservatism exhibited by the estimator. The normal value of κ for C&S equipment is $0.5 < \kappa < 0.8$ [45].

According to Mular [45] the fixed costs k_{C_fix} for crushing can be calculated using Equation 2.4.

$$k_{C\_fix} = 97790 \cdot MT_{p\_day}^{0.5}$$

Equation 2.4

Where MT_{p_day} is capacity per day in short tons (1 short ton = 907.18 kg).

The equipment cost ratio is found by multiplying categories of equipment of similar nature by corresponding ratio factors and calculating the sum.

$$K_{C\_Plant} = \sum_{i=1}^{i=n} F_i \cdot K_{0i}$$

Equation 2.5

Where n is the number of major items of equipment and K_{0i} is the investment cost for equipment i. By experience in the field, F_i for crushers is $F_i = 3.5$ [45].

According to Mular [45], the US Bureau of Mines Information Circular 9298 presents approximate estimations of the cost to develop mineral deposits. Costs are based on average 1989 US dollars and perform simplified capital/operating cost estimations. The cost-capital equations need to be updated before use. Mular says that “the methods are adaptable to most deposits” [45].

Summary: Mular presents a fast way of making cost calculations for mineral processing plants. The method in his paper gives an approximate estimation that can be used in pre-surveys for rapid calculation of the outcome of possible process alternatives, before going to equipment suppliers for actual quotations.

2.4.2 Crushing operating costs in 911 Metallurgist

One of the most popular sites for mineral processing engineers is 911 Metallurgist [46]. The 911 Metallurgist reference provides a diagram for rapid checking of the production cost for different capacities in gold ore processing, see **Figure 2.1**.

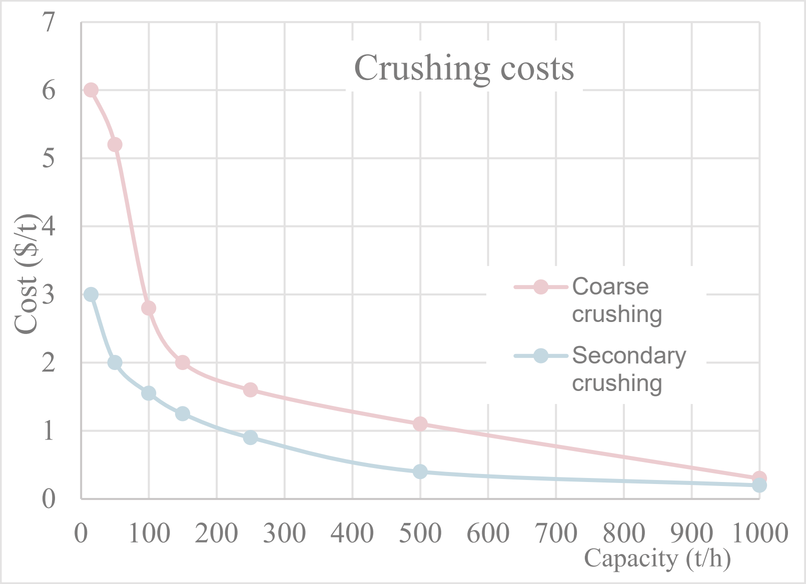

***Figure 2.1** Crushing costs for gold ore processing [46].*

C&S itself cannot directly reduce solid rock to final size. Therefore, the size reduction chain must include other operations such as drilling and blasting. There is a minimum cost to obtaining a particular particle size in a reduction chain of rock using drilling/blasting and crushing/screening, depending on the sequence of equipment used. As the cost of creating smaller sizes in drilling/blasting is considerably higher than the cost of crushing and screening, a combination of these two size reduction operations can create a proper balance for the lowest cost of size reduction [4].

Summary: 911 Metallurgist shows the easiest way of determining production crushing costs for gold ores. However, it is not directly transferable to other feed materials.

2.4.3 Simulation and optimization of crushing plant performance

According to Svedensten [15], the cost function is crucial in C&S to get the best results from optimization routines. There are several optimization routines such as "gross profit," "maximize one final product," "minimize one final product." However, the "production costs of every product are needed to calculate the gross profit of the plant" according to Equation 2.8. The notation defined by Svedensten is used in the equations below.

The total cost per ton of product produced in each crushing step is calculated according to [15] as:

$$C_{tot,i}(X) = C_{ton,i}(X) + \frac{C_{hour,i}}{m_{rock,i}(X)} \qquad \textit{Equation 2.6}$$

Where $C_{hour,i}$ is a fixed cost per hour and $C_{ton,i}(X)$ is the variable cost per hour. The fixed cost per hour is divided by the material flow expressed in tons per hour. The variables X describe all the individual factors that affect the crushing process, such as wear and maintenance costs. Svedensten [15] also describes the cost in the cross process in two parts by distinguishing between the cost related to wear and maintenance and costs for unrelated wear, respectively.

$$C_{tot,i}(X) = C_{ton,non\,wear,i} + C_{wear,i}(X) \qquad \textit{Equation 2.7}$$

$C_{a,b}(X)$ describes how an optimization can be done based on all variables X. This analysis also includes costs for downtime $C_{downtime}$ per hour and costs for raw material C_{init}.

In a closed crushing process, the material can go through one and the same crushing step several times, depending on the raw material including the product dimensions and the equipment's properties and degree of wear. Svedensten has modeled the costs for re-feeding material using a general utilization factor μ [X]. This factor is calculated by Svedensten through a simulation program he developed. The value of the factor is not known to the user as it is hidden in the current simulation program. From experience, the material recycling of the same material can take place several times, which the author later in this work considers a loss of pace. The cost per hour and ton is described according to equation 2.8.

$$C_{h,tot}(X) = \sum_{i=1}^{i=n} \mu_{h,_i}(X) \cdot C_{tot,i}(X)$$
$$0 \leq \mu_{h,_i}(X) \leq \infty \qquad \textit{Equation 2.8}$$

$C_{tot,i}$ is the cost of product h in crushing stage i and $\mu_h(X)$ is the utilization factor for product h. According to Svedensten the gross profit can be calculated as:

$$\dot{P}_h(X) = \left(V_h - C_{h,tot}(X) - C_{init}\right) \cdot \dot{m}_{rock,h}(X) \qquad \textit{Equation 2.9}$$

V_h is the sales value of product h and $m_{rock,h}$ is the average mass flow per hour. The total gross profit per hour for a total number of products q be calculated as:

$$\dot{P}_{tot,production}(X) = \sum_{h=1}^{q} \dot{P}_h(X) =$$
$$\sum_{h=1}^{q}\left(V_h - C_{h,tot}(X) - C_{init}\right) \cdot m_{rock,h}(X) \qquad \textit{Equation 2.10}$$

According to Svedensten [15] the cost function for optimization can be calculated by introducing the availability α_{tot} related to downtimes:

$$\dot{P}_{tot}(X) = \alpha_{tot} \cdot \dot{P}_{tot,production} - (1 - \alpha_{tot}) \cdot$$
$$\dot{C}_{downtime} \qquad \textit{Equation 2.11}$$

α_{tot} is the availability of the plant and P_{tot} profit per hour.

Summary: Svedensten has shown a way of optimizing C&S plants by using gross profit as the tool for determining the best solution for the plant.

2.4.4 Dynamic profit optimization comminution circuit

Bengtsson et al. [27] use dynamic profit plant simulations through an optimization flowsheet (**Figure 2.2**).

Bengtsson et al. [27] describes the influence of wear on capacity and product quality and then produce cost estimations:

$$C_p = C_1 + C_2 + (C_1 + C_2 + C_3) \cdot \frac{Q_{re}}{Q_p} \qquad \textit{Equation 2.12}$$

C_p is the total cost of product p, C_1, C_2 and C_3 are costs for each item, Q_p is the amount of product p, and Q_{re} is the amount of recirculation flow. The mean time to failure (MTTF) for equipment in the crushing plant is very important. Bengtsson shows that MTTF can be used to calculate the maintenance frequency:

$$\gamma = \frac{MTTF_{400}}{MTTF_{300}} \qquad \text{Equation 2.13}$$

$MTTF_{400}$ and $MTTF_{300}$ are the mean times to failure for different eccentric speeds on the crusher. Changes in the properties of the plant operations such as feed distributions, CSS (close side setting of crusher), hydraulic pressure, and changes in the moisture content in the feed will have a direct impact on the product properties.

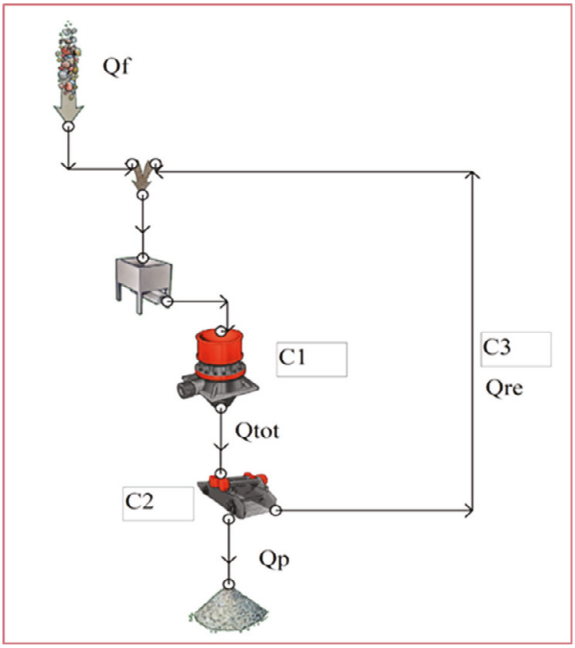

Figure 2.2 *Flowsheet of closed circuit.*

According to Bengtsson et al. “The generic cost model is described in its simplest form since the costs for all the equipment are considered to be constant with time. It is assumed that the wear rate is proportional to the mass flow passing the equipment.”

In the paper Bengtsson et al. also say, “The change in one parameter will result in process variations that cannot be foreseen by observing the process layout. This work shows that wear will have tremendous effect on both capacity and quality of the product. Furthermore, it can be concluded that that optimization of a wide range of products will result in a trade-off regarding yield and quality and therefore a multi object perspective must be defined in order to address this problem” [27].

Summary: Bengtsson et al. have shown the complexity of C&S plants during operation, which means that the best way to simulate the processes is to use dynamic models [27]. Bengtsson is building on earlier work such as that of Svedensten [15] to use profit as the tool for optimization of the process.

2.4.5 Cost evaluation of producing different aggregate sizes

Busuyi [47] shows the cost evaluation of producing aggregate sizes in two quarries in Ondo, Nigeria. The production costs include labor salary costs, energy costs, equipment costs with repairs, maintenance costs, miscellaneous costs and government revenue, taxes, and royalty costs. Two quarries were studied, the first with a production of 31 200 t/month and the second with 15 000 t/month. All data obtained and collected from the company was critically analyzed, examined, and processed. The result shows that the cost for producing these aggregates is:

Quarry 1: 981 Nigerian Naira per ton ≈ 27 US$/ton
Quarry 2: 678 Nigerian Naira per ton ≈ 19 US$/ton

The allocation of the costs for Quarry 1 is illustrated in **Figure 2.3**. The paper also shows a profit calculation for both quarries:

Quarry 1: 37,242,000 Nigerian Naira per month ≈ 1024.15 US$/month
Quarry 2: 22,461,000 Nigerian Naira per month ≈ 617.61 US$/month

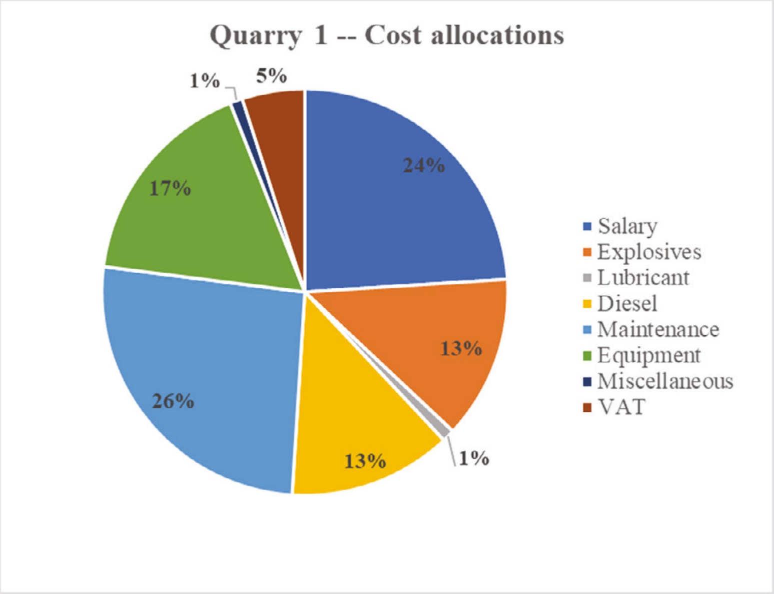

Figure 2.3 *Cost allocation for Quarry 1 [47].*

Summary: Busuyi [47] has shown the most fundamental production cost items in C&S plants; however, the paper reflects only an overall (not detailed) analysis. The paper presents only a collection of the production costs and does now indicate how to make cost calculations in new C&S plant applications. However, the paper does give a good overview of actual C&S plant cost items.

2.4.6 Crushing cost studies

Reitz [48] presented a case study for costs related to a C&S plant. The study does not include any planning and design costs for plant construction. Despite this limitation, the study is well detailed regarding costs. It was conducted in 1967 and the plant had a production capacity of 8.4 million STPY (short tons per year) for oil shale crushing. The investment costs for this plant are presented in **Table 2.2** and the distribution of different cost for the plant can be seen in **Figure 2.4**.

***Table 2.2** Investment costs, indirect investment including engineering, contractors, and contingency costs [48].*

Type	Price million US$
Primary crusher	2.005
Mine to plant conveyor	2.800
Surge area	6.421
Final C&S plant	5.655
Total direct investment	16.881
Indirect investment	7.934
Tax & freight	894
Fixed capital investment	25.709

The capital cost according to the paper per year will be 2$5,358,164 /year, giving capital costs per ton as 5,358,164/(8.4 x 10^6) = $0.6379.

From the paper the total cost for maintenance labor will be $1,323,000, equal to $0.16 /ton. There are 8 foremen and 62 operators to run the plant, at $611,284 /year, The equipment installed amounts to a total power of 6,352 kW, equal to 0.6 kWh/ton. Taxes are estimated at $0.0121 /ton.

Summary: Reitz [48] shows the product cost calculations for an oil shale C&S plant. In this case, the interest rate linked to investments was chosen as 10 %.

The costs of processing different types of minerals vary widely. For example, in this case the costs of wear and spare parts are relatively low compared to the same costs when, for example, crushing gold-bearing minerals.

A circle diagram, **Figure 2.4**, show the proportion of cost when crushing the oil shale.

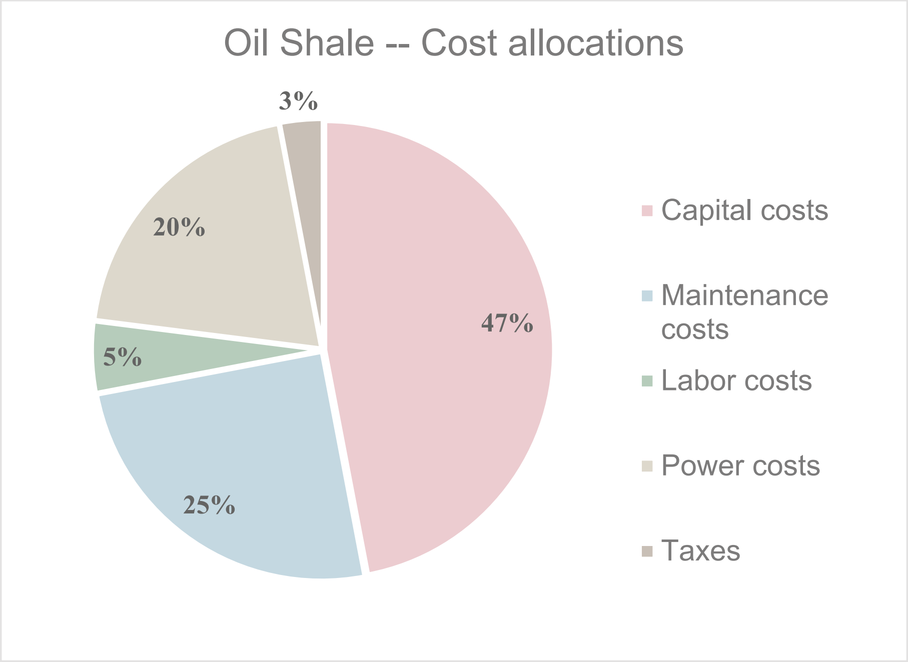

Figure 2.4 *Examples of cost distribution in oil shale crushing [48].*

2.4.7 Improvement of efficiency in stone crushing

Mali [49] describes two different setups for a mineral crushing plant: the existing plant and a proposed C&S plant. The study incorporates

- Monitoring of all stages of the plant to obtain detailed knowledge.
- Collection of data to be analyzed for calculation of the availability and utilization of the plant.
- Description and improvement of the new plant.

The economic analysis gives the following investment costs for the new plant, presented in **Table 2.3** to **Table 2.5**.

Table 2.3 *Examples of equipment investment costs (INR, Indian rupee) in C&S plant [49].*

Type	**Price (INR)**	**%**
Crushers	600,000	11.1
Screens	120,000	2.2
Handling material equipment	662,000	12.3
Transportation vehicles	3,000,000	55.8
Diesel generators	300,000	5.6
Civil works	600,000	11.1
Dust control system	100,000	1.9
Total	5,382,000	100.0

Table 2.4 *Examples of labor costs (INR, Indian rupee) in C&S plant [49].*

Type	**Number**	**INR/month**
Operators	4	48 000
Office	4	23 000
Transport	6	42 000

Table 2.5 *Examples of electricity costs (INR, Indian rupee) in C&S plant [49].*

Type	**Cost (INR/t)**
Power consumption	36.4

According to Mali [49] the cost per ton produced in the new C&S plant, using the data presented above, is 13.84 INR/h and with a production improvement of 16 %.

Summary: Mali's [49] study and analysis of the old plant process compared with that in the new plant shows that it is possible to increase production by 16 % through new investments. Moreover, the report shows a detailed cost analysis of the plant. This shows that detailed cost analyses can constitute an important decision support tool in connection with investments, so offering further support for the work done in the present dissertation.

2.4.8 Capital and operating costs of mineral processing plants

Before any mining/mineral projects/plants can start, an economic assessment of the business is necessary [50]. These plants will have both capital costs and operating costs. Normally there are several process layout alternatives to achieve the desired final products. To select the correct alternative from equal process solutions, one must make product cost calculations to find the alternative that will give the lowest costs for the final products in a long-term perspective.

The **capital costs** are the total amount of resources for investment. The capital costs can be split into two main parts.

- Fixed capital, used to purchase and install the plant equipment.
- Working capital, money tied up in the day-to-day operating expenses.

The American Association of Cost Engineering classifies estimates as follows:

1. Estimation, calculated from cost capacity diagram and cost capacity ratios. Normally –30 % to +50 % accuracy. Required work time: 1–7 days.
2. Budget calculated using flowsheets, layouts, and equipment details. Normally –5 % to +30 % accuracy. Required work time: 1 week to 2 months.
3. Definitive, calculated using defined engineering data, basic drawings, and detailed sketches. Normally –5 % to +15 % accuracy. Required work time: 3–12 months.
4. Detailed, calculated from finalized engineering drawings. Normally –2 % to +10 % accuracy. Required work time: 2–9 months.

To save time, it is recommended that best process alternative should be identified after the budget cost estimations and that other options should then be rejected.

Cost indexing must be considered before using cost estimations. The cost index is a cost change ratio from a specified base year. The most used cost index in mining/mineral projects is the Marshall and Stevens cost index. Capital cost estimations depend on the accuracy of estimation required. Capital costs k_C of a mining or mineral project do not vary linearly with the plant capacity MT_{php}. The generally accepted expression according to Pascoe [50] can be approximated by Equation 2.14.

$$k_C = k \cdot MT_{php}^{\kappa} \qquad \textit{Equation 2.14}$$

$\kappa \approx 0.7$ for mineral processing projects and k is a constant (see also earlier Equation 2.3, based on the investments costs). For a plant component cost ratio, first calculate the equipment costs according to Equation 2.14.

Then calculate as follows:

1. Purchased equipment costs from current index basis
2. Installation cost calculated as 0.17 to 0.25 of item 1
3. Electrical material and labor as 0.13 to 0.25 times item 1
4. Process buildings as 0.33 to 0.50 times item 1
5. Site improvements as 0.07 to 0.15 times item 1
6. Field expenses as 0.10 to 0.12 times item 1
7. Project management as 0.30 to 0.33 times 1

8. The sum of 1–7 will then be the fixed capital costs

After calculation of the capital cost, it is necessary to calculate the **operational costs** for the project plant._One of the main operating expenses in a mining/mineral plant is the cost of electricity or power. Depending on where the plant is going to be placed, one needs to determine the electricity tariff for the plant site. The global variation in electricity tariffs is very large.

Operating costs can be classified as follows:

- Raw materials such as wear parts and spare parts
- Utilities such as electricity and fuel
- Direct labor
- Maintenance labor and supplies: as a rule of thumb 0.1 to 0.15 times the installed equipment cost
- Operating suppliers such as safety equipment, normally 0.15 times plant maintenance cost
- Laboratory and quality control
- Final product(s) shipping
- Royalties, patents, and license costs

Indirect costs refer to plant overheads and include, for example, administration, research and development, and technical services. Normally this is about 0.5 times direct labor cost.

A good way of evaluating operating costs calculations is to compare the calculated results with existing up and running mining/mineral plants. One useful source of operating cost information is the annually published Mining Sourcebook [51].

Summary: Pascoe shows a detailed way of making final product cost calculations in mining/mineral plants. Some of the items included are specified, but others are only mentioned. Most of his work is based on Mular's [45] calculation methods, but his model has been further developed.

2.5 Conclusions of the literature review

Table 2.6. provides a quick overview of the reviewed product cost calculation proposals and general classification of the type of model.

Table 2.6 Overview of the reviewed product cost calculation proposals.

Model / Reference	[28]	[44]	[45]	[46]	[15]	[27]	[47]	[48]	[49]	[50]
Simple			X	X						
Detailed/Extensive	X	X			X	X	X	X	X	X
Existing plants	X	X	X	(X)	X	X		X	X	
New/Suggested plants	X	X	X	(X)	X	X	X	X	X	X
General	X	X	X	X	X	X		X		
Specific	(X)						X		X	X

The ten papers [15, 27-28, 44-50] present the product costs in C&S plants in different ways. There are two examples of how to make rapid product cost calculations [45 and 46]. Both provide rough estimations of production costs per ton produced.

The two papers by Mular [45] and 911 Metallurgist [46] give the product cost function/calculations as totals with little or no detailed information. While the papers by Svedensten [15] and Bengtsson [27] are the two most complexed ones of the reviewed. Busuyi [47] and Reitz [48 show more detailed approaches to product costs calculations. The paper from Busuyi [47] is for existing plants. The paper by Reitz [48] is for a proposed plant. Neither paper shows how to perform a product cost calculation from a general point of view.

The paper by Mali [49] compares product costs for an existing plant and an improved plant. The methodology is to first make an economic analysis of the existing plant and then use this to calculate costs for the new plant. No product cost calculation can be made for the new plant without information from the old plant.

Finally, the paper from Pascoe [50] includes more information on how to perform cost calculations/estimations in mineral engineering plants. The paper has a detailed model of what should be included in the capital cost structure. There are suggestions of what should be included for operating costs, but there are no details on how to calculate the number of plant operators needed.

This review of existing literature presenting models and cases for estimating product costs in C&S plants in the mining/mineral industries shows that none of the reviewed publications includes information on the technical lifetime of C&S equipment, which can differ widely. For example, the technical lifetime for a crusher can be up to ten years, while that of a screen may be five years [24]. Thus, to obtain better accuracy/reliability of the models for final product cost calculations, annual machine/equipment costs should be used, not just the total investment cost.

None of the ten papers indicate how to allocate/distribute the costs if the plant produces more than one final product.

Table 2.7 summarizes the cost items included in each reference. However, it should be pointed out that each author may have different definitions.

***Table 2.7** Description of the level of detail of input cost items in reported cost models for C&S plants.*

Model / Reference	**[28]**	**[44]**	**[45]**	**[46]**	**[15]**	**[27]**	**[47]**	**[48]**	**[49]**	**[50]**
Raw material costs	X									
Personnel costs	X	X			(X)	X	X	X	X	X
Equipment costs	X	X	X		X	X	X	X	X	X
Capital costs	X		(X)		(X)		X			
WP costs	X	X	(X)		X		X	X		X
SP costs	X	X					X	X		X
TO costs	X									
MS costs	X	X			X	X				
Power costs	X	X	X		X	X	X	X	X	X
Fees and taxation						X	X		X	
Environmental costs										
Land/building cost								X		
Shared cost		X								
Allocation keys		(X)								(X)
Site preparation costs							X		X	X
Plant restoration cost										
Total production costs	X	X	X	X	X	X	X	X	X	X

Almost all proposals include power and equipment costs. Some papers, for example [45, 46], mention very few cost items. As previously mentioned, the technical lifetime of crushers, screens and equipment in C&S plants is very different. This means that the cost of capital per year becomes important when making the total calculation of the final product costs. Only Ståhl [28] shows a method for calculating capital costs.

In C&S plants with multiple end products, it is essential to have a way to distribute costs in a fair, balanced, and accurate way. This aspect is hardly mentioned in these papers.

Ståhl's general production cost model [28] is the only one that explicitly takes raw material costs into account. None of the papers include costs for renting land and buildings. In addition, none of the methods includes direct environmental costs and restoration costs. This type of cost item will have an increasingly important impact.

The philosophy when creating a C&S plant process is to have the highest load in the last C&S stage [4, 24]. Depending on the working time/operating time ratio, the utilization of the C&S plant can be calculated. This gives two main types of time: working during operating time (uptime) and not working during operating time (downtime). In most C&S plants there are fewer operators than machines and equipment, so the operators monitor and work the machines when needed.

Costs such as rent of land and buildings, security and protection, lighting and heating/cooling are usually general and cannot normally be directly linked to individual machines/equipment and/or end products [4].

3. Research Methodology

This chapter explains the research approach taken and introduces the research methodology employed in obtaining the results reported in the thesis.

3.1 Theory and methodology

There is no uniform and established research or development methodology in this research area. The reason is that the subject is interdisciplinary and has no actual domicile within traditional academic subjects. Equipment for C&S is used primarily in the mining, construction and contracting industries, while the equipment is developed in the engineering field based on machining processes. In terms of education, the area falls between the traditional programs for mechanical engineering, mining engineering, and civil engineering.

3.1.1 Theories, models, and philosophies

There are several different approaches to solving the area's research issues. Scientific approaches to problem solving have been taken from different subjects in different studies. For example, Asbjörnsson [52] based his research on simulation using a control-technical approach to manage the dynamics within a C&S plant. Other researchers have solved output problems in equipment such as crushers by basing the work on simulation and strength of materials.

The present work is based on a research tradition borrowed from the discrete manufacturing industry. The entire process is first broken down into steps and sequences. Cost analyses are performed on each of the steps to determine losses and value creation. This form of research approach makes it possible to link technical performance to economic data that enables a valuation and description of various alternative configurations and development paths.

Figure 3.1 below illustrates the various research activities that are common in the field of discrete production. The approach is based on dividing the process, in this case a C&S process, into a physical representation and a virtual representation, often described as a digital twin. The physical process is observed and combined with measurement or registration of physical quantities such as power consumption, mass flow, return flow, downtime, and capacity utilization. Corresponding physical quantities can be calculated or simulated using known input data and developed models for the plant. Comparisons can then be made between actual outcomes and simulated outcomes. The consequences of different decisions or circumstances can thus be assessed.

Production technology research and development normally involves the following common fields of work and activities [29]:

I. The manufacturing process with associated equipment and automation
II. Process models that can form the basis for simulation and digital twins
III. Measurement and analysis techniques, including manual or digital observations
IV. Simulation, analysis, and optimization
V. Process development linked to equipment with improved performance and further developed working methods and procedures
VI. Development of new process models
VII. Development of new measurement and analysis technology
VIII. Development of simulation aids based, for example, on digital twins.

When assessing various research and development projects, the projects are within one or more of the areas shown in **Figure 3.1**.

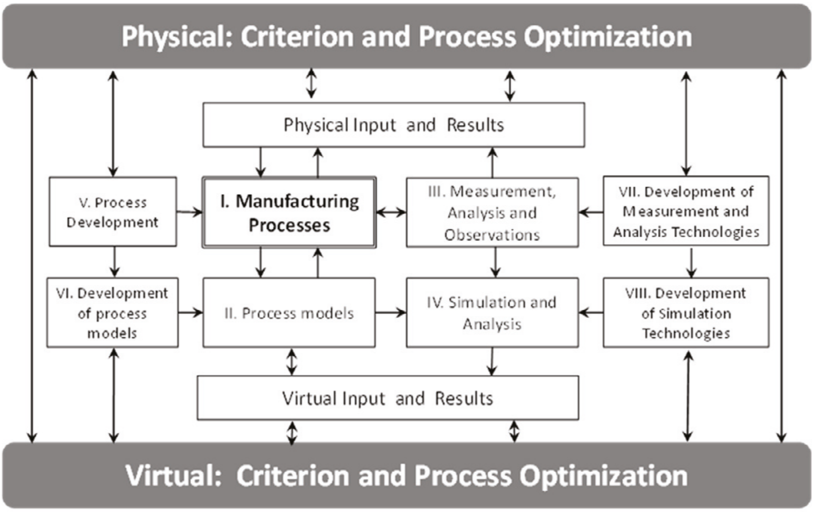

Figure 3.1 *Research paradigm in the field of production including the concept of digital twins [29].*

Based on the research questions, the present work is focused on the key activities I, II, III and IV as set out in **Figure 3.1**. However, cost modeling is also included using economic input data.

This model is a purposeful representation of reality. In general, modeling refers to mathematical modeling, which is a formulation that is an approximation used to study specific phenomena [43], in this particular case, costs for C&S under different and general conditions.

The three foundations for the present study are as follows:

1. Mining and mineral processing engineering education.
2. My professional C&S process experience.
3. The concept that production costs should be calculated at the same time as the process flowsheet.

My more than 40 years of work on C&S processes involving designing, selling, mapping, evaluating, guarantees with verification, and developing and adapting systems for different raw materials and different end products has undoubtedly influenced this thesis. The timeline of my work is illustrated in **Figure 3.2**.

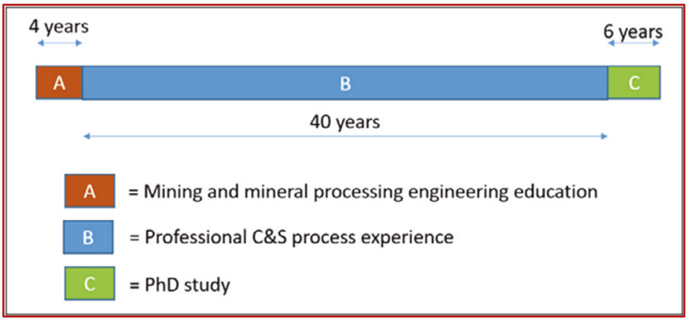

Figure 3.2 *General overview of the complete work and the building of experience and the final study period.*

The subcontent in the two educations sections are linked to a large volume of experience, knowledge, ideas, theories, and possible setups. The research follows the path of the overview of the thesis shown in **Figure 3.3** (a) – (c).

Modern research plays and has played an important role in discovering and finding solutions, for example, in space exploration, cracking the mysteries of life, new technologies, and social problems. In general research follows two main paths [53].

1. Fundamental research. The creation of new knowledge or the expanding existing knowledge, where the driving force is curiosity.
2. Applied research. The finding of the solution to a specific problem or answers to certain questions, where the driving force is the need to solve the problem.

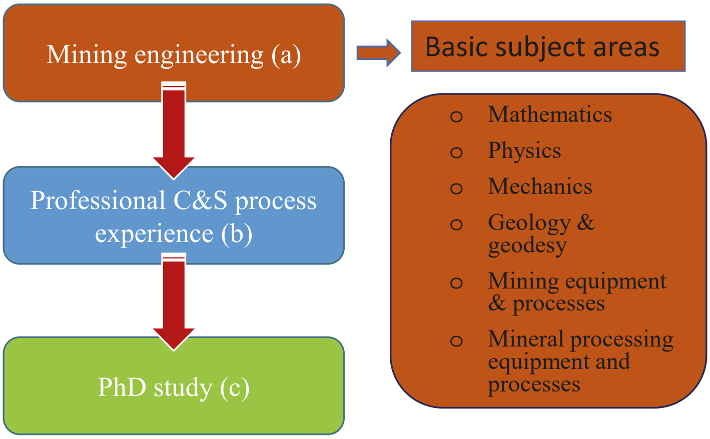

Figure 3.3 *(a) Detail overview of the study approach and the thesis.*

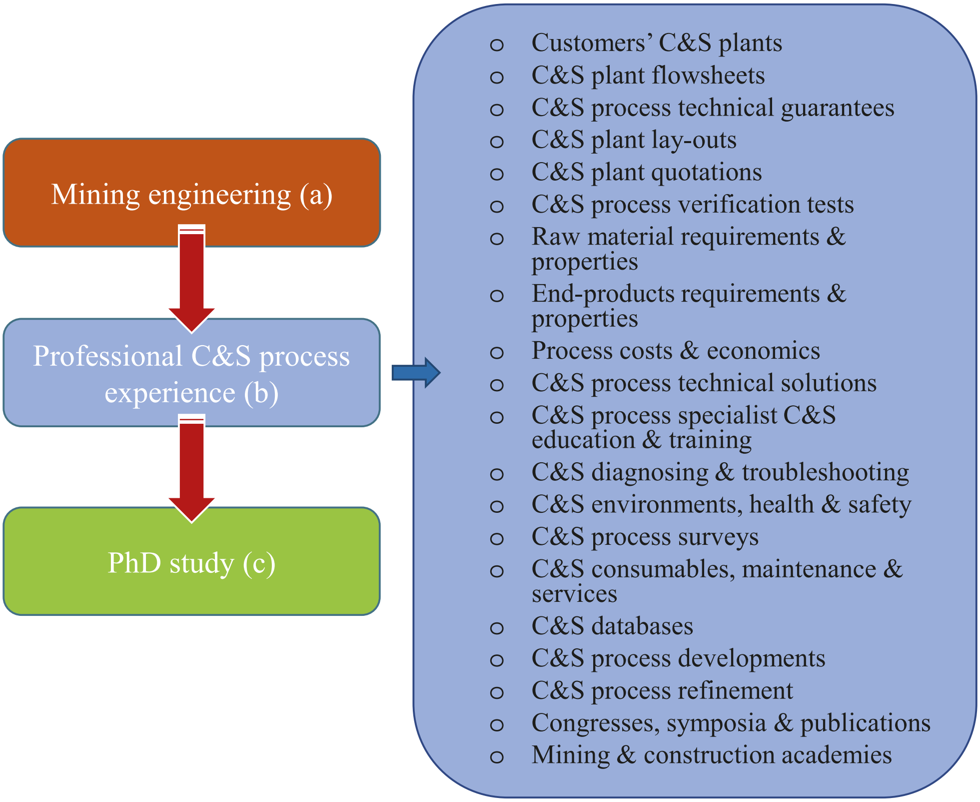

Figure 3.3 *(b) Detail overview of the study approach and the thesis.*

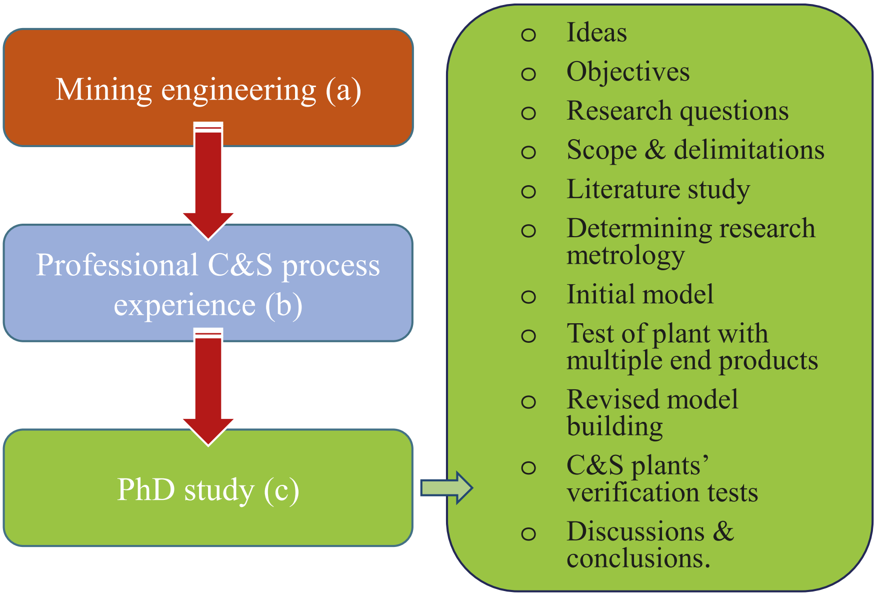

Figure 3.3 *(c) Detail overview of the study approach and the thesis.*

This thesis can be considered as applied and practical research that lies in both the scientific and the industrial sectors.

There are two different types of data, quantitative and qualitative. Quantitative data is in the form of numbers, and qualitative data is in the form of descriptions, feelings, and thoughts. This type of data is based on experience, images, or language, and can be collected through methods of observation. The data from C&S plants consists of items like capacities, consumption of wear parts (WP) and spare parts (SP) including prices, investment costs, and salary costs that generally belong to quantitative data. Process experience leans on qualitative data. So, the author's more than 40 years of experience with C&S processes provides a good addition to the qualitative data gathering and input to this dissertation.

Theoretical research explores and discusses the research object using abstract theoretical structures and philosophical concepts, while empirical research makes it possible to explore an object on the basis of experience and observations of the object studied. In empirical research, one obtains data and results by making concrete observations and by analyzing and measuring the object. The collected data is the focus of the research and functions as the starting point for research [28]. This thesis uses both these approaches, but with the focus on empirical research.

This dissertation uses both inductive and deductive research. The inductive approach begins by collecting data that is relevant to the topic. Once a substantial amount of data has been collected, the researcher will pause from data collection and step back for a bird's-eye view of the data. Deductive research begins by proposing a theory and then testing this theory and its consequences, see **Figure 3.4** below.

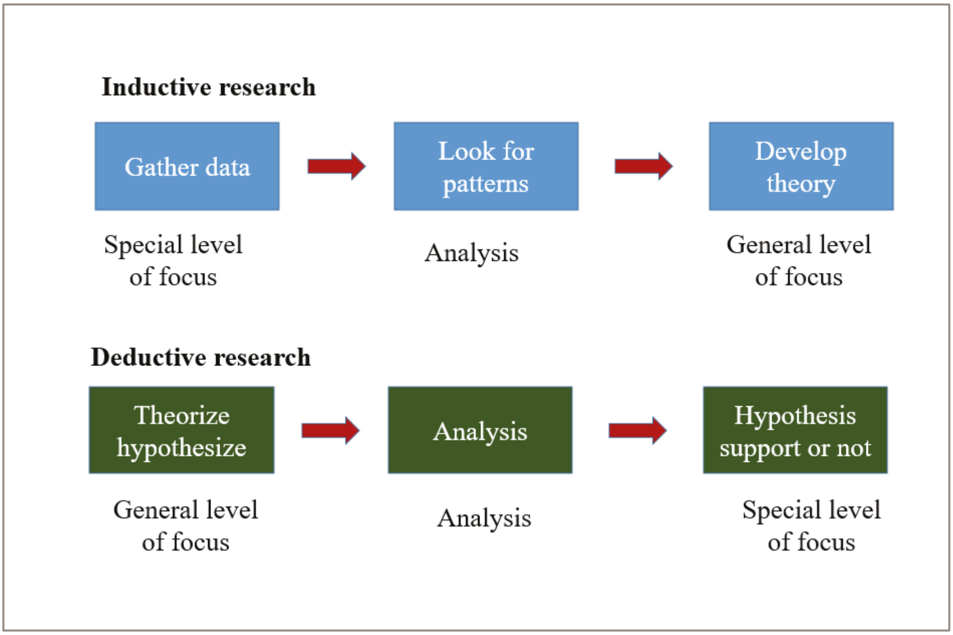

Figure 3.4 *Inductive and deductive research, after Schmitz [54].*

This research started by theorizing hypotheses on how to calculate the production costs in C&S plants, which shaped the initial model in chapter 4. This was followed by analyzing and testing the model in the first C&S plant. Analysis revealed that the model needed to be adapted to the situation when a C&S plant produces more than one end product. Using an inductive research method, I gathered new data for the second C&S plant. While analyzing these data, I discovered a way of distributing the production costs for different end products by using allocation keys, see section 5.2.4.

While inductive and deductive approaches in research may seem quite different, they can be complementary. Complementary research in this thesis includes several components, from both inductive and deductive research. The research began as deductive research, but during development the method changed to more inductive research to develop the cost calculation model.

The research ethics in this dissertation follow the core values and general conduct guidelines of Lund University [55]. The field testing of the C&S plants was conducted in several countries, under different political and religious regulations and laws. The gathered data was of two main types, namely, open and closed data/information. Open information/data can freely be used, while closed information/data can only be used after permission and presented in protected coded form.

3.1.2 Methodology

The methodology in this research is divided into three branches

1. From ideas and theories to model building
2. Sampling of the data as input to the model
3. Testing the model versus actual and well-known examples, with evaluation of the cost models.

The first two items may be in direct or reverse order, depending on the chosen research approach.

From ideas/theories to model building

The main concept when it came to calculating production costs in C&S is to treat C&S process production the same as standard mechanical part manufacturing. Each step has associated mathematical calculation formulas for the costs of each machine. This is repeated for each subflow in order to calculate the total production cost and all the product costs in the C&S plant.

One disparity with Ståhl's generic production cost model [28] relates to the cost per unit. Mining and construction measure the final products by weight. The production cost calculation model has to be redesigned to work in C&S processes in mining and construction. Many of the parameters and items (**Table 2.1**) need to be changed, adapted, and developed to increase the confidence and improve the calculated result.

Finally, all expressions and items were checked, so that the objects and parameters in the model are well-defined according to current and normal principles and to ensure that no actual parameters, parts, and contents have been excluded from the model for production costs.

The development of the equations involved data analysis, clean up, transforming, and modeling with the goal of discovering useful information, conclusions, and support for decision-making. If a plant produces more than one final product, allocation keys must be created for each machine/equipment so the costs can be distributed according to final products. The allocation keys for the machines/equipment will vary depending on the process setup and the extraction order of the final products.

Sampling of the data for the model

A data sheet that describes the production cost calculation model may be used to assemble all information that will be needed for the production cost calculations in

C&S. Appendix H shows one example of a data sheet that can be used when sampling production cost calculations in an existing C&S plant.

Costs and prices can be sampled, directly or indirectly, from the actual C&S plant, while the costs for a simulated C&S plant must be calculated from external sources [24].

There are several ways to calculate wear consumption in C&S. Many of these wear calculation methods use the Bond wear abrasion index [16]. This index is linked through experience to actual wear consumption for different types of materials and different types of crushers. The wear consumption can be quite difficult to calculate due to factors like the feeding arrangement to the machine/equipment, or changes in the particle size distribution in the feed to machines, both of which affect the life of the wear parts. Here personal expertise and knowledge about the consumption of wear parts can be useful and increase the reliability of the wear consumption estimates. One can also always contact the machine suppliers to ask about WP consumptions and prices. For mantle and concave in-cone crushers, for example, approximately 40 % of the wear part's weight can be utilized before the wear parts are worn out [16].

There are several so-called "Free Spare Parts Calculators" on the Internet, but these must be used with care since one normally needs expert knowledge to estimate the average time between part failures or the time required to change the parts. It may be helpful to contact the suppliers and have them estimate the consumption rates for machine spare parts and provide updated prices for these items.

3.1.3 Testing of model vs. actual example

A spreadsheet was developed to improve and simplify the calculation of the production/product costs. This spread sheet can be used both for actual data and for calculated data, see Appendix C. By using equivalent spreadsheets for both actual and calculated data, the results can be directly compared.

A reasonable method is required to compare actual and calculated production costs. Appendix I explains the reasoning behind a new criterion called conformity in detail. Conformity (CF) in equation I.1 allows this comparison. In an actual example C&S plant, the capacities need to be tested, for all flows and subflows. The capacity test procedure follows the method for testing and analyzing in Sandvik's Plant Process Guarantee [73] after substituting the appropriate values, see Appendix D.

Work structure

The approach of this project consists of the following thirteen main steps.

1. Map a process flowsheet for the whole C&S plant and divide the flow into natural, well-defined subprocesses.
2. Measure all transport speeds on each conveyor belt. The capacity of the conveyor belt is calculated according to Capacity = Weight of Material x Belt Speed x (3600/1000), where capacity will be in MTPH when the weight of material is in kg and belt speed in m/s.
3. Perform a full-scale test with the C&S plant running at maximum production. Normally a 1 m length sample on each conveyor is removed for measurement. All test samples must be dried before any analysis.
4. Perform the full-scale test three times to achieve an equalized or average condition. If the variation between the three throughput tests is less than 10 %, the tests can be accepted. If the tests show larger variation, three more tests should be carried out.
5. Weigh all samples and determine their particle size distribution.
6. Sample plant operating data:
    a. Determine utilization by monitoring production time rather than using total planned operating time in the calculation. Sample, calculate, and estimate downtime for each machine, as well as the plant as a whole.
    b. Sampling, see appendix D
    c. Determine power consumption by monitoring consumed power and finding the tariff for energy/power.
    d. Determine the number of operators and their salaries. Monitor the number of employees in the C&S plant and check the payroll.
    e. Gather all extra auxiliary costs.
7. Calculate the capital costs after determining all equipment costs and the technical lifetimes of equipment.
8. Sample the consumption of WP, SP and TO. Document the consumption costs for WP, SP and TO.
9. Sample, calculate, and estimate the production rate in terms of product flow, expressed in ton/h.
10. Sample, calculate, and estimate machine costs, including planned maintenance and service costs, expressed in cost/h for each machine, as well as for the plant as a whole.

11. Sample, calculate, and estimate balancing losses for each machine (over/under capacities).
12. Based on the information from steps 1–11, create and develop the production/product cost calculation model (PCCM) concept for C&S plants. The result will be the production costs of each final product(s), and the total production costs.
13. Validate the results from the newly developed PCCM with actual C&S plant examples.

Figure 3.5 presents a schematic flow of the work and the thesis structure.

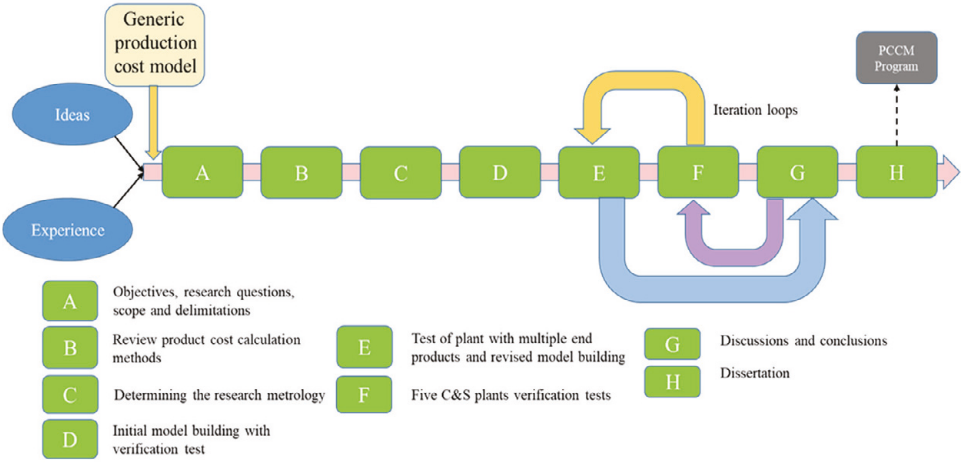

Figure 3.5 *Schematic flow of the work and the thesis structure.*

Sampling of the data from the existing C&S plants is done through direct full-scale tests of the C&S plant, supplemented by face-to-face interviews with those responsible for the operation of the C&S plant. In cases where I needed additional information about and around the C&S plant, I conducted follow-up interviews over the phone with the site managers or the owners of the C&S plant.

However, the level of difficulty is high because a lot of information is needed and the sources of information for several parameters change during production. These changes can occur for reasons such as variations in feed, wear, particle size distribution, ore/minerals crushability, and moisture content [4]. This complexity and the data uncertainty related to C&S plants may require Monte Carlo simulations on parameters where exact results are difficult to obtain.

3.2 Mapping the process flowsheet

The process flowsheet of a C&S plant (both for existing and new applications) is created using graphical simulation programs for C&S such as Sandvik's PlantDesigner, Metso's Bruno, or Bedrock's AggFlow (Appendix B). These software programs use the drag and drop method to create the flowsheet. The selection of what the flow chart should look follows two main paths. For an existing plant, the chart should follow the way it is built. For proposed plants, the chart can be built up according to the drafter's experience and knowledge of C&S plant processes. Appendix B lists some of the major graphical flowsheet simulation programs used in C&S.

After creating the process flowsheet, one needs to divide the flowsheet into natural well-defined subprocess systems to facilitate the production/product cost calculations.

It is advisable to name all the substreams in the process so as to easily keep track of their quantities and qualities. The capacity of a C&S plant is defined as the condition when at least one of the main machines/equipment has reached 100 % load, which gives the maximum momentary throughput of the plant.

3.2.1 Sampling, calculation, and estimation of production rate

The C&S plant capacity is established by the flow calculations, but the production volume is also needed to calculate the production costs. The production volume V_p can be calculated as:

$$V_p = MT_{php} \cdot U_{RP} \cdot t_{OP} \qquad \textit{Equation 3.1}$$

To estimate the C&S plant utilization, several factors must be taken into consideration, including

- Wear parts rate in the machines/equipment
- Spare parts rate in the machines/equipment
- Time for service and maintenance, including charges for wear parts and spare parts
- Operating time duration: 1 shift, 2 shifts, or 3 shifts per day, from 5 days/week up to 7 days/week (continuously for the whole year)
- Other factors such as weather changes, operator skill levels, and the level and degree of automation

If the plant produces more than one final product, one must keep track of the number of products when the plant is running at full load. This is necessary to calculate the general allocation key, see section 5.3 for more information. Normal utilization, U, of a crushing plant is approximately 80 % [24]. As a rule of thumb, the values in **Table 3.1** can be used to estimate C&S plant utilization.

Table 3.1 *Normal utilization in a C&S plant [24].*

Shift(s)/day	Days/week	Utilization, U [%]
One	Five	70–90
Two	Six	60–80
Three	Seven	50–75

The general utilization rate U is composed of several factors, including technical and administrative disruptions. This utilization grade U is closely related to the concept of availability A, depending on the application area. The general utilization rate U should not be confused with downtime (standstill) and the associated utilization degree, U_{RP}, caused by overcapacity or lack of demand for a product.

Sampling of flow streams in an actual C&S plant

To determine these values, the plant is stopped when in full production. Each of the substreams is sampled and analyzed for quantity and quality. At least three full-scale tests need to be done. The final product capacities from each test run should be within 10 % of each other. If not, at least three more full-scale tests must be done before calculating the average capacity of the plant.

Calculations of flow streams in a simulated C&S plant

After examining and calculating the operating time and utilization, one can calculate the production rate and production of final product(s), according to Equation 3.1.

Sampling, calculation, and estimation of downtime

Downtime (T_{DT}) means periods during which equipment, a machine, or a plant is not functional or cannot work. This may be due to technical failure, machine adjustment, maintenance, or non-availability of inputs such as materials and power [24].

Through time observation during production of an existing C&S plant, one can obtain information on the downtime of each main machine and for the whole C&S plant. For the simulated C&S plant, the downtime is more difficult to estimate. But for both types of plants, the relative downtime for a machine/equipment in a C&S plant can be calculated according to:

$$q_S = \frac{T_{DT}}{T_{DT}+T_{Op}} \qquad \textit{Equation 3.2}$$

T_{DT} is the downtime and T_{Op} is the operating time. The utilization U_{RP} with respect to free capacity or over capacity can be calculated for C&S line i as:

$$U_{RP,i} = \frac{T_{Plan} - T_{Free,i}}{T_{DTi} + T_{Opi} + T_{Free,i}} = \frac{T_{Plan} - T_{Free,i}}{T_{Plan}} \qquad \textit{Equation 3.3}$$

where T_{Free} is stopped time related to overcapacity during paid and planned time T_{plan}. The same equation in summed form can also be used for the whole C&S plant.

Sampling, calculation, and estimation of machine costs

The data for investment costs, technical lifetime, wear parts, spare parts, and maintenance/service consumption should be available for existing C&S plants. These costs must be determined and recorded. Power consumption in total and for each machine/equipment must be determined together with the cost of 1 kWh.

To determine the cost of 1 kWh for simulated C&S plants, one can, for example, use the energy guide in [56]. Direct salary costs per year should be determined, and the number of employees in the C&S plant documented. Salary costs are distributed to each machine/equipment by using allocation keys that are unique to each C&S plant.

Items such as rent of land, power for lightning, de-dusting, and/or other general costs of the final products in the C&S plant are auxiliary costs. These costs can also incorporate the costs of the raw/feed material. Auxiliary costs are distributed by prorating the end products.

In simulated C&S plants, the best way of collecting the investment costs is to use a quotation for the C&S plant. Normally there are two types of quotations: budget and actual quotations. Budget quotations are less precise than actual quotations. The technical lifetime for all machines and equipment must be decided next. As a rule of thumb, the technical lifetime in **Table 3.2** may be used.

Table 3.2 *Normal approximate technical lifetimes for machines/equipment in C&S plants, based on experience [16, 24].*

Machine/equipment	Approximate technical lifetime (*)
Jaw and cone crushers	10 years
Horizontal shaft impactors	6 years
Vertical shaft impactors	6 years
Vibrating screens	6 years
Vibrating feeders	6 years
Conveyors	10 years

(*) Assumed ≈ 2 000 working hours/year

As a rule of thumb, the technical life in **Table 3.2** may be used. The technical lifetimes in **Table 3.2** above are approximate and valid for one shift per five day working week. Contact the respective manufacturer, supplier, or dealer for a more accurate technical life. But the technical lifetime of the machines also depends on how well the machines are run/operated, maintained and serviced by the owner/user [24]. When two or more shifts are operating per day the technical lifetime must be reduced. For other machines/equipment, contact the supplier for advice or use your own experience.

In actual C&S plants the number of operators is known, and so it is relatively easy to determine the salary cost per year. But in a simulated C&S plant you must estimate the number of operators. There are several ways of doing this. One can use, for example, the *Improvement Kata Handbook* [57] or "How many people will be running your plant?" [58]. Of course, one's own experience can always be used. Once the number of operators has been decided, then the cost of each operator per hour must be found. If you do not know this, their salaries in different countries are available on the Internet [59].

In existing and applied C&S plant, the payroll costs must be allocated to each machine/equipment. To distribute these costs, several methods may be used, such as according to the distribution of main machines, distribution of power consumption, distribution of the W&S parts consumption, or distribution of final products.

3.3 Sampling, calculation, and balancing losses

In section 3.2 we established that the C&S plant capacity is reached when one of the main machines has 100 % load and the utilization $U_{RP} = 1.0$. This is the bottleneck capacity of the C&S plant. When the bottleneck capacity has been found for the C&S plant, the balancing loss D can be calculated for all the other main machines/equipment by comparing actual throughput with the main machine's capacity. The main definition of balancing losses is expressed by Equation 3.4:

$$D_j = 1 - E_j = 1 - \frac{MT_{ph,output,j}}{MT_{ph,j}}$$ *Equation 3.4*

E_j is the process efficiency, related to the ratio of the output ($MT_{ph,output,j}$) and the maximum capacity ($MT_{ph,j}$) for C&S line j. In existing C&S plants, the capacity for each main machine must be established. In simulated C&S plants, the flowsheet flow calculations show the capacity of the C&S plant and the loads of each and every main machine. If, however, the C&S plant does not meet the production goal when one of the main machines is at 100 % load, then the C&S plant is too small. To reach the production goal, it will be necessary to upgrade the C&S plant or extend/increase the production time of the plant [24].

3.4 Creating and developing the PCCM

The steps for the production cost calculation model (PCCM) are:

- Cost of production uptime
- Cost of production downtime
- Cost of salaries
- Cost of auxiliaries

This follows Ståhl’s method [28] of making production cost calculations for production engineering, but with the development of using auxiliary costs for additional essential costs such as rent of land for the C&S plant, power costs for lighting/heating of the C&S plant, and cost of raw material.

The main constituents in the cost of production uptime are capital costs distributed by allocation keys and the dynamic costs for the process. The main constituent in the production costs of downtime are the capital costs distributed through the allocation keys.

The full theory for the PCCM is shown in sections 4 and 5 in this thesis.

3.5 Validation of the developed PCCM

The first model from chapter 4 was tested and evaluated in the C&S plant named CSP1. In accordance with the non-disclosure agreements with the customers, I have as far as possible coded the customers’ specific information to reduce the possibility of identifying the customer and the C&S plant and to protect against loss of competitive information. The production costs in section 6.1, section 6.2 and section 6.5 have been converted from local currency to US dollars to minimize customer and plant identification. I have used the same exchange rate for both actual production costs and calculated production costs. The actual production costs are the ones specified by the customers themselves and I have provided these cost as they were given to me, with the exception in section 6.1, 6.2 and 6.5, see above.

4. Basic PCCM Model for C&S

This chapter provides explanations and equations related to C&S and presents the original model for production costs calculations for C&S as well as the associated research. The first application of the developed model is also presented in the form of a case study.

The following section describes the mass flows that can be linked to open and closed C&S systems. In **Table 4.0** there are some explanations for variables used in the equations in chapter 4.

Table 4.0 Explanation of variables and index used in the equations.

Variables	Meaning
L_{0j}	Feed to machine/equipment j (C = crusher, S = screen)
L_0	Feed to plant
L_{1R}	Recirculation amount
MT_{phj}	Capacity for machine/equipment j (C = crusher, S = screen)
pf_i	Proportion of product i
Investment cost	The actual cost when the equipment/machine is bought
EACC	Equal annual capital cost, see equation 5.3.

4.1 Process comparison for cost calculations

As mentioned previously, C&S processes normally operate continuously. They generate both main product(s) and byproduct(s), ranging in size from large to small. These particles will vary greatly in their qualities, depending on which crushing stage produced them. In mining, the goal is to reduce particle sizes maximally in each crushing stage, but when producing construction aggregate the products right qualities were achieved earlier through "gentle" crushing but now the processes go towards higher crushing pressure and long fractions to achieve the quality of shape. In C&S processes, the waste is normally the dust generated in the crushing process [24]. The amount of dust generated in a compression crushing process involving hard rock is rather low [60]. Dust is normally the only solid waste from C&S plants because less wanted fabricated products are normally sold as byproducts, mainly to private persons [24].

Crushing and screening of flow processes can be divided into two main streams (chapter 1) in open or closed circuits, as shown in **Figure 4.1**, which differ greatly when making cost calculations. In open circuits, all flow entering the system leaves the system in the same quantity, and the full quantity flows only in one direction from start point to end point.

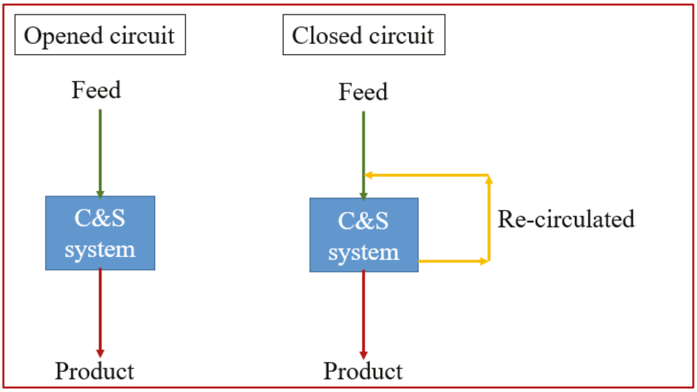

***Figure 4.1** Open and closed circuits in C&S.*

However, in closed circuits, “unfinished” material is recycled within the system itself until the proper material size properties have been achieved through re-crushing. This results in higher cost for the net production in closed circuit machines compared to open circuit machines.

The maximum capacity of the crusher stage is the same as the capacity of the specific crusher measured in m^3/h in an open circuit. As a result of the feedback flow in a closed circuit, the maximum capacity of the crusher step is less than the capacity of the specific crusher, and the capacity is reduced by the return flow volume. The return flow therefore contributes to a rate loss, which is denoted by q_P in this thesis. This has a direct negative impact on the final cost of the product. But if the crusher cannot produce the required top size of the wanted product in open circuit, a closed circuit or two crushing stages must be used [24].

4.2 Open and closed crushing circuit analysis

4.2.1 Open C&S circuits

In open C&S circuits, the material flows in a straight line from feed to product, **Figure 4.2**.

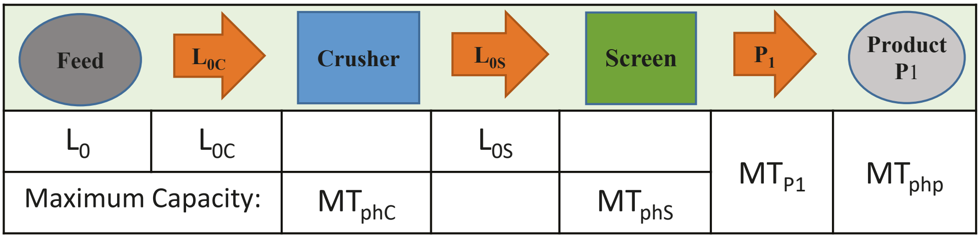

Figure 4.2 *Open C&S circuit.*

In this case the flow is $L_0 = L_{0C} = L_{0S} = MT_{P1}$, in terms of quantities. However, based on experience, there are losses in the form of extra small particles and dust, normally less than 1%, but the amount of dust created in crushing, differs due to feed properties/characteristics, crusher type, crushing stage and/or product size [24]. Open C&S circuits are normally used in the first and second stage of a C&S plant. Practically, the mass flowrate value MT_{php} will be the lowest value of MT_{phC} and/or MT_{phS}.

4.2.2 Closed C&S circuits

In a closed C&S circuit, part of the flow, normally the oversize particles, is recirculated and re-crushed, **Figure 4.3**.

In this closed circuit, $L_0 + L_{1R} = L_{0S} = MT_{P1} + L_{1R}$. This is valid if waste materials such as small particles and dust are not considered. Closed C&S circuits can be used in all stages of the C&S plant, but normally they are used in later stages. For the case of recirculation of the L_{1R} tonnage:

$$MT_{php} = pf_1 \cdot MT_{phC} \quad if \quad MT_{phC} \leq MT_{phS} \qquad \textit{Equation 4.1}$$

$$if \quad MT_{phC} > MT_{phS} \quad then \quad MT_{php} \leq MT_{phS}$$

and

$$MT_{P1} = pf_1 \cdot L_0 \qquad \textit{Equation 4.2}$$

$$L_{1R} = \left(1 - pf_1\right) \cdot L_0 \qquad \textit{Equation 4.3}$$

Where pf_1 is proportion of product P1. According to these equations, the production of actual product will always be higher in an open circuit compared with a closed-circuit using equipment with the same nominal capacity, so MT_{php} (open) > MT_{php} (closed). This is not an axiom due to that closed circuit have big advantages compared to the open circuit, if the opened circuit need more than one crushing stage, to achieve the right end top size product.

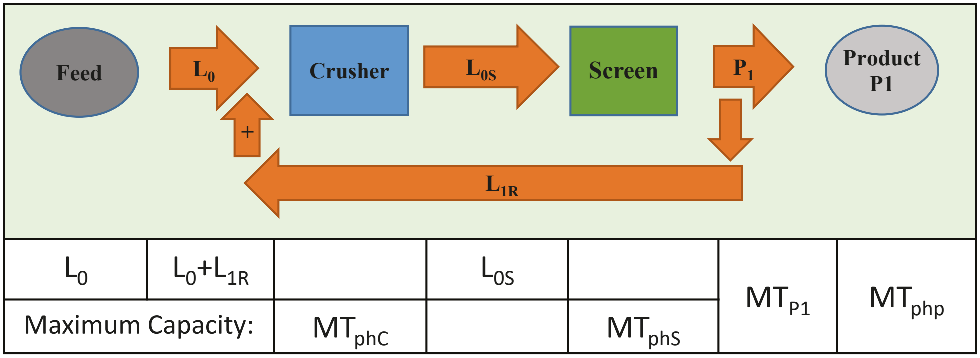

Figure 4.3 *Closed C&S circuit.*

The capacity in C&S normally uses the amount as MT_{ph}. However, since this capacity is actually the amount of volume, the bulk density (BD) must be adapted to the solid density (SD) of the rock [24]. A rough estimation is that the SD of 2.7 ton/m^3 is approximately equal to a BD of 1.6 t/m^3 [24].

$$BD = \frac{1.6 \cdot SD}{2.7} \qquad \textit{Equation 4.4}$$

A variation in particle size distribution (PSD) will also change the BD of the rock material, but this is less important than the SD [4]. The most common type of C&S plant in mining is a plant that produces one end product. When producing one end product, this product will account for the full production costs of the plant.

A quick way to calculate production cost for this type of C&S plant is to use a black box approach that gathers all the subprocesses into a system of one united main process, illustrated in **Figure 4.4**.

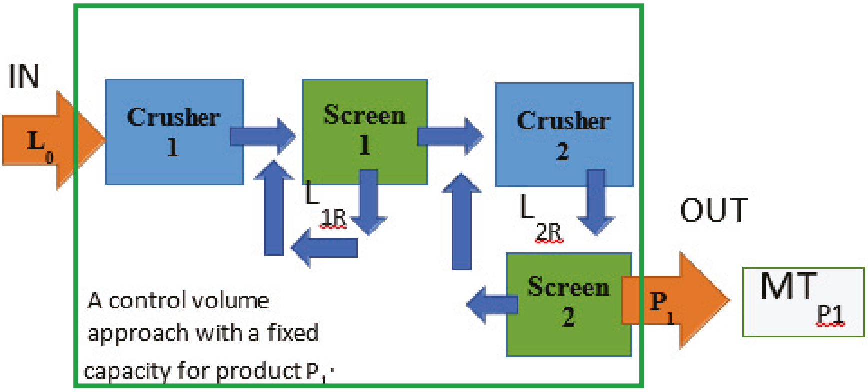

Figure 4.4 *The black box model or a control volume approach: one united main process.*

In this approach, the production process will be treated as one united process, ignoring the various subprocesses in the system. The production costs will be calculated as total costs, total capital costs, total dynamic costs, total payroll costs, and total other costs. A manual comparison between different manufacturing processes will reveal whether it is possible to use Ståhl's generic production cost model [28].

Section 1.3 showed that metals are one of the main resources in our society when producing parts or complete common products such as equipment, machines and building materials. Metal mining, metal metallurgy, and machining are the processes that mine, extract, and produce the metal in the right dimensions, form/shape, and quality for further processing to the desired product. The differences between the manufacturing processes are presented in **Table 2.1**. These differences will result in various methods of calculating product costs for mining C&S, metallurgy casting, and machining. These three processes all create the right properties and conditions for further processing and the creation of added value. The central differences between them are that C&S is conducted continuously while casting and machining are, in most cases, performed in discrete production batches.

C&S production is measured in tons/year while casting and machining are measured in number of parts or batches per year. C&S always has fewer operators than main machines, casting normally has more operators than main machines, and machining generally has one or fewer operators per main machine [4, 10, 61].

The differences in quality for the selected processes

In C&S, the size of the end products is the main quality. However, the plant should also produce the planned amount of end products. For casting, the required qualities are the correct properties of the cast metal, with a correct mix of alloys, the correct surface finish, acceptable porosity within the casting, and an acceptable casting form/shape. In machining process, the qualities are surface finish, correct dimensions, and acceptable form.

One major concern is that the generic model presents the result in cost per part, but mining and construction measures the final products by weight. The proposed production cost model is presented below.

Table 4.1 shows the difference between the three types of manufacturing processes, which results in different ways of costing and analyzing each of them. For the product cost calculation model for C&S, mining and construction processes, the generic model parameters must be developed, added, removed, modified, expanded, adapted, purified, and cleaned up in the new production cost calculations, partly based on the first model presented, the first attempt with a modified C&S approach on Sthål's general cost model [62]. Equation 4.5 can be used for these cases in **Figure 4.1** in an approximate way. The following paragraphs are a description of how the standard equation presented earlier for cost calculation (Equation 2.1) has been adapted for one product undergoing one or more crusher steps.

***Table 4.1** Overview of manufacturing in C&S, casting, and machining [4, 10, 61].*

Issue	C&S	Casting	Machining
Operation	Continuous	Batch	Batch
Process	Multiple	Single/multiple	Single/multiple
Quantity	t/h, t/y	Number of parts per operating time	Number of parts per operating time
Working time	Net production time per year or time period	Cycle time, heating, casting, solidification, cooling and cleaning	Cycle time, setup, handling, tool change and waiting times
Utilization	Ratio of load/maximum load	Operating time/Planned and paid time	Operating time/Planned and paid time
Operators	Fewer operators than main machines	In general, more operators than main machines	Fewer to equal number of operators per main machine
Activity	Outdoors. But due climate, environment and/or lay-out etc. Some of the C&S plants are build indoors.	Indoors	Indoors
Quality	End product sizes. (Construction aggregates shape)	Inspection, composition, properties, surface, porosity, form, and shape	Surface, dimensions, and form

4.2.3 Cost model for a product in C&S

At the operational level, an adapted manufacturing economy model can be built up in five parts, each of which deals with materials and process costs (B + CP), costs for downtime and overcapacity (S + RP), and costs for personnel (D). The respective introductory terms and variables are described in detail in the following sections.

The cost to produce a ton of product P_1 can generally be calculated as:

$$k_{1MT} = k_{1B} + k_{1CP} + k_{1S} + k_{1D} \qquad \textit{Equation 4.5}$$

The material cost k_{1B} for a product P_1 can be calculated according to Eq 4.5. The calculation includes losses q_{B1} corresponding to its part of the total share of q_{B0}.

$$k_{1B} = \frac{k_B}{1-q_B} \qquad \textit{Equation 4.6}$$

Process costs k_{1CP} can be calculated for a product P_1 according to Equation 4.7. The connection takes into account rate losses and the fact that all material, including losses, passes through the entire process.

$$k_{1CP} = \frac{\alpha_f \cdot K_{0sum} \cdot (1-q_S) + k_{CPdyn} \cdot E_{12}}{T_{plan} \cdot MT_{ph}} \cdot \frac{1}{(1-q_{B0}) \cdot (1-q_{P12}) \cdot (1-D_1)}$$

$$t_{pMT} = \frac{1}{MT_{ph}}$$

Equation 4.7

Equation 4.7 also shows t_{pMT}, the time required to produce one ton of the product P_1 at maximum capacity MT_{ph}. Below, however, the relationships will be based on maximum capacity (pace = the max feed rate) and not time consumption. The two views on pace and cycle time have previously been described in Chapter 3.

Costs for downtime and overcapacity k_{1CS} can be calculated for a product P_1 according to Equation 4.*8*. The utilization rate U_{RP} is used to describe the cost of overcapacity. The cost of the free capacity is distributed over the current production.

$$k_{1CS} = \frac{\alpha_f \cdot K_{0sum} + k_{CS} \cdot (1-E_{12})}{T_{plan} \cdot MT_{ph}} \cdot \left[\frac{q_S}{(1-q_{B0}) \cdot (1-q_{P12}) \cdot (1-q_S) \cdot (1-D_1)} + \frac{1-U_{RP}}{U_{RP}}\right]$$

Equation 4.8

The personnel cost k_{1D} for producing one ton of product P_1 can be calculated according to Equation 4.*9*. All paid time per hour is distributed over the number of tons of MT_{ph} produced by product P_1 during one hour of operation calculated over a given time period.

$$k_{1D} = \frac{n_{op} \cdot k_D}{MT_{ph}} \cdot \left[\frac{1}{(1-q_{B0}) \cdot (1-q_{P12}) \cdot (1-q_S) \cdot (1-D_1)} + \frac{1-U_{RP}}{U_{RP}}\right]$$

Equation 4.9

In this formulation, it is assumed that all planned production time T_{plan} has the same hourly cost for every hour during all shifts. A varying hourly rate can be taken into account by using a factor that handles varying personnel costs in different shifts. The individual personnel cost k_D is an average value representative of the production line or the plant in question. The number of n_{op} operators does not have to be an integer as one operator can work on several production lines at the same time.

By compiling the cost items with their respective variables and constants reported in Equation 4.5, the cost model for producing the product P_1 is obtained. The reported model takes into account losses and the utilization rate in a C&S plant.

$$k_{1MT} = \frac{k_B}{1-q_B} + \frac{\alpha_f \cdot K_{0sum} \cdot (1-q_S) + k_{CPdyn} \cdot E_{12}}{T_{plan} \cdot MT_{ph}} \cdot \frac{1}{(1-q_{B0}) \cdot (1-q_{P12}) \cdot (1-D_1)} +$$

$$\frac{\alpha_f \cdot K_{0sum} + k_{CS} \cdot (1-E_{12})}{T_{plan} \cdot MT_{ph}} \cdot \left[\frac{q_S}{(1-q_{B0}) \cdot (1-q_{P12}) \cdot (1-q_S) \cdot (1-D_1)} + \frac{1-U_{RP}}{U_{RP}}\right] +$$

$$\frac{n_{op} \cdot k_D}{MT_{ph}} \cdot \left[\frac{1}{(1-q_{B0}) \cdot (1-q_{P12}) \cdot (1-q_S) \cdot (1-D_1)} + \frac{1-U_{RP}}{U_{RP}}\right]$$

Equation 4.10

It should be noted that the equation only applies to a product P_1 that uses the entire capacity. In a later chapter the model will be further developed to describe the costs for several products that are manufactured in parallel.

The sections below report how parameters and variables in the standard model have been adapted and defined to be used in the C&S model in Equation 4.10 above.

4.2.4 Cost per metric ton of product j, k_j

It was found early on that the generic model would not be adequate to analyze the production cost for mining and construction. One reason is that there are often multiple products at a C&S plant. The generic model is made for a production system with one product and needed to be changed to make it work for the current application. The goal was to be able to choose any product at a plant and determine the cost for this particular product. Two things were altered in the generic model. The most important issue was how to distribute the different costs between the different product fractions. To make the cost distribution fair, it was decided to investigate the flow for each product fraction at every stage of the process. The mass fraction pf_j is defined as the fraction of one product j at the end of the process [57, 58].

The generic model also handles several products or components by summing the individual cost contribution of the components. But whereas for machining, for example, the costs for tools, fixtures, and measuring equipment are usually product specific, in C&S the variable costs of wear and spare parts are common to several products. This cost allocation may also vary over time depending on actual mineral properties.

For an example involving two products, consider the case when one ton of raw material is run through the process, producing 650 kg of product one. This leads to a pf_1 of 0.65, and hence to a pf_2 of 0.35 for product two. These factors affect the material cost term k_B and the payroll cost term k_D as these costs need to be distributed proportionally for the different products.

The second issue was how to distribute the machine costs (k_{CP} and k_{CS}) in a meaningful way. It was decided to find the ratio of each product in every machine and then allocate a proportionate cost to each product fraction. This is done by monitoring the distribution of particle size through every machine in the process, and thus making every product account for as much of the machine cost as it utilizes in each machine. This specific utilization factor is called pf_{ij} and is denoted as the flow of product j in machine i. The cost of a product is presented as a share of one metric ton, to allocate the cost per product [57, 58].

Descriptions of process and equipment costs

The equipment cost per hour k_{CP} is denoted as the cost of operating a station or machine during processing and includes only the costs related to uptime. This hourly cost k_{CP} is defined by Ståhl [28] in Equation 4.*11*.

The annual capital cost is divided by the number of planned operating hours per year T_{plan}. The total cost of capital is based on the basic investment K_0 and the total costs for upgrading and renovating the equipment over the life of the equipment. Equation 4.*11* also includes terms that handle the cost of the plant's installation and ongoing maintenance costs, as well as a variable operating cost per hour.

$$k_{CP} = \frac{\alpha_f \cdot (K_0 - R_0) \cdot (1 + \bar{k}_{ren} \cdot N_{ren}) + Y \cdot k_y + T_{plan} \cdot \left(\frac{k_{Mh}}{h_M} + k_{ph}\right)}{T_{plan}} \qquad \textit{Equation 4.11}$$

The equivalent annual capital cost $EACC_j$ for machine/equipment j can be calculated with the annuity method according to Equation 4.12. The original model does not consider any form of residual value R of the equipment as equipment in high-tech industrial companies is often sold when the techno-economic lifetime has passed. The residual value R_{nj} (residual value year n for machine/equipment j) and R_{0j} (residual value year 0 for machine/equipment j) can be considered to reduce the investment K_0 according to Equation 4.12.

$$EACC_j = \alpha_{fj} \cdot \left(K_{0j} - R_{0j}\right) = \frac{p \cdot (1+p)^n}{(1+p)^n - 1} \cdot \left(K_{0j} - R_{nj}\right) \qquad \textit{Equation 4.12}$$

Interviews established that it is possible to recoup approximate 10% of the original investment cost after the expected lifetime of both screens and crushers [4, 24]. With this knowledge the residual value R was represented according to the net present value method [62]. Where R_{0j} and R_{nj} are the residual value year 0 and year n.

$$R_{0j} = \frac{R_{nj}}{(1+p)^n} \qquad \textit{Equation 4.13}$$

Alternatively, R_{0j} can also be calculated as $r_0 \cdot K_{0j}$.

$$r_0 = 1 - \frac{r}{(1+p)^n} \qquad \textit{Equation 4.14}$$

where r_0 is the residual value in percent of the original investment j at year 0, r is the residual value in percent of the original investment j at year n, p is the internal rate (yearly cost for capital in %), and n is the expected technical lifetime. Using this factor gives a more precise production cost per produced metric ton.

K_{0j} is the original investment, including costs for transportation, installation, and all other costs associated with commissioning a new machine.

$$\bar{k}_{ren} = \frac{\sum_{1}^{N_{ren}} \frac{k_{ren}}{(1+p)^{n_{ren}}}}{K_0 \cdot N_{ren}} \qquad \textit{Equation 4.15}$$

The cost k_{ren} is the average cost for a renovation and is based on all estimated renovations done over a machine’s lifetime. It is calculated as a fraction of the original investment. N_{ren}, an integer, is the number of renovations done over the machine’s lifetime [28]. N_{ren} can be calculated according to Equation 4.16.

$$N_{ren} = integer\left[\frac{n \cdot \frac{T_{plan}}{h_y}}{n_{syren}}\right] \qquad \textit{Equation 4.16}$$

Where $T_{plan} \cdot n$ is the total lifetime of the equipment expressed in number of hours. Dividing by h_y, the total hours per shift, gives the total number of shifts over the lifetime of the equipment. The number of renovations N_{ren} is given by dividing the total number of shifts by n_{syren}, the number of shift-years between renovations.

The basic investment K_0 including renovation costs is the total investment described below as K_{0sum}. The product $Y \cdot k_y$ is the cost for the C&S plant or facility in terms of rent [28].

The variable cost K_{Dyn} for planned and ongoing maintenance can be calculated for discrete manufacture according to [28] as:

$$k_{Dyn} = T_{plan} \cdot \left(\frac{k_{Mh}}{h_M} + k_{ph}\right) \qquad \textit{Equation 4.17}$$

In this formulation, k_{ph} describes a variable cost per hour that can represent electricity consumption or other infrastructure costs.

This part of the equation is the planned maintenance cost per hour divided by the number of hours of operation per hour of maintenance [28]. In addition, there are variable machine time costs, such as the cost for electricity consumption. After adding all the uptime costs for the equipment, the total cost is divided by the planned production time per year according to Equation 4.*11*.

Costs for wear parts and spare parts can be relatively high compared to other industries. With this in mind, the variable costs of a C&S plant can be described using Equation 4.18.

$$k_{CPDyn} = \frac{k_{wp} + k_{sp} + k_{to} + T_{plan} \cdot \left(k_{en} \cdot k_{kwh} + \frac{k_{Mh}}{h_M} + k_{hdyn}\right)}{T_{plan}} \qquad \textit{Equation 4.18}$$

This includes the annual costs for wear parts k_{wp}, spare parts k_{sp}, tools k_t, as well as associated energy costs per hour in the form of the product $k_{en} \cdot k_{kwh}$. The dynamic term includes maintenance costs per operating hour, in the same way as in the standard equation, and a variable cost k_{hdyn} per operating hour in addition to the electricity cost.

The machine cost k_{CS} for downtime is described by Equation 4.19 using the standard formulation [28].

$$k_{CS} = \frac{\alpha_f \cdot (K_0 - R_0) \cdot (1 + \bar{k}_{ren} \cdot N_{ren}) + Y \cdot k_y}{T_{plan}} \qquad \textit{Equation 4.19}$$

For C&S plants, the fixed costs excluding basic investment and renovations (k_{0sum}) can be calculated using:

$$k_{CSDyn} = \frac{k_{wpCS} + k_{spCS} + k_{toCS}}{T_{plan}} \qquad \textit{Equation 4.20}$$

The cost calculated according to Equation 4.20 can be debated and could be seen as completely variable. Each application needs to be assessed in this regard. In the current formulation, the fixed part of the electricity cost has been regarded as a variable cost.

In general, the cost for downtime consists of the same parameters as the cost for uptime except for the last dynamic term. The cost parameter $n_{op} \cdot k_D$ (Equation 4.*9*) is the costs for all personnel connected with the production line at hand, the number of personnel and the average hourly cost. This includes costs for salary, social security costs, and holiday compensation. Visits and live sampling were used [57, 58] to complete the mapping of the process flow for a C&S plant and to obtain correct input data for simulation.

Cycle time, t_0

Another example of a difference between normal parts production and C&S plants is the cost for machines. This is defined as the cycle time t_0 multiplied by the hourly machine cost k_{CP}. An additional parameter, t_{mf}, is introduced, representing the time to process one metric ton of raw material, where the material flow m_f is described in metric tons per hour. This results in the parameter t_0 being replaced by t_{mf} and the result became cost per metric ton, which was the original intention.

The relationships between the time variable and the variable flow can be written as:

$$t_{mf} = \frac{1}{m_f} \qquad \textit{Equation 4.21}$$

Where mf is material flow. The relationship between the time variable and the maximum flow through a crusher has previously been reported in Equation 4.7.

Batch size N_0 and the setup time T_{su}

The batch size present in all terms in the generic model must be changed, since mining and construction products are measured by weight and not by number of parts. The selected solution is to replace N_0 by $\mathbf{M_0}$**,** which is defined as the number of metric tons of raw material entered in the process between adjustments of the chamber gap due to regular wear.

When adjusting the equipment, the equipment will be stationary for a time T_{M0} which corresponds to the setup time T_{su} during discrete manufacture according in the previous Equation 2.2. This additional time is distributed over the number of tons produced, M_0. It creates additional costs for personnel ($n_{op} \cdot k_D$) and equipment costs k_{CS} during this downtime. These costs can be calculated according to Equation 4.22.

$$k_{M0} = \left(n_{op}.k_D + k_{CS}\right) \cdot \frac{T_{M0}}{M_0} \qquad \textit{Equation 4.22}$$

The cost term reported in Equation 4.22 has not been taken into account in the described cost term compilation according to Equation 4.10. In practical terms, the time T_{M0} can be regarded as downtime, and included in the downtime that is the basis for calculating the downtime share, q_S.

Material waste rate, q_B

Since C&S in general does not separate material from a main product but produces it in different fractions, there is no material waste to consider, except for a negligible fraction that disappears as dust or unusable small particles. C&S deals with great weights and volumes, and most products command a value, either positive or negative, which needs to be accounted for.

In the case of manufactured products that have no market value, the share of this product has been denoted by q_{B0}.

Rejection rate, q_Q

There are no rejects in mining and construction, as a product cannot be destroyed or scrapped. In some cases, material such as sand and some kinds of gravel are considered scrap and represent a part of q_{B0}. In C&S, q_Q can be equated with q_B for an unsaleable fraction of particles. Large particles are recirculated in the process and contribute to an increased rate loss q_P. This has resulted in removal of the reject rate from the proposed model [62].

Rate losses, q_P

There is a loss of pace when equipment does not produce at a speed consistent with the nominal capacity. Normally scrap is not counted as a rate loss, but discarded parts form part of the nominal capacity. However, there are situations where discarded components are returned to the process. This occurs, for example, when sand casting or injection molding components in thermoplastics. Similarly, in C&S processes large particles are returned to the flow and pass through the crush step at least once more. Under these conditions, when the same material quantity passes through the crush step several times, the output does not correspond to the maximum capacity. This results in a rate loss, defined below.

$$q_P = \frac{L_{1R}}{L_0 + L_{1R}} \qquad \text{Equation 4.23}$$

Material flows L_0 and L_{1R} were illustrated previously in **Figure 4.2** and **Figure 4.3.**

The rate loss can also be expressed using the flow components. If the material losses can be neglected, the rate loss during recirculation will correspond to the flow rate of recirculated material.

Balancing losses, D

An important parameter in C&S processes is the presence of balancing losses D. Balancing loss is defined as the downtime caused by a previous station due to different cycle times. An example is when a crusher is waiting for material from a slow feed. Crushers are designed to run at maximum capacity. A cone crusher is either down or running at 100 % capacity. However, the aim is normally to have utilization for a crusher at around 80 %, depending on its position in the process. For example, the utilization should be higher, preferably close to 100 %, in the last crushing stage [57, 58].

The flow L_0 is usually less than the maximum capacity MT_{ph} through a crusher for example. This gives rise to a balancing loss for product P_1 which can be calculated according to Equation 4.23. With a recycled flow in the production of the product P_1, $L_0 + L_{1R}$ is always $\leq MT_{ph}$. D_{12} is the balancing loss in a recycled flow corresponding to the proportion pf_2 and is always ≥ 0.

$$E_1 = \frac{L_0}{MT_{ph}} \qquad \text{Equation 4.24}$$

$$D_1 = 1 - E_1 = 1 - \frac{L_0}{MT_{ph}}$$

$$D_{12} = 1 - E_{12} = 1 - \frac{L_0 \cdot (1 + pf_2)}{MT_{ph}} \qquad \text{Equation 4.25}$$

Equation 4.26

In these cases, E_1 and E_{12}, respectively, are the plant efficiency for product P_1 during production with or without recycled flow.

4.2.5 The ideal cost, k_{1Idel}

The ideal cost k_{1Idel} can be calculated by setting all losses $q_i = 0$ and the balancing loss $D = 0$ at the same time as the plant has a full occupancy rate, that is, $U_{RP} = 1.0$. The ideal cost is the lowest cost in order to produce a ton of the product P_1 and can be calculated according to Equation 4.10 and can be simplified to Equation 4.27.

$$k_{1Idel} = k_B + \frac{\alpha_f \cdot K_{0sum} + K_{CPdyn}}{T_{plan} \cdot MT_{ph}} + \frac{n_{op} \cdot k_D}{MT_{ph}} \qquad \text{Equation 4.27}$$

According to Equation 4.27, ideal costs consist of material costs, fixed and variable equipment costs, and personnel costs.

4.2.6 Multiple stations and bottleneck identification

The generic model is designed to focus on the bottleneck station of the process. This means that all calculations are based on this station, and all other stations are adapted accordingly. In order to increase the accuracy and quality of the results in this thesis, it was decided to make calculations for each station or machine in the process. This means that both terms c1 and c2 will be changed into their sums for all stages in the C&S process. Making these changes will lead to more precise information being available, making the results even more accurate than with the generic model [57, 58].

4.2.7 Cost calculation for one product in a single crush step

The above techno-economic relationships are exemplified below in the form of a simple cost simulation of an application where a product P_1 is manufactured under different conditions according to **Figure 4.5. Table 4.2** provides basic data for the current simulation. The data given are representative of a part of a production line that is fed with a raw material that costs k_B per ton.

In addition to the given basic data that can vary depending on conditions, there is also a set of variables that can be more or less affected. The variables selected in the reported example are:

- The flow through the crusher L_0
- Return flow L_{1R} and its share pf_2
- The material loss in the process corresponding to the proportion of pf_0
- Downtime rate q_S
- Utilization U_{RP}

In the reported example, setup times T_{M0} are included in the standstill proportion.

Figure 4.6 shows the ideal cost k_{Idel}, that is, the manufacturing cost of producing one ton without any losses. The ideal cost is described as a function of the occupancy rate for two-shift work with a planned production time $T_{plan} = 3400$ h. The difference between the actual production cost and the ideal cost can be regarded as development potential for the plant in question. It should be mentioned, however, that in industrial manufacturing in general, the ideal cost can only be achieved in a few unique cases.

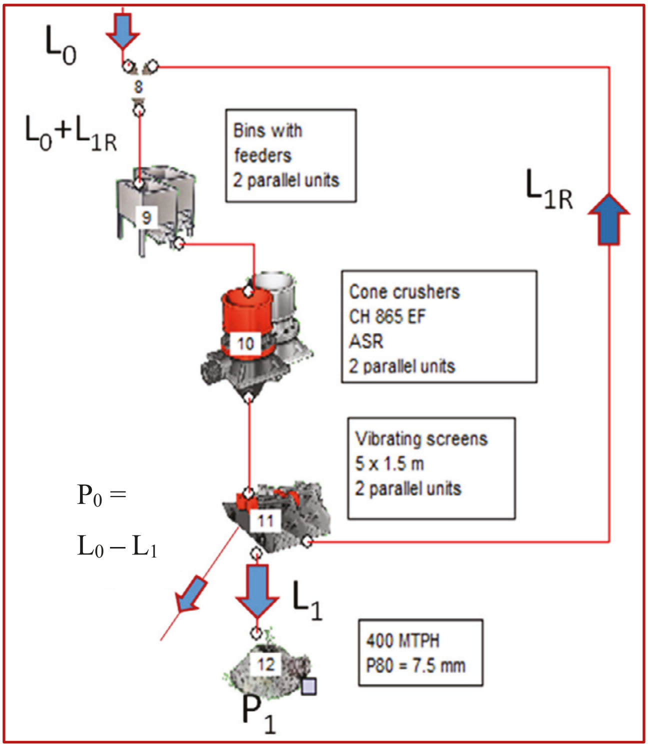

Figure 4.5 *Production flow with recirculation for product P_1.*

The cost terms according to Equation 4.5 gradually add up to the total cost according to **Figure 4.7**. In the current example, it can be stated that the process cost dominates at all the production speeds (flows) studied, L_0. The production cost and its distribution show a strong volume dependence, which illustrates the importance of the degree of utilization of the equipment.

Figure 4.8 illustrates the cost effect caused by a recirculated flow pf_2 which contributes to a rate loss q_P of the same magnitude according to Equation 4.23. The cost effect of recycling flow is significant, as can be seen when comparing the black and red curves. With increased flow through the production line, the cost decreases until the maximum capacity is reached, which in the current example is 400 MTPH. In the reported diagram, the ideal cost k_{Idel} according to Equation 4.27 is also exemplified. However, this cannot be achieved due to losses, among other things. The ideal cost is obtained for full occupancy without losses and disturbances and for operating corresponding to the maximum capacity MT_{ph}.

Table 4.2 *Selected basic data for the reported calculation example.*

Designation		**Minimum value**	**Nominal value**	**Maximal value**	**Unit**	**Ref. Sec./Eq.**
k_B	Material cost	-	5	-	SEK/ton	*Equation 4.6*
K_{0sum}	Total investment	18	20	30	MSEK	
p	Interest cost	0.03	0.05	0.07	-	
n	Expected lifetime	6	8	10	year	
T_{plan}	Planned production time	-	3400	-	h/year	
K_{wp}	Wear part cost	90	100	200	kSEK/year	
K_{sp}	Spare part cost	15	20	60	kSEK/year	
K_t	Tool costs	-	-	-	kSEK/year	
k_{en}	Power consumption	800	1 000	1 200	kW	
k_{kWh}	Cost per kWh	0.80	1.0	1.50	SEK/kWh	
k_D	Personnel cost	-	250	-	SEK/h	
n_{op}	Number of operators	2.5	3	3.5	-	
MT_{ph}	Maximal capacity	-	400	-	ton/h	
Process characteristics (parameters and variables)						
q_P	Speed losses (pf_2)	0.10	0.20	0.40	-	
q_S	Downtime	0.15	0.20	0.30	-	

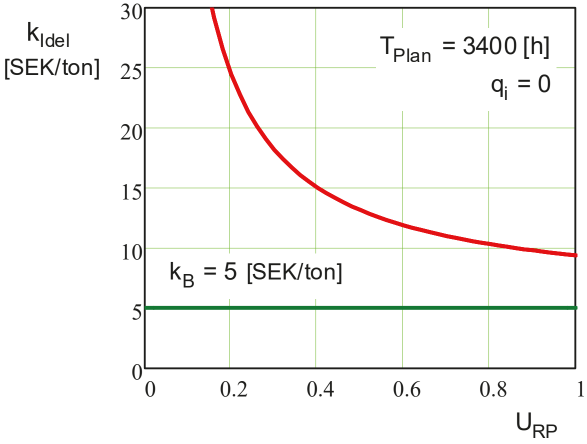

Figure 4.6 *Example of the ideal cost k_{Idel} as a function of the utilization U_{RP}.*

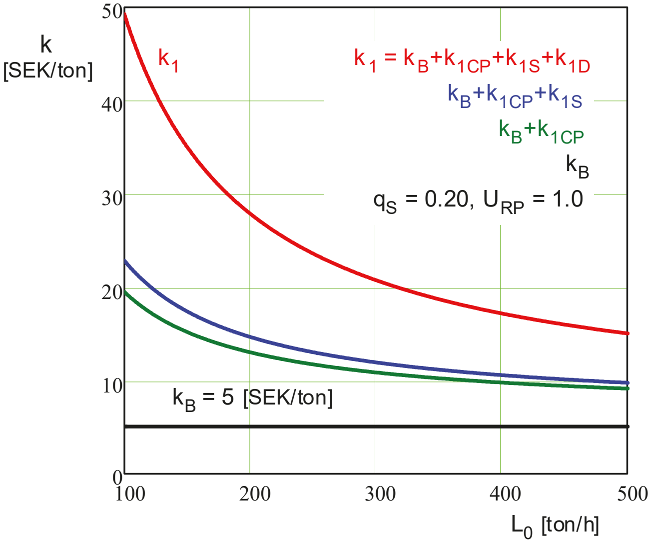

Figure 4.7 *The build-up of cost by successive accumulation of current cost terms in the production of product* P_1 *for* $pf_2 = 0.4$.

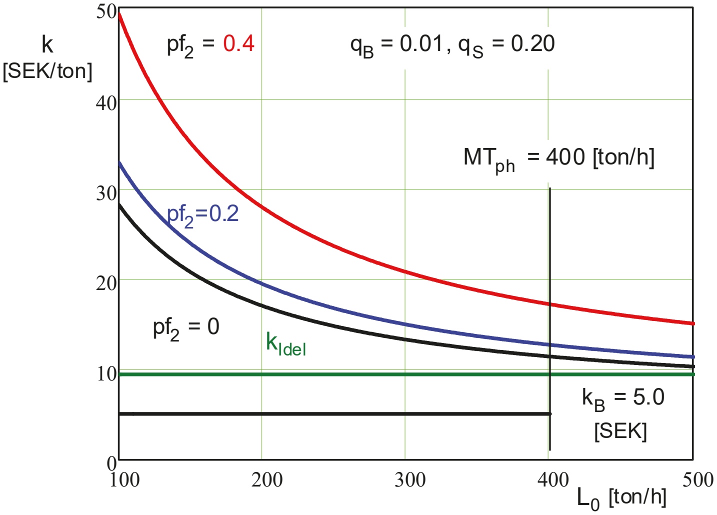

Figure 4.8 *The cost k per ton as a function of the flow (feed)* L_0 *for different proportions of recirculation* pf_2 *(0, 0.2 and 0.4) in production of product* P_1 *for a downtime rate* $q_S = 0.2$.

4.3 Dynamic cost simulation

To be able to present results with a strong connection to reality, it was decided early on to use simulation where exact results were difficult or even impossible to obtain. The goal is to present all cost drivers and parameters of the adapted cost model with confidence intervals or outcomes in statistical terms. Dynamic simulation using Monte Carlo simulation was used. This simulation method is based on statistical distributions for uncertain or unknown input data and parameters.

This method also enables additional data to be generated based on different assumptions [74]. The cost influence or strength of various parameters can thus be simulated, which also enables an assessment of the cost effect associated with incorrect or uncertain input data. Assumptions made in the simulation can be followed up in several different ways, such as:

1. Follow-up and measurements in existing facilities or other observations.
2. Interviews with experts or operating staff at current C&S facilities.
3. Data retrieved from the literature or information from available databases.
4. Qualified guesses and assumptions.

However, the method requires that the distribution function for each parameter or input data be known. A simple Weibull distribution was chosen for each parameter in accordance with the nature of the substance. For other cases with cooperating or dependent inputs, mixed distributions can be used Ståhl [74]. In the current case, the available data has not justified this more complex simulation.

4.3.1 The basics of dynamic simulation of current costs

Dynamic simulation of manufacturing costs has been performed previously, for example in scenario analysis for new research projects or innovations [74]. Dynamic simulation involves the following sequence of work steps:

1. Select the respective parameter to be studied, in the case below represented by the rate loss q_P.
2. Select a distribution function that can describe the rate loss q_P. This can be based on experience or available measurements.
3. Determine the constituent constants in the selected distribution function; in the current case, α and β for αq_P and βq_P.
4. Select the number of q_P values N (vector length N) to be used in the simulation.
5. Calculate the values in the q_P vector with the number N, which is done with a rectangular random vector of length N with data in the interval [0, 1.0].

Assessment of the reasonableness and quality of the generated vector q_P.

By rewriting a distribution function as shown in equation 4.28, the q_P vector can be created using the above-mentioned slum vector $SUFV_j \approx$ the down-hill trend. In the present case, the inverse of a Weibull distribution has been used to create the vector q_{Pj}.

$$F(q_P) = 1 - e^{-\left(\frac{q_P}{\beta_{qP}}\right)^{\alpha}} \longrightarrow q_{Pj} = \beta_{qP} \cdot \left(-\ln(1 - S_{UFVj})\right)^{\frac{1}{\alpha_{qP}}} \qquad \textit{Equation 4.28}$$

Figure 4.9 graphically illustrates the method for creating the current q_P vector q_{Pj}. The values in a selected probability distribution can be determined in several different ways. One is to set a known or assumed value for minimum and maximum value with a given probability, in the current example q_{Pmin} and q_{Pmax}, for example with the probabilities of 2.5 and 97.5%, respectively. This assumption gives us two equations with two unknown parameters α_{qP} and β_{qP}, which can be solved.

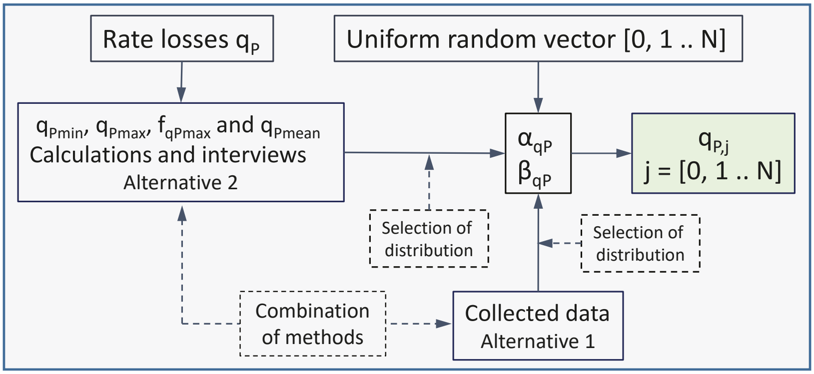

Figure 4.9 *Generation of a vector with data representing an assumed rate loss q_P with a given distribution function, modified after Ståhl [74].*

Another possibility is to use a calculated or assumed mean value or corresponding most common value (median value) to create two equations in order to be able to solve the unknown parameters. A safer and more accurate determination of the parameters can be made by basing the calculations on collected data. Collected measurement data can also be used to select the best probability distribution.

The above method can also be used in cases where the distribution function cannot be expressed in inverse form. In these cases, an iterative procedure must be used, which is necessary for the normal and gamma distributions, for example.

4.3.2 Example of dynamic simulation of C&S

The example below illustrates three different boundaries for dynamic simulation of C&S facilities:

a) **Investment and annual capital costs** and their influence on the cost of manufacturing product P_1 with regard to the basic investment K_0, the associated interest cost p, the expected number of years of use n, and the occupancy (or utilization) rate U_{RP}.

$$k_{1j} = k_1(K_{0j}, p_j, n_j, U_{RP}) \qquad \textit{Equation 4.29}$$

b) **Capacity and production costs** related to operating conditions and their influence on the cost of manufacturing product P_1 with respect to rate losses q_P caused by material recycling, downtime q_S, and occupancy rate U_{RP}.

$$k_{1j} = k_1(q_{Pj}, q_{Sj}, U_{RP}) \qquad \textit{Equation 4.30}$$

c) **Service, operating, and maintenance costs** and their influence on the cost of manufacturing product P_1 with regard to the cost of wear parts K_{wp}, spare parts K_{sp}, energy cost k_{kWh}, and occupancy rate U_{RP}. Costs for specific tools and lifting equipment K_t in connection with repairs and maintenance are included in the basic investment.

$$k_{1j} = k_1(k_{wpj}, k_{spj}, k_{kwhj}, U_{RP}) \qquad \textit{Equation 4.31}$$

All variables and parameters that are included in equation 4.10 can be simulated dynamically. The variation or dynamics in the manufacturing cost k_1 for product P_1 according to case a) above is exemplified in **Figure 4.10**. This form of simulation can be done before investing in a facility to be able to determine the effect of different investment levels and associated capital costs. An important factor in this case is to be able to assess the service life of the equipment, which requires experience based on operating similar facilities under different conditions.

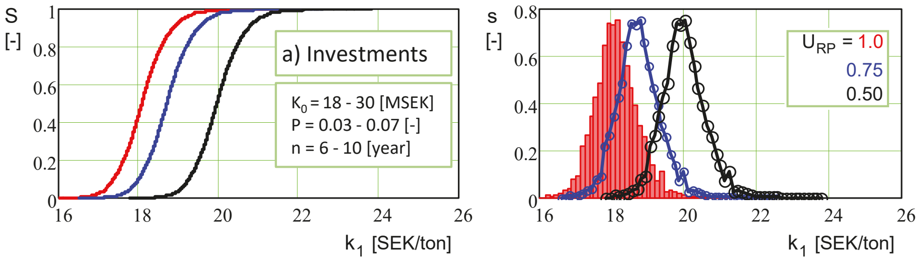

Figure 4.10 *The distribution S (left) and the frequency function s (right) of the production cost k_1 when varying the investment level K_0, the interest cost p, and the plant's life n for three different occupancy rates U_{RP}.*

A simulation for case b) studies the cost effect of two different losses, rate losses q_P due to the return flow (L_{1R}) according to **Figure 4.5** and downtime losses q_S caused by maintenance work, power outages, and material shortages, for example. **Figure 4.11** exemplifies the variation in k_1 caused by different values of the losses described by the downtime percentage q_S and the rate loss q_P. The rate loss q_P is strongly dependent on how well the crushing equipment is adapted to the size of the product in question and the crushing properties of the mineral. The two parameters q_P and q_S are partly dependent on each other. Using maintenance measures and adjustment, the return flow and rate losses can be reduced at the same time as these measures lead to increased production loss and downtime.

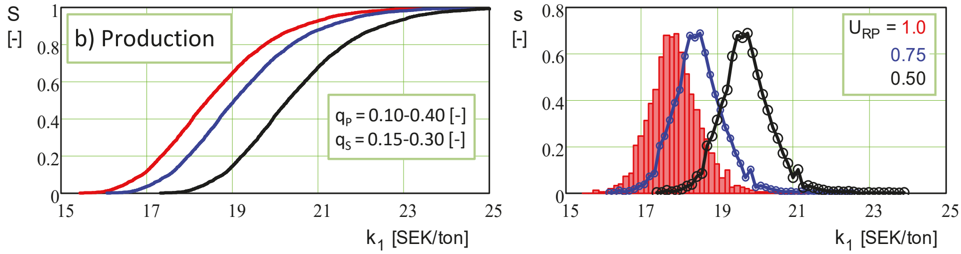

Figure 4.11 *The distribution S (left) and the frequency function s (right) on the manufacturing cost k_1 when varying the rate loss q_P and the downtime percentage q_S for three different occupancy rates U_{RP}.*

A simulation of case c) simulates cost variations related to operating costs in the form of wear parts, spare parts, and electricity costs. **Figure 4.12** demonstrates how the variation in operating costs affects the final cost of manufacturing P_1 in SEK/ton.

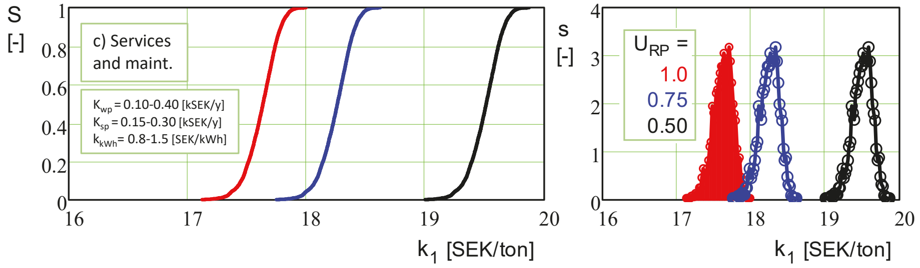

Figure 4.12 *The distribution S (left) and the frequency function s (right)on the manufacturing cost k_1 by varying the costs for wear parts K_{wp}, spare parts K_{sp}, and electricity cost k_{kwh} for three different levels of the occupancy rate U_{RP}.*

By inserting all studied variables and parameters in the form of vectors according to the principle illustrated in Equation 4.32, the entire outcome space can be studied with regard to the total statistical variation for other parameters constant with values according to **Table 4.2**.

$$k_{1j} = k_1(K_{0j}, p_j, n_j, q_{Pj}, q_{Sj}, k_{wpj}, k_{spj}, k_{kwhj}, U_{RP})$$

Equation 4.32

Figure 4.13 illustrates the spread in cost per ton for all 9 variables studied. An increased number of variables studied generally entails an increased spread in cost per ton.

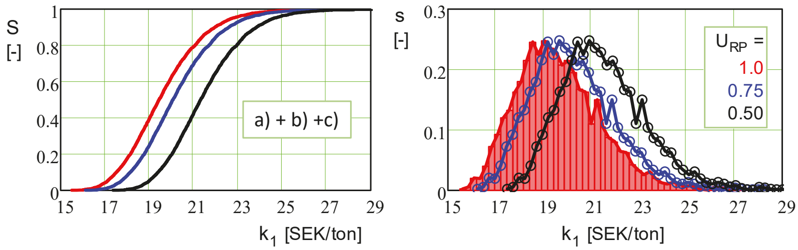

Figure 4.13 *The distribution S (left) and the frequency function s (right) of variations in all studied variables and parameters according to cases a), b) and c).*

4.3.3 Results and discussion

Calculations were performed based on an application where conditions and data are well known in order to be able to verify the developed cost model for product P_1. Estimated manufacturing costs are directly compared with the post-calculations performed with the approximate data provided by customer. **Figure 4.14** shows a flow chart of the current application which consists of three crushing steps from mineral (ore) to finished product.

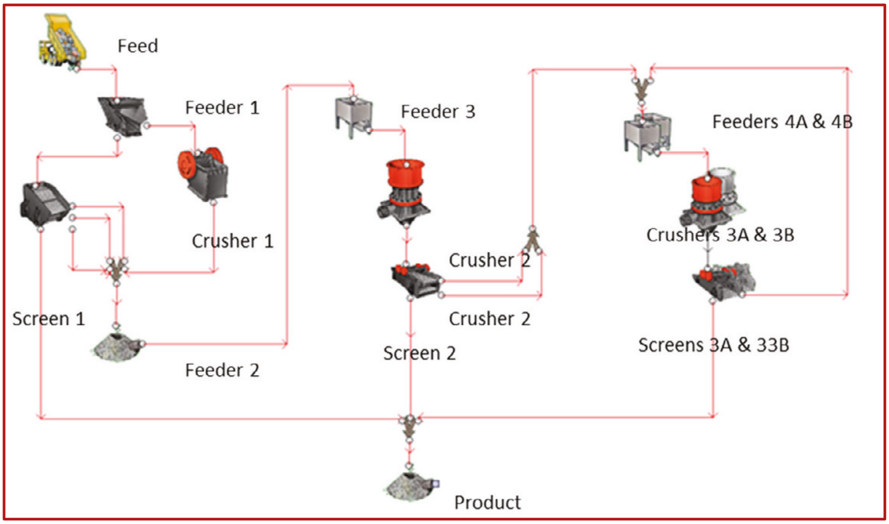

Figure 4.14 *Flowsheet of the gold ore C&S plant.*

The model indicated a total mean production cost of 44 SEK/ton, consisting of mean costs for raw material, payroll costs, machine costs during uptime, and machine costs during downtime of 15.9, 5.3, 20.5, and 2.5 SEK/ton respectively. Four cost terms along with the total production cost are presented below. **Table 4.3** shows overall data for this case.

***Table 4.3** Overall data for calculated costs.*

Process data:	
Ore type:	Blasted gold ore
Annual production:	1 200 000 MT
Operating time:	4 000 h per year

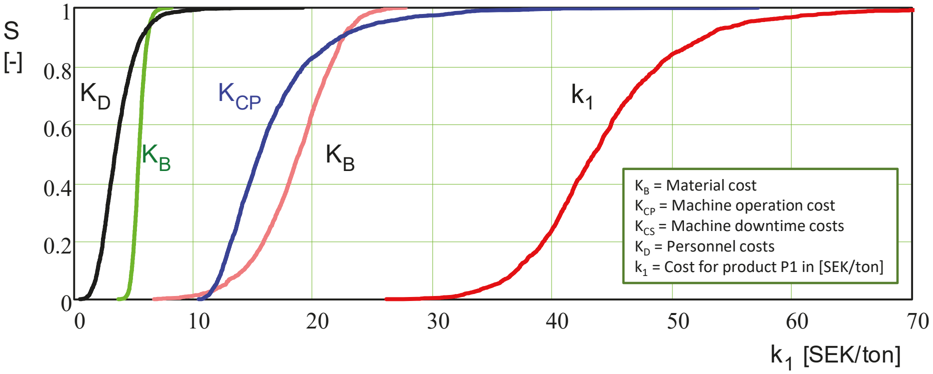

***Figure 4.15** All cost term based on Weibull distribution functions together with the total cost k_1 [62].*

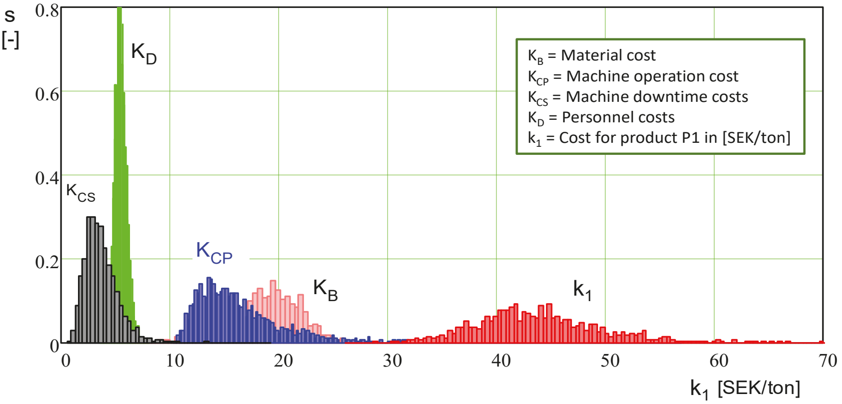

***Figure 4.16** Frequency functions for all cost terms based on Weibull distributions together with the total cost k_1 [62].*

Since it is difficult to determine exact results and distribute costs in the industry, it is difficult to argue for or against the validity of each figure. But an important sensitivity analysis [42] regarding investment costs showed that the model's results were close to the original plant's own costs after removing the investment costs of all the equipment and the raw material, according to **Figure 4.17**. This verifies the validity of the model since the plant's own costs were calculated without investment costs. The actual cost per ton was calculated at SEK 26.30/ton, while the simulated cost was calculated at 28.3 SEK/ton. The cost conformity, CF, compares the results of the simulation with actual results, as shown in Appendix I. In this case CF = 28.30/26.30 = 1.08, excluding capital and raw material costs.

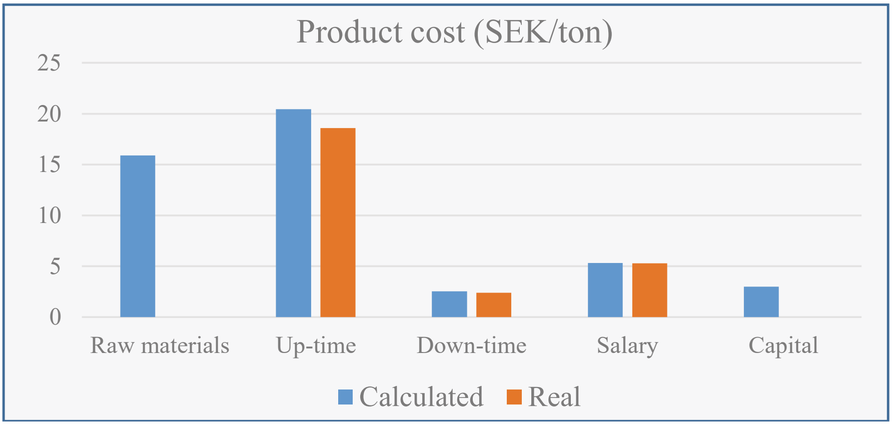

Figure 4.17 *Calculated and actual product costs [58].*

4.4 Conclusions of the initial PCCM model

The model looks promising for a C&S plant that only produces one final product as it has an accuracy of approximately 90 %. The calculated dynamic production costs were overestimated, but relatively close to the actual costs. When a C&S plant only produces one final product, this final product must bear all costs, so no allocation keys are needed.

However, the initial model cannot predict the production costs of each machine/equipment as all “individual” costs are added/sampled together. In addition, normally whatever fraction of the product meets the final requirements already in an early C&S stage in mining will be further size reduced and then extracted in the final stage. In construction, the end products from the early C&S stage normally do not meet the quality requirements of the end products and must therefore be size reduced further [4]. The above means that in C&S plants that produce more than one final product the pf_j factor does not become quite accurate in allocating the production costs to the end products and each machine/equipment in a balanced and fair way. Normally all prices for machines, equipment, WP and SP bound for C&S plants are local. This means that when searching for the investment costs, you need to contact the manufacture, supplier, or dealer in the area where the crusher will be installed.

5. Model Refining for Several Products

This chapter deals with further development of the model to a more comprehensive version that can handle several different products from one plant. In order to do this, it is necessary to be able to separate operating costs and allocate them to each product. The problem to be addressed is when several products pass through the same equipment and contribute to cost items such as wear parts, spare parts, and energy consumption. This second phase of the work was carried out after further information gathering and experience based on the previous chapter. An important part of this approach is the use of allocation keys when the C&S plant produces more than one end product.

5.1 Introduction to complex analysis

In mining C&S plants, only one end product is normally produced. In unusual applications, mining C&S plants can produce two or more end products. Some complex production C&S plants in Quarrying/Construction can produce up to ten different end products [24]. This complexity places specific demands on cost models and the way the problem is approached. The final product may be extracted at the last C&S stage of the plant, but often in mining a portion of the final product is extracted in each process stage, i.e. taken out the "ready" produce sizes. In typical construction C&S plants, several end products are produced. Each product has its own properties such as particle size, particle size distribution, particle shape, and over/undersize content in the ballast fractions. The end products can be extracted at the final C&S stages and/or earlier stages, depending on the required construction aggregate fraction sizes and properties.

The initial black box model in chapter 4 does not provide the production costs for each machine or piece of equipment. It is now necessary to keep track of and calculate all the subitem costs to find the solution/process that provides the lowest production costs when comparing different solution/process subsystems that produce equally satisfactory products. This can be done by using the discrete model approach, see **Figure 5.1**.

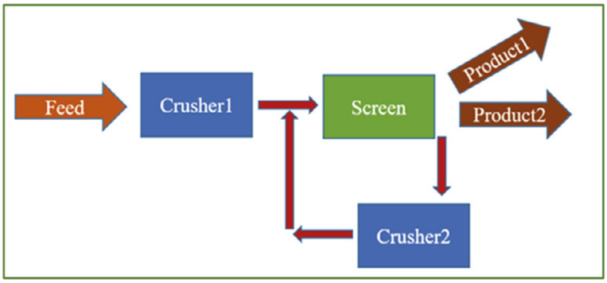

Figure 5.1 *The Discrete model – all individual subprocesses in a C&S system.*

In the discrete model approach, the production process will be treated as individual processes by all the different subprocesses in the system. The production costs will be calculated as individual and allocated costs, individual and allocated capital costs, individual and allocated dynamic costs, allocated payroll costs, and allocated auxiliary costs.

5.2 Improved cost model developments

In the initial model some of the common production costs were reported for each part of the cost calculation model. However, a simpler way is to gather all common production costs as auxiliary costs. All these common production costs will normally be allocated according to the proportion of the end products produced [63]. When using this revised approach to develop and design the calculation model for production costs, the PCCM will have three main cost items, special costs created for each machine/equipment, payroll cost for the C&S plant, and the part of the common costs that should be borne by the C&S plant.

According to section 4.4 the pf_j flow-factor will not be perfect when allocating common costs to each machine/equipment. In the revised model, the allocation keys were developed to be used instead. Using allocation keys in the calculation model for production costs allows costs to be better distributed, resulting in fair and balanced distribution of the special production costs and the common production costs to each machine/equipment and each end product. This part of the work has been difficult to evaluate in a purely objective way. The development of allocation keys has been based on, and required, significant experience in the field.

5.2.1 One end product

The easiest process flowsheet from product cost allocation point of view is when a C&S plant produces one end product extracted at the last C&S stage (**Figure 5.2**). Alternatively, a plant could produce only one end product, but the end product is extracted at each stage as shown in **Figure 5.3**. When producing only one end product, this product will be the total product cost carrier. This means that all production costs will be attributed to this single product.

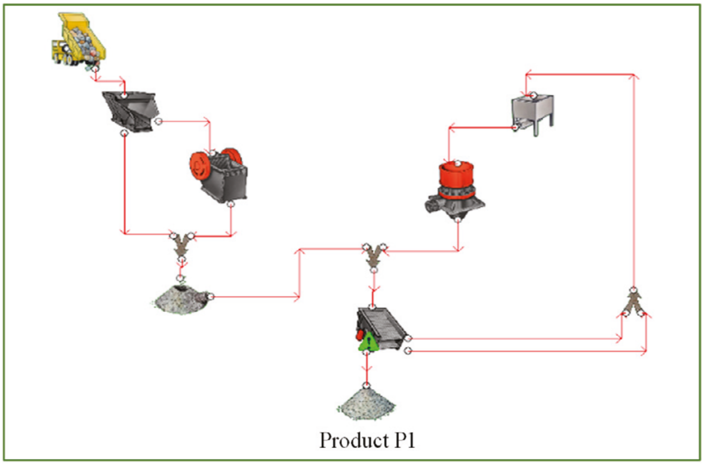

Figure 5.2 *A typical process flow with one end product extracted at the last C&S stage.*

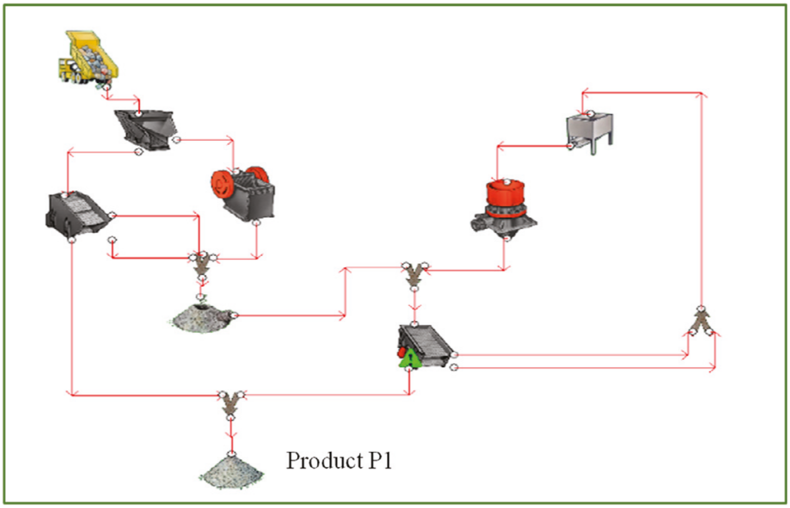

Figure 5.3 *A C&S plant with one end product, where the end product is extracted when created.*

5.2.2 Two, three, or more end products

When C&S plants produce more than one end product, there is more than one production cost carrier. More end products make the process flow more complex.

Figure 5.4 shows the simplest process flow with two end products, when both products are extracted at the final stage of the plant. The cost allocation will be a little trickier with two end products because the production costs must be distributed between the two end products. In cases like this, where the final products are taken out in the last stage of the C&S plant, the production costs are normally allocated in the proportion produced.

Especially in construction, aggregate C&S plant end products can be extracted in earlier C&S stages to produce the desired factions, for example, railway aggregates [4]. In these cases, some of the end products never use all the C&S stages, as in **Figure 5.5**.

The production costs in a C&S plant can be considered as common and special production costs. The common costs are the costs not attributable to a specific cost object, for example, the cost of raw material, renting of land, lighting, and heating etc. The special production costs are the production costs of each machine. In addition, the salary costs will be distributed to each machine and each end product to obtain a complete production cost.

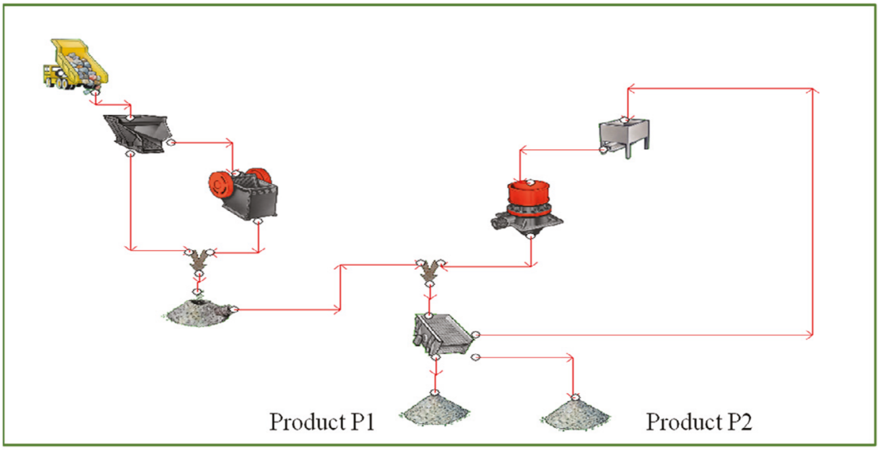

Figure 5.4 *A typical C&S plant with two end products.*

Only the distributed special production costs, including the distributed salary cost from the machines needed to manufacture the product, should be included in the production cost of the individual end product. All end products will be cost carriers, but the production costs should be distributed to each and every end product using a fair, balanced, and accurate approach. There are several ways of distributing the production costs to the end products, as in **Table 5.1**.

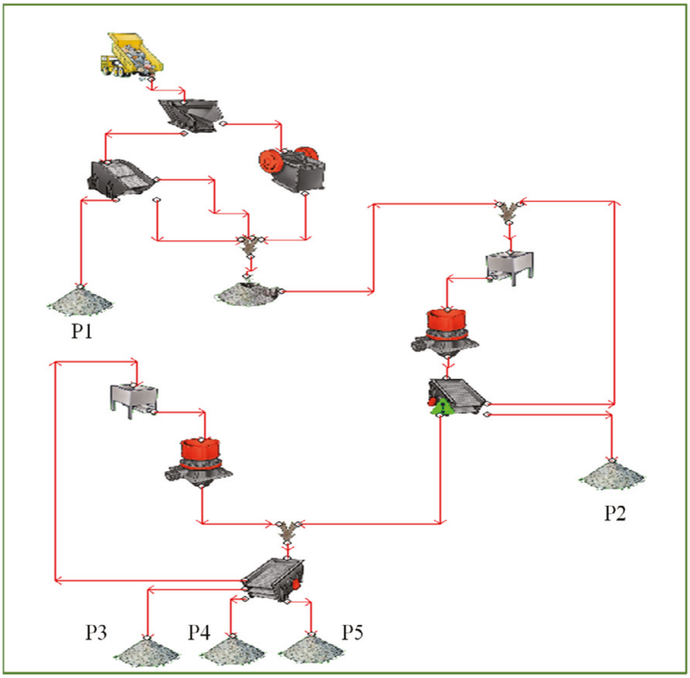

Figure 5.5 *A typical C&S plant with multiple end products (P_1–P_5) where some of them are extracted in earlier C&S stages.*

Table 5.1 *Overview of type of allocation models.*

Type of end product	Cost allocation model to distribute the costs (*)
Equal end products	In proportion to the end products produced.
Main and supplementary end products	If one of the end products is the main product required, this product should be the main cost carrier.
When an end product is extracted before the last stage	The end product that is extracted in one C&S stage will not be a cost carrier for production costs that occur further down the C&S process chain.
Sales demand for a single fraction	A special infrastructure project may need large amounts of a single fraction of aggregates. The single fraction aggregate should bear all the extra cost.
Increased quality requirements	An end product that requires extra careful manufacturing should bear the entire extra cost of this special manufacturing.
Allocation of salaries	In C&S plants there are normally more machines/equipment than plant operators and managers. The salary costs must be distributed to each machine/equipment. hours worked (time subscription).
Other methods	There are several other ways to distribute the production costs to the end products.

(*) The distribution of the production costs between the end products may also be a combination of two or more of the methods.

Proportion of the end products: This cost allocation method uses the proportion of end products produced to distribute the production costs to each end product. The method is used when all end products are extracted in the last C&S stage.

Main and supplementary end products: If one of the end products is the main product required, this product should be the main cost carrier. All other end products will be supplementary products manufactured when the main product is fabricated. These supplementary products will be smaller cost carriers. The cost ratio between the main cost carrier and the smaller cost carriers must be decided in each individual case. The income ratio for each end product can play an important role when determining the cost distribution.

When the end product is extracted before the last stage: The end product that is extracted in one C&S stage will not be a cost carrier for production costs that occur further down the C&S process chain.

Sales demand: A special infrastructure project may need large amounts of a single fraction of aggregates. But to fabricate just that fraction, the C&S plant will also produce amounts of unwanted fractions. The single fraction aggregate should bear all the extra cost of producing the increased demand of this special demand product.

Increased quality requirements on the end product: An end product that requires extra careful process manufacturing should bear the entire extra cost of this special manufacturing even though other end products may also be produced.

Allocation of salary costs: In C&S plants there are normally more machines or equipment than plant operators and managers. The salary costs must be distributed to each machine/equipment. There are two main ways of distributing the salary costs depending on whether it is an existing C&S plant or a simulated C&S plant.

In existing C&S plant, the payroll costs will be dividing the allocated according to the ratio of labor hours worked at each machine/equipment by the total labor hours worked (time subscription). This time ratio subscription principle should be used for all personnel costs belonging to the C&S plant.

To distribute salary costs in a simulated in C&S plant, several methods may be used, such as in the ratio of the distribution of the main machines, the distribution of the power consumption, the distribution of the W&S parts consumption, the ratio of produced end products with the required properties, the distribution of final products, or a combination of these. The selected distribution principle is then used for all personnel costs that belonging to the C&S plant.

There are several other ways to distribute production costs to the end products. For example, using the proportion of used power, proportion of the capital cost of the equipment, or the portion of used area by the equipment.

The distribution of the production costs between the end products may also be a combination of two or more of the above methods.

5.2.3 Utilization of the C&S plant

One of the main criteria in the annual production of a C&S plant is the utilization of the plant. Several factors have a high impact on C&S plant utilization, including the annual production time (the number of shifts per working day and the number of working days), which is the main factor when determining utilization. A higher utilization can be expected for a plant working five days a week with one shift/day than for a plant that works around the clock the whole year. This is because time for the maintenance and servicing of the plant working one shift/day for five days/week is available outside plant working time. A plant working around the clock the whole year has no free time for maintenance and servicing as production keeps running. Therefore, when maintenance and servicing are required, the plant must stop production.

Sales demand for end products may affect the utilization of aggregate C&S plants. For example, sales may fluctuate seasonally during the year, which affects utilization of construction aggregate C&S plants.

Other factors that affect utilization are products that are difficult to produce with the right end product properties, automation and control of the plant, the skill level of operators, weather conditions, lack of WP/SP, lack of energy, lack of raw materials, or a lack of other resources.

Normal uptime is when a plant is in production. When a C&S plant has two or more parallel process lines, the plant can continue working as long as at least one of the parallel process lines is operating. Although the plant will then have a lower production rate, parallel production lines will increase plant utilization.

Another factor that increases existing plant utilization is intermediate storage, with feeders that can take up process fluctuations and feed out from storage at the desired and required rate to the next process stage. Furthermore, optimizing the process, upgrading machines, and replacing old heavy maintenance machines/equipment with new low maintenance ones can increase the utilization [4, 24].

5.2.4 Allocation keys

Using allocation keys allows the production costs to be distributed to each end product in an easy, organized, and assigned way when a C&S plant produces more than one end product. The allocation keys can be defined either on the basis of the proportion of products produced or by specific designation for each end product to each machine/equipment. The first method is normally used to distribute the common product for common and united costs for the whole C&S plant, to distribute these common costs through general allocation keys, while the second is used to distribute individual production costs for each machine/equipment through special allocation keys.

General allocation keys

Allocation key AK_{gi} for general costs to product P_i is normally calculated as the proportion of products produced, according to the principle of cost carried according to the weight share.

$$AK_{gi} = \frac{MT_{Pi}}{\sum_{i=1}^{i=n_p} MT_{Pi}} \qquad \textit{Equation 5.1}$$

Where P_i is an end product and $\sum MT_{Pi}$ is the sum MT of all end products, and n_p is the number of products.

Salary costs are normally distributed through the proportion of work time used at each machine/equipment. This will be on record in an actual C&S plant but is more difficult to determine for a simulated plant. One way to do this is to distribute the salary costs in the same proportion as the main equipment. Sometimes, however, the salary costs may also have to be distributed by considering the difficulty of achieving the right properties for the end products.

Special allocation keys

Special allocation keys are valid when all final products are extracted at the same station at the end of the process chain. Thus the same allocation keys will be used when distributing the costs.

$$AK_{ji} = \frac{MT_{j,i}}{\sum_{i=1}^{i=n_p} MT_{j,i}} \qquad \textit{Equation 5.2}$$

If, however, final products are extracted at different positions along the process chain or at different C&S process lines, the allocation keys will be different at the stations, see **Figure 5.6** below.

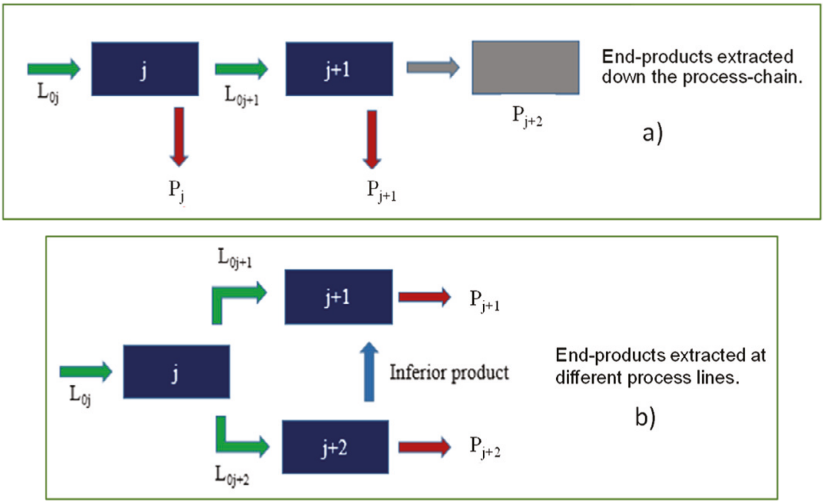

Figure 5.6 *Crushing circuits, process chain with extraction of final products at different stations or in different process lines.*

Extracting products along the process chain

Below is a general analysis of flows within a process chain and various withdrawals of products along the process chain. These principles will form the basis for further development of the cost analysis for more complex plants with several different products. Different products will load different equipment to different extents and consume different amounts of resources in the form of wear parts and energy for example. For example, product P_4 in **Figure 5.7** will pass more sections of equipment than product P_1; however, the flows associated with each product may differ markedly.

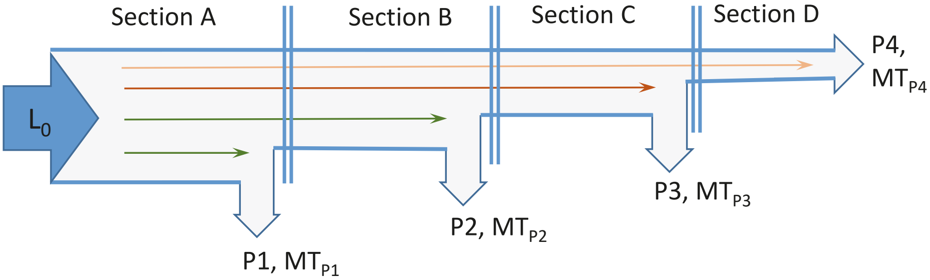

Figure 5.7 *In principle, how products are extracted out along a process chain and thus burden the equipment in different ways and use resources in different levels.*

At station j:

$AK_{ji} = pP_i/(\text{Sum of all final product parts} = 1.0)$

Mass balance at steady state gives:

$L_0 = MT_{Pi} + MT_{Pi+1}$

$pf_1 + (1 - (pf_{jp1} + pf_{jp2})) = 1.0$, when not all material is produced as P_1 and P_2.

In this case there are three different substreams.

Where part of Product i pP_i can be calculated as:

$pPi = pPi$, before Pi is extracted and
$pPi = 0$, after Pi is extracted

At station j+1:

$AK_{(j+1)(i+1)} = pP_{i+1}/(1 - pP_i)$

Where:

$pP_{i+1} = P_{i+1}$, before P_{i+1} is extracted
$pP_{i+1} = 0$, after P_{i+1} is extracted

If there are more end products extracted further down in the C&S processes, the allocation keys will be defined in the same way as the above stations.

Extraction of products in different process lines

At station j:

At steady state the mass balance will be

$L_{0j} = L_{0j+1} + L_{0j+2} = MT_{Pi+1} + MT_{Pi+2}$

$L_{0j+1} = MT_{Pi+1}$

$L_{0j+2} = MT_{Pi+2}$

$AK_{ji+1} = L_{0j+1}/(L_{0j+1} + L_{0j+2})$

$AK_{ji+2} = L_{0j+2}/(L_{0j+1} + L_{0j+2})$

If there are more process lines, the allocation keys will be defined in the same way. If end products are extracted further down the process line, the allocation keys will be defined as shown in the previous section.

5.3 An actual C&S plant with two end products

As the initial cost model looked promising, the next step was to gather data from a C&S plant that produces two end products. The C&S plant selected was an iron ore C&S plant that produces two products: 0–5 mm and 5–20 mm. Annual production is 6,500,000 ton/year. The C&S plant flowsheet is shown in **Figure 5.8**.

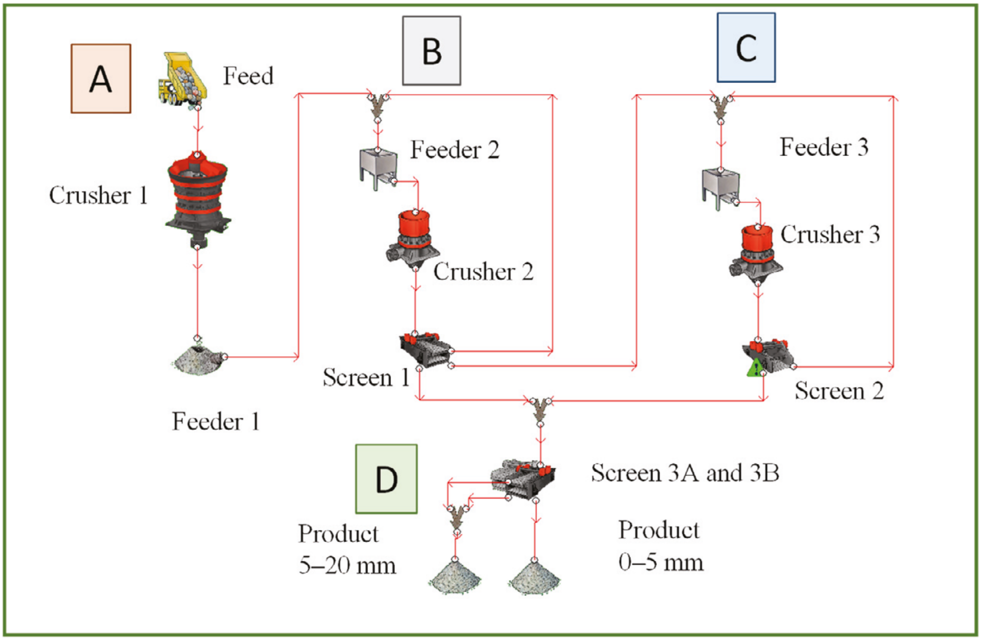

__Figure 5.8__ The iron ore C&S plant with each section, A, B, C, and D [64].

5.3.1 Flow analysis and mass balances

The first focus is the primary station that runs in open circuit as in **Figure 5.9**. Compare this also with **Figure 4.2**.

__Figure 5.9__ An open C&S circuit.

For a steady state C&S process, the material flow in the open circuit will be as shown in the mass balance equations below, see also **Figure 5.10**.

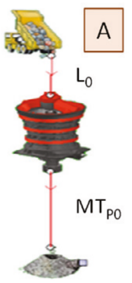	At steady state the material flow in the open C&S circuit will be as shown in the mass balance equation below. **Where**: $L_0 = P_0$ but with different particles size distributions.

__Figure 5.10__ The primary station with mass balances (A).

The second focus is the secondary station that runs in closed circuit, see **Figure 5.11**.

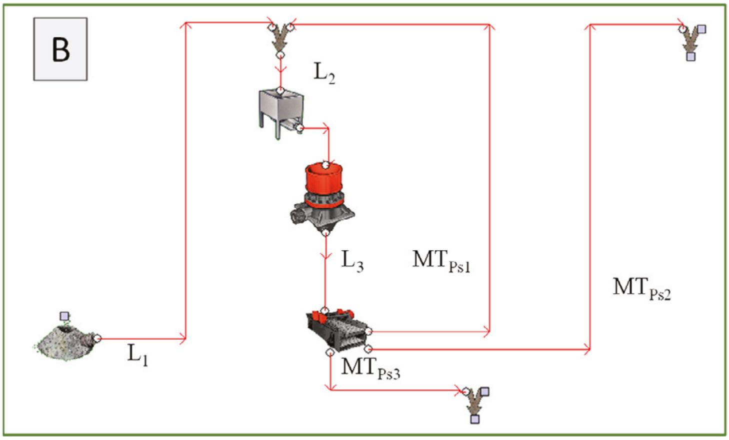

Figure 5.11 *The secondary station with mass balances (B).*

The mass balances in the second station at steady state will be:

$L_1 = MT_{Ps2} + MT_{Ps3}$

$L_2 = L_3 = MT_{Ps1} + MT_{Ps2} + MT_{Ps3}$

$L_2 = L_1 + MT_{Ps1}$

and leaving the screen:

$MT_{Ps3} + MT_{Ps2} + MT_{Ps1} = (pf_{s1ps3} \cdot L_3) + (pf_{s1ps2} \cdot L_3) + (1 - (pf_{s1ps2} + pf_{s1ps3})) \cdot L_3)$

where $pf_{s1ps3} + pf_{s1ps2} + pf_{s1ps1} = 1 \quad => pf_{s1ps1} = 1 - (pf_{s1ps2} + pf_{s1ps3})$

The third focus is the tertiary station running in closed circuit in **Figure 5.12**.

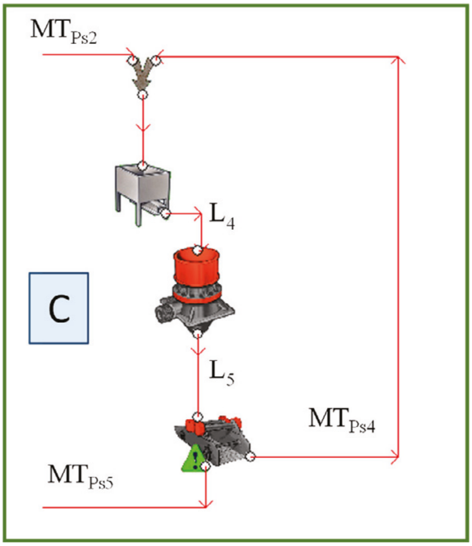

Figure 5.12 *The tertiary station with mass balances C.*

The mass balances in the tertiary station at steady state will be:

$L_4 = MT_{Ps2} + MT_{Ps4}$
$L_4 = L_5 = MT_{Ps4} + MT_{Ps5}$
and leaving the screen:

$MT_{Ps4} + MT_{Ps5} = (pf_{s2ps4} \cdot L_5) + (1 - (pf_{s2ps24})) \cdot L_5)$
where $pf_{s2ps4} + pf_{s2ps5} = 1 \quad => pf_{s2ps5} = 1 - (pf_{s2ps4})$

At the final production stage, the two end products are screened out as 5–20 mm (P_{s9}) and 0–5 mm (P_{s8}) shown in **Figure 5.13**.

$L_6 = MT_{Ps6} + MT_{Ps7} + MT_{Ps8}$
$MT_{Ps9} = MT_{Ps6} + MT_{Ps7}$
$pf_{s3ps6} + pf_{s3ps7} + pf_{s3ps8} = 1 \quad => pf_{s3ps8} = pf_{s3ps6} + pf_{s3ps7} + (1 - pf_{s3ps6} + pf_{s3ps7})$
and
$MT_{Ps9} = (pf_{s3ps6} \cdot L_6) + pf_{s3ps7} \cdot L_6$, and $MT_{Ps8} = pf_{s3ps8} \cdot L_6$

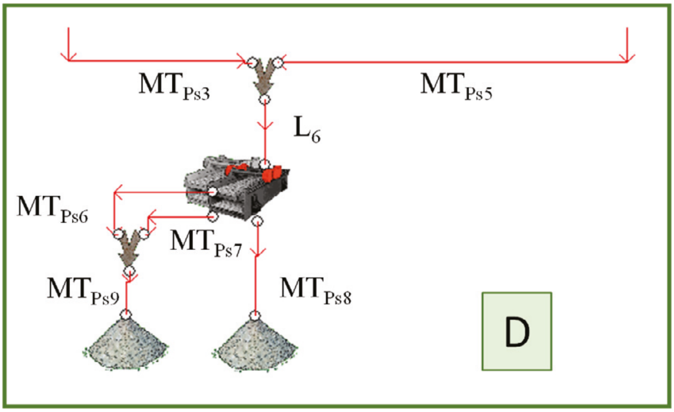

Figure 5.13 *The final production station with mass balances D.*

Table 5.2 *Flow production and investment: the iron ore C&S plant (**Figure 5.8**).*

Project: P18-23		**MTPY**				
Section	**Machine/ equipment**	**Flow in**	**Flow out 1**	**Flow out 2**	**Flow out 3**	**Investment (USD)**
A	Crusher 1	6,500,000	6,500,000			2,200,000
A	Feeder 1					48,500
A	Others 1	-	-			2,151 500
B	Crusher 2	7 610 790	7 610 790			2,321,420
B	Screen 1	7 610 790	1 110 890	1 211 345	5 288 555	337,500
B	Feeder 2					70,000
B	Others 2					2,728,920
C	Crusher 3	1 364 980	1 364 980			1,344,086
C	Feeder 3					15,000
C	Screen 2	1 364 980	153 635	1 211 345		264,000
C	Others 3					690,000
D	Screen 3 A&B	6,500,000	2 736 440	1 387 810	2 375 750	675,000
D	Others 4					705,000

Most of the total production costs were provided by the customer, but some extra costs, such as maintenance and service, are based on confidential sources by personal permission. **Table 5.3** shows the yearly production of the two products.

Table 5.3 *The yearly production of the end products for the iron ore C&S plant.*

Item	Product	MTPY	%
P_1	5–20 mm	4 124 250	63.4
P_2	0–5 mm	2 375 750	36.6
	Total	6,500,000	100

5.3.2 Capital costs

Capital costs per year can calculated in different ways, for example, by the net present value method (NPV) or by the equivalent annual cost method (EAC) [61, 62]. In this dissertation, I have used the EAC method as equivalent annual capital cost ($EACC_j$) for machine/equipment j.

Since the machines/equipment in a C&S plant have very different technical lifetimes, the EAC method makes the calculation of the capital costs, as money per year, a little easier as most of the other production costs are annual.

The major capital costs k_{0i} for product i will be:

$$EACC_i = \sum_{j=1}^{j=N_m} a_{fj} \cdot AK_{j,i} \cdot \left[K_{0j} - \frac{R_{nj}}{NPV_{fj}}\right] \qquad \textit{Equation 5.3}$$

where

K_{0j} is the investment cost for machine/equipment j,
R_{nj} is the residual value for machine/equipment j at year n,
a_{fj} is annuity factor for equipment j as $a_{fj} = \frac{p}{(1-(1+p)^{-n})}$,when $p > 0$ %.
NPV_{fj} is the net present value factor for machine/equipment j at year 0
$NPV_{fj} = \frac{p}{(1-(1+p)^{-n})}$ when $p > 0$ %,
p is the interest rate
n is the technical lifetime of equipment j
N_m is the number of major machines.

The normal technical lifetime, n, applies when the machine is loaded during its entire technical lifetime. If the machine has lower load, this will increase the overall technical life of the machine.

If the interest rate is 0 %, then $a_{fj} = 1/n$ and $NPV_{fj} = 1.0$. Then using $AK_{j,i}$ the allocation key at equipment j for product i, the capital costs for each product i will be:

Uptime:
$$k_{0iupt} = U_{RP} \cdot \sum_{j=1}^{j=N_{m,i}} AK_{j,i} \cdot EACC_j \qquad \textit{Equation 5.4}$$

Downtime: $$k_{0idwt} = (1 - U_{RP}) \cdot \sum_{j=1}^{j=N_{m,i}} AK_{j,i} \cdot EACC_j$$ *Equation 5.5*

Table 5.4 provides an example of an allocation matrix.

***Table 5.4** Example of an allocation matrix for calculating AK values for Pn products in a plant with N_m machines.*

Product	N_1	N_2	N_3	N_4	N_j	. . .
P_1	1.0, MT_{11}	1.0, MT_{21}	0			
P_2	1.0, MT_{12}	1.0, MT_{22}	1.0, MT_{32}	0		
P_3	1.0, MT_{13}	1.0, MT_{23}	1.0, MT_{33}	1.0, MT_{43}	0	
P_i	1.0, MT_{1i}					
. . .						
P_{np}						

Table 5.5 presents the equivalent annual capital costs (EACC).

One of the main factors in the annual capital cost is the interest rate. This rate is normally specific to each country and can differ significantly depending on the company itself [83]. **Figure 5.14** shows annuity factors for normal technical lifetimes (2–10 years) for machines/equipment in C&S. The cost of capital dominates if the equipment has a short lifespan, as illustrated by the accompanying diagram.

***Table 5.5** Equivalent annual capital costs for product P_1 and P_2, with interest rate 5 %.*

Section	**Machine or equipment**	**EACC P_1 (USD)**	**EACC P_2 (USD)**
A	C1, others	364 046	209 707
B	C2, S1, others	526 319	303 183
C	C3, S2, others	378 629	218 807
D	S3, others	80 166	46 179

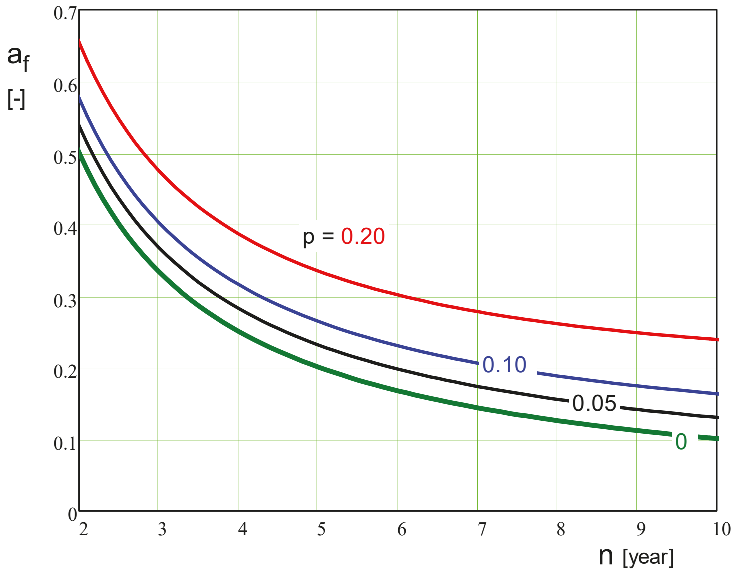

Figure 5.14 *Annuity factors for different technical lifetimes and different interest rates.*

Normally production systems time can be divided into uptime and downtime. Uptime is when the plant is working and available. When at least one parallel process line is working in a plant with parallel process lines, it is still considered to be in uptime. However, the work time needs to be reduced according to the proportion of the parallel process lines operating. Downtime is the opposite of uptime and is counted when the plant is unavailable. The annual capital costs are then distributed in accordance with the C&S plant utilization in uptime and downtime. The working time is only counted when the C&S plant is producing end products.

5.3.3 Dynamic costs during operation and downtime

All dynamic costs, such as cost of WP (wear parts), SP (spare parts), TO (Tools) and power are added. Thus the dynamic costs of uptime as follows:

$$k_{wp_i} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{wpj}$$ *Equation 5.6*

$$k_{sp_i} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{spj}$$ *Equation 5.7*

$$k_{to_i} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{toj}$$

Equation 5.8

and

$$k_{pow_i} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot T_{plan} \cdot k_{enj} \cdot k_{kwh} \cdot \left(1 - D_j\right) \cdot U_{RP}$$ *Equation 5.9*

Table 5.6 shows the annual cost for WP, SP, TO, and power for the main machines.

***Table 5.6** Examples of annual costs of WP, SP, TO, and power for two products, P_1 and P_2.*

Sec-tion	**Machine**	**WP P1**	**WP P2**	**SP P_1**	**SP P_2**	**TO P_1**	**TO P_2**	**EN P_1**	**EN P_2**
		($/y)	**($/y)**	**($/y)**	**($/y)**	**($/y)**	**($/y)**	**($/y)**	**($/y)**
A	C1	42 180	24 297	59 052	34 016	10 123	5 831	281 199	161 983
B	C2	73 112	42 116	146 223	84 231	21 934	12 635	303 934	174 702
B	S1	1 692	975	740	426	430	140	50 616	29 157
C	C3	44 992	25 917	89 984	51 835	13 498	7 775	151 847	87 471
C	S2	2 538	1 462	1 079	621	362	208	56 240	32 397
D	S3	4 061	2 339	1 700	980	576	332	47 804	27 537

The only dynamic cost during downtime is the idle power used ($k_{enid,j}$).

$$k_{CSdyn,_i} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot T_{plan} \cdot k_{enid,j} \cdot k_{kwh} \cdot \left(1 - D_j\right) \cdot U_{RP}$$ *Equation 5.10*

5.3.4 Salary costs

According to earlier sections the salary costs may be distributed in the same proportion as the main machines as shown in **Table 5.7**.

This C&S plant runs around the clock 365 days per year ≈ 7,800 operating hours per year. With three shifts per day, they employ five operators and one manager per shift, plus two extra workers (one shift per day, five days per working week) for larger maintenance and services. This gives almost 6.5 workers per shift around the clock for the full year.

***Table 5.7** Distribution of salary costs.*

Section	**Machines**	**Salary allocation**	**Salary costs P_1 ($/y)**	**Salary costs P_2 ($/y)**
A	C1, F1	0.15	96 495	55 586
B	C2, S1, F2	0.38	244 455	140 817
C	C3, S2, F3	0.35	225 156	129 700
D	S3 A&B	0.12	77 196	44 469

In general, the salary cost allocated to each final product i can be described as:

$$K_{D,_i} = AK_{g,i} \cdot \frac{N_{m,i}}{\sum N_{m,j}} \cdot \frac{n_{op} \cdot k_D \cdot T_{plan}}{\sum_{i=0}^{i=n_p} MT_{Pi}} \qquad \textit{Equation 5.11}$$

In this case, there are no auxiliary costs on record. However, the general auxiliary cost equation for each end product will be:

$$K_{aux,_i} = AK_{g,i} \cdot \sum_{1year} k_{aux} \qquad \textit{Equation 5.12}$$

5.3.5 Cost example of product P_1 and P_2

Then all elements for P_1 and P_2 are added together.

P_1 =	**4 124 250 MTPY**	3 398 069 US$/y
P_2 =	**2 375 730 MTPY**	1 957 438 US$/y

The final production costs for P1 and P2 will be 5,355,507 US$/year. That will give the production cost of 0.82 USD/t, equal for both products due to they are extracted both at the last section of the C&S plant.

The costs per section of the C&S plant is presented in **Figure 5.15** below.

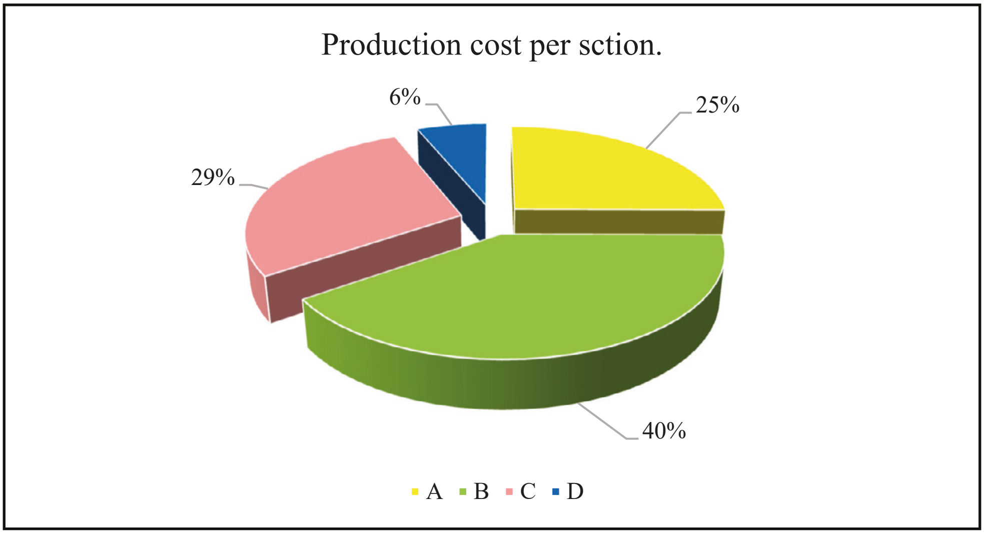

Figure 5.15 *The costs per section of the C&S iron ore plant.*

The low abrasion index for this magnetite ore increases the life of the wear parts by 3–4 times the normal lifetime and reduces the WP costs to the same extent.

5.3.6 Cost conformity, CF

The CF is defined in appendix I as,

CF = (Calculated production costs)/(Actual production costs)

The values of CF are shown in **Table 5.8.**

Table 5.8 *The conformity for P1, P2 and total in relation to available customer information.*

CF – P1	CF – P2	CF – Total
≈1.13	≈ 1.14	≈ 1.14

The total CF is just below the conformity of P_2 as P_2 is the dominant product produced.

5.4 The improved PCCM model

The revised PCCM now consists of four main parts.

Production costs =
Production costs during uptime
+ ***Production costs during downtime***
+ ***Salary costs***
+ ***Auxiliary costs***

The uptime costs include capital and the dynamic production costs.

Downtime capital costs include all costs for power consumed by machine/equipment during the downtime period.

Payroll costs include the salary costs for all personnel directly bound for the C&S plant operation such as operators, operation shift supervisors, service and maintenance workers, C&S plant manager, and C&S plant administrators.

Auxiliary costs include cost of raw material, costs for rent of land and buildings, cost of energy for lighting and heating, cost of shared resources (common resources with other activities), environmental costs, site security costs, site preparation costs and restoration costs.

5.4.1 Production costs during uptime

Cost for the process CP, during uptime, for product P_i, can be calculated as:

$$k_{CP,_{Pi}} = \frac{k_{0iupt}+k_{CPdyn,Pi}}{T_{plan} \cdot MT_{ph,Pi}}$$ *Equation 5.13*

Where the capital costs, k_{0iupt}, are calculated based on EACC, according to Equation 5.4 and the dynamic production costs for product P_i will be calculated as:

$$k_{wp,_{Pi}} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{wpj}$$ *Equation 5.14*

$$k_{sp,_{Pi}} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{spj}$$

Equation 5.15

$$k_{to,Pi} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{to,j}$$

$$k_{pow,Pi} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot T_{plan} \cdot k_{en,j} \cdot k_{kwh} \cdot (1 - D_j) \cdot U_{RP}$$

Equation 5.16

Equation 5.17

And

$$k_{CPdyn,_{Pi}} = k_{wpPi} + k_{spPi} + k_{toPi} + k_{powPi}$$ *Equation 5.18*

5.4.2 Production costs during downtime

The major production cost during downtime $k_{CS,Pi}$ is the part of the EACC according to q_S, D, and U_{RP}:

$$k_{CS,_{Pi}} = \frac{k_{0idwt} + k_{podtwi}}{T_{plan} \cdot MT_{ph,Pi}}$$ *Equation 5.19*

where k_{podtwi} is the cost during downtime for idle power used.

5.4.3 Payroll and auxiliary costs

The salary cost, k_{DPi}, is calculated for product P_i as:

$$k_{D,_{Pi}} = AK_{gi} \cdot \frac{\sum_{t=0}^{t=T_{plan}} n_{op} \cdot k_D}{T_{plan} \cdot MT_{ph,Pi}}$$ *Equation 5.20*

The allocation of salary costs to each main machine/equipment can be made in relation to the proportion of main machines as $j_{\text{main}} / \sum j_{\text{main}}$, but other allocation keys can be used, such as the proportion of power used in the main machines/equipment.

The auxiliary k_{aux} cost for the product P_i is calculated as

$$k_{aux,_{Pi}} = AK_{gi} \cdot \frac{K_{aux}}{T_{plan} \cdot MT_{ph,Pi}}$$ *Equation 5.21*

K_{aux} is the sum of all auxiliary costs per year.

The allocation of the auxiliary costs toward each end product can be done in several ways. The allocation keys for each end product can be in proportion to each of the end products, in proportion of main machines/equipment used, or in proportion to the area used by the main machines/equipment.

Then total cost k_{Pi} for processing product P_i per ton can be calculated as:

$$k_{Pi} = k_{CP,Pi} + k_{CS,Pi} + k_{D,Pi} + k_{aux,Pi} \qquad \textit{Equation 5.22}$$

5.5 Conclusion

The improved product calculation model

- Covers C&S plants with one and/or several end products.
- The main subproduct costs are
    - Production uptime costs
    - Production downtime costs
    - Payroll costs
    - Auxiliary costs
    - The main subproduct cost items can consist of one or several sub-subcost items.
- Can distribute the production costs to each and every end product by using allocation keys. But there are no definitely and/or establish models on how to create correct, proper, and fair allocation keys to distribute the production costs to the end products, as discussed in section 5.2.4.

6. Model Verification

In this chapter the PCCM calculation model is tested against five existing C&S plants to assess the conformity between the actual values provided and calculated values. Of these five cases, two are mining C&S plants and three are construction C&S plants. Thereafter, the PCCM is used on one simulated C&S circuit with two alternatives to find the alternative with the lowest special production costs. The production costs in earlier sections have been converted from local currency to US $, in order to compare the values given by customers and calculated or simulated values. This will make it possible to compare different applications from different places in the world.

6.1 Prerequisites and assumptions

In many technical and economic contexts, it can be difficult to compare actual outcomes and calculations due to factors such as data uncertainty, interpretation of data, depreciation rules, and varying practices. The verification below is based on comparing calculated and simulated production costs with real production costs or data provided by customers or users of C&S plant for calculate the real production costs.

The author has as far as possible used the same input data in the form, for example, of capital costs and equipment life made in the applications studied. In some cases, this has not been possible due to confidentiality or difficulties in accessing current information. In these cases, the most common data in the industry have been used.

The author also wishes to clarify that data obtained from customers or users of C&S facilities should not be regarded as exact but as probable and reasonable guidelines.

Moreover, I have not separately validated costs, data and facts, obtained from the customer or C&S plant users.

6.2 C&S iron ore plant, product 0–16 mm

This C&S plant produces one end product sized 0–16 mm from blasted iron ore of the hematite type. The plant is in a region that has monsoon rains for one month each year, which reduces the utilization of the C&S plant [22, 25, 65, 66, 67, 68, 69].

The plant operates two shifts per day all year round, except during the monsoon period. During that period, the plant can produce for only one quarter of the available time.

Operating properties:

- Two eight hour shifts per day
- Working week 5 days, all year round
- Annual production 2 million tons
- Product fines 0–16 mm

The flowsheet for this C&S plant is shown in **Figure 6.1**.

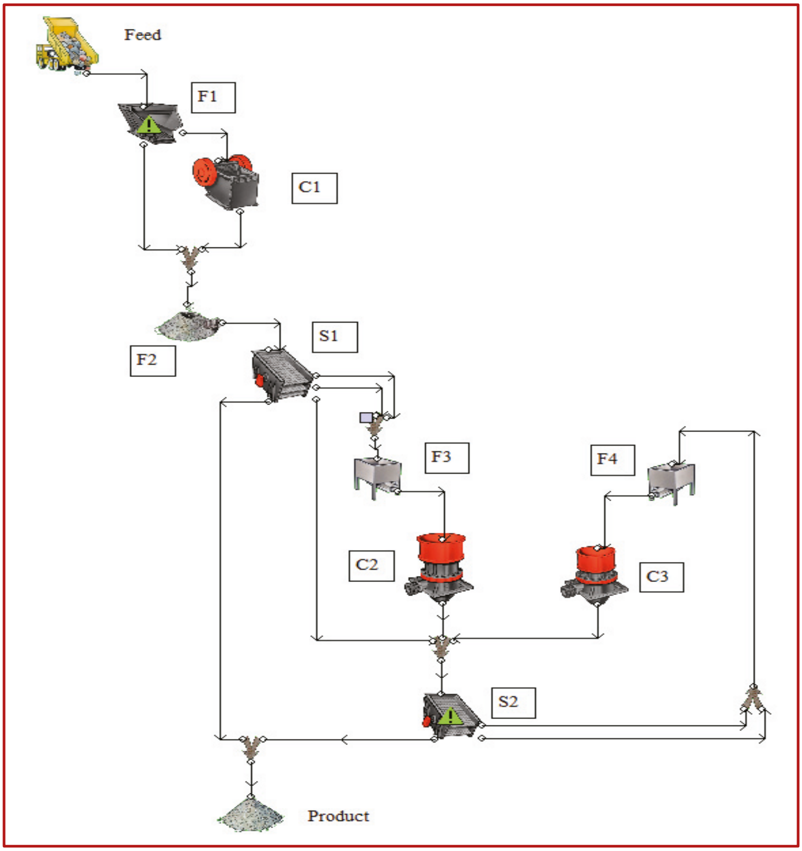

Figure 6.1 *The flowsheet for the 0–16 mm iron ore C&S plant (CSP 3).*

The ore is fed into the hopper of the grizzly feeder F1 by dump trucks. The grizzly feeder has a screen deck that scalps coarse material and fine material. The coarse material is pre-crushed in crusher C1. The crushed product from C1 and the fines from the screen deck on the grizzly feeder are combined and conveyed to a surge pile with a feeder in the bottom. The material from the surge pile is transported to a three-deck screen S1 where the coarse material is fed to a surge bin with a feeder. Intermediate material bypasses crusher C2 and the fine material is transported to the product stockpile. The coarse material is crushed in open circuit in crusher C2.

Intermediate material and material crushed in C2 are fed to a double-decked screen S2. There the coarse material from both the first and second decks is crushed in C3, which is also in closed circuit with screen S2. The fines from S2 are transported to the product stockpile.

The plant is quite old and, according to the customer, fully depreciated. The only equipment costs/capital costs are when some equipment stops working completely. However, in my opinion, the customer is confusing capital costs with depreciation costs, two different budgetary approaches. Capital costs are costs required to buy an item of equipment when its technical life ends. Depreciation costs are a way of reporting that it costs money to buy an asset today and replace it in the future. These depreciation costs follow the tax rules in each country.

6.2.1 Actual identified production costs

The data for production cost obtained from the customer are shown in **Table 6.1**.

***Table 6.1** Product costs according to customer.*

Item	**Cost** (US$/t)	**Remarks**
Equipment	0.00	See my comments above
WP, SP, TO	0.32	
Power	0.11	
Salary	0.09	
Auxiliary	0.10	
Total	0.62	Low, due to no equipment costs

6.2.2 Calculated production costs in Appendix F3.

Table 6.2 shows manufacturing costs obtained for the production of iron ore sized 0–16 mm by using the developed PCCM.

***Table 6.2** Calculated product costs based on PCCM (Appendix F3).*

Item	**Cost** (US$/t)	**Remarks**
Equipment	0.38	Interest rate 5 % (*)
WP, SP, TO	0.35	
Power	0.15	
Salary	0.10	
Auxiliary	n.a.	Lack of information
Total	0.98	Low, due to no auxiliary costs

(*) The selection of 5 % comes from 2018 in the country where the C&S plant is located [80].

The conformity equation (calculated product cost)/(actual product cost) gives

$$CF_a = 0.98/\ 0.62 = 1.59$$

Without capital and auxiliary costs:

$$CF_b = 0.60/\ 0.52 = 1.15$$

This first example shows the difficulties of comparing obtained and calculated values if not all costs are sampled and recorded. Inspection showed that two important cost items were not included in the values received from the user of the C&S plant. Despite adjusting the input data, the deviation is relatively large, which may possibly be explained by how personnel costs are distributed between different processing steps.

6.3 C&S plant in copper mine, 1/4" product

The C&S plant produces 0–¼" fines from blasted copper ore with an annual production of 3,000,000 t/year. The C&S plant operates 4,000 h per year, normally with two shifts per day, all year round [22, 25, 65, 66, 67, 68, 69]. The general process flow is shown in **Figure 6.2**.

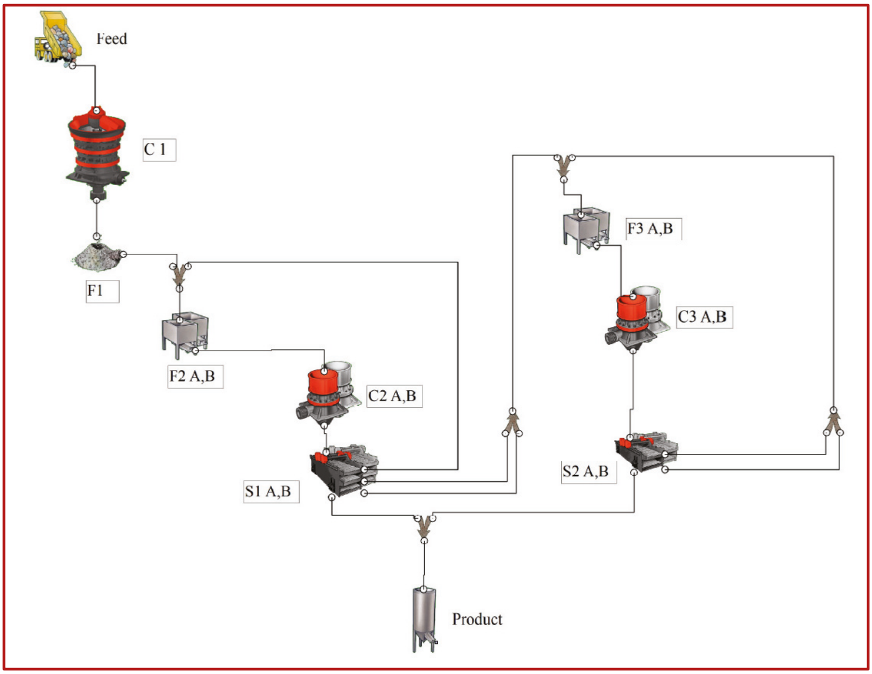

Figure 6.2 *The flowsheet for the 0–¼" copper ore C&S plant (CSP4).*

The blasted Cu ore is fed to the dump hopper of the primary crusher, C1, by mining trucks. The blasted ore is crushed in open circuit in crusher C1. The primary crusher's product is conveyed to a big surge pile with tunnel feed below. This surge pile takes up the material flow fluctuation and uses the tunnel feeders to even out the flow to the second crushing stage. Ahead of the second crushers (C2 A & B) there are two surge bins with feeders to achieve choke feeding conditions to the crushers C2 A & B. The C2 crushers run in closed circuit with two parallel three-deck screens, S1 A & B. The coarse material from the top decks is recirculated to C2 A & B. The intermediate products from decks 2 and 3 are combined and transported for further treatment. Fines from screens 1 A & B are transported to the end product silo. The intermediate product from S1 A & B is crushed in closed circuit in crushers C3 A & B, that have two surge bins with feeders ahead of them. These crushers run in closed circuit with the two-deck screens S2 A & B. Coarse and intermediate material from the screens S2 A & B is recirculated to crushers C3 A & B. The fines from screen S2 A & B are transported to the end product silo.

6.3.1 Given production costs for plant CSP 4

In this C&S plant the given production costs come from both the customer and Sandvik's plant information database [25].

***Table 6.3** Actual product costs related to the copper ore C&S plant according to customer and Sandvik [25].*

Item	**Cost** (US$/t)	**Remarks**
Equipment	0.61	
Dynamic product costs	0.56	
Salary	0.16	
Total	1.33	

6.3.2 Calculated production costs

Calculations based on the PCCM give production costs in **Table 6.4**.

***Table 6.4** Calculated product costs based on PCCM (Appendix F4).*

Item	**Cost** (US$/t)	**Remarks**
Equipment	0.72	Interest rate 2.5 % (*)
Dynamic product costs	0.60	
Salary	0.17	
Total	1.49	

(*) The selection of 2.5 % comes from 2019 in the country where the C&S plant is located [80].

The conformity equation gives:

$$\boxed{CF = 1.49/\ 1.33 = 1.12}$$

In this case, the deviations are primarily due to equipment costs and assumed values of the interest rate p. By assuming values of p between 1 and 5 %, the conformity varies between 1.1 and 1.20.

6.4 Mobile C&S plant with three products

This case investigates a mobile C&S plant, which moves around to different sites and jobs, producing three end products. It is designed for capacities between 100 to 300 MTPH, depending on feed particle size distribution, type of rock, and the requirements of the end products [22, 24, 25, 65, 66, 67, 68, 69]. The present setup specifications are:

- Feed material, sand, and gravel 0–300 mm
- Estimated annual production 250,000 ton
- Three products, coarse (P1), intermediate (P2), and fines (P3).

The three mobile C&S units are run by two operators who also handle loading and unloading of the C&S plant. They run and control the C&S plant using automation and remote controls in their wheel loaders.

The flow sheet for the mobile C&S plant is shown in **Figure 6.3**.

This type of mobile C&S plant is designed to be moved and set up at different locations with different production and different product requirements, it seldom runs at the same site producing the same products all year round. I have calculated an assumed annual production by extending the present setup and requirements to a full year.

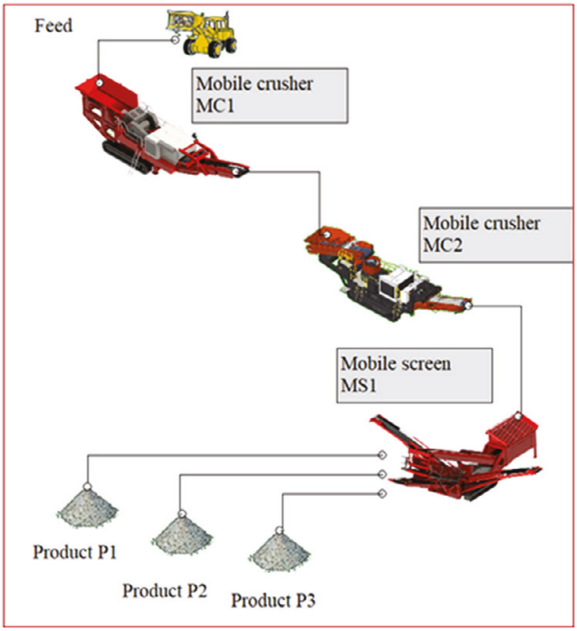

Figure 6.3 *The flowsheet of the mobile C&S plant (CSP 5).*

The sand and gravel material is fed into the feed hopper of the first mobile crusher by a wheel loader. This unit has a grizzly feeder and a jaw crusher onboard. The grizzly feeder separates coarse and fines. The coarse material is crushed in the jaw crusher and then recombines on the discharge conveyor with the fines from the grizzly that bypassed the crusher. The discharge conveyor sends the material to the feed hopper of the feed conveyor on the second mobile crushing unit. All material is crushed in the secondary crusher and conveyed to the feed hopper of the mobile screening unit. The screening unit has a two-deck screen that separates the coarse, intermediate, and fine materials. The separated products are conveyed to stockpiles.

6.4.1 Given production costs for plant CSP 5.

Table 6.5 displays the compiled and structured data. The figures are based on actual production data costs, coming from both the customer and Sandvik's plant information database [25].

Table 6.5 *Actual product costs according to customer and Sandvik [25].*

Item	**Cost** (SEK/t)	**Remarks**
Equipment	4.22	The customer normally sells his mobile units abroad after approximately five years'

		operation. He tries to recoup ≈ 50 % of the original price paid for the units.
Dynamic product costs	4.15	
Salary	n.a.	The customer will not divulge salaries to protect the privacy of the only two employees involved.
Auxiliary	n.a.	
Total	8.37	Excluding salary and auxiliary costs.

6.4.2 Calculated production costs

The PCCM production costs are set out in **Table 6.6**. In this case all products are extracted from the last stage of the plant. Allocation keys were used according to the proportion of the final products produced.

Excluding the salary costs and using the high and low values for the production costs, the conformity can be calculated as:

$$\boxed{CF = 9.58 / 8.37 = 1.14}$$

However according to the PCCM calculations in this the specific case, the salary cost is in the range of 40 % of the total production cost, which is a substantial part, see Appendix F3. Salary costs should always be included to obtain sufficient accuracy in determining or calculating total production costs. But in this case the Salary and the Auxiliary costs were not ed out by the customer.

For this plant, the PCCM overestimates the dynamic production costs compared to the cost given by the customer and Sandvik’s plant information database [25].

***Table 6.6** Calculated product costs based on PCCM.*

Item	**Cost** (SEK/t)	**Remarks**
Equipment	4.98	Assuming equipment sold after five years recoups 50 %. Interest rate of 1.0 % (*)
Dynamic product costs	4.60	
Salary	3.47	
Auxiliary	n.a.	
Total	9.58 13.05	Excluding salary & auxiliary costs Excluding auxiliary costs

(*) The selection of 1 % comes from 2019 in the country where the C&S plant is located [80].

If only the dynamic costs are considered, PCCM achieves a better consistency between the actual costs and the estimated costs.

6.5 C&S plant 500 MTPH with six products

This is a fixed C&S plant with annual production of 750,000 t with six products [22, 25, 65, 66, 67, 68, 69]. The production during the year depends on market activity but we have obtained the average normal production for this plant. Product P1 is quarry fines that are directly removed as "sand" for private users/customers. This "sand" is of low quality and cannot be upgraded. Product P2 is railway aggregates, with high shape requirements. The remaining products P3 – P6 are used as construction aggregates for concrete or asphalt.

Specifications:

- Operating time of 2,000 h/year
- Located in central Europe
- 1 shift per day of 8 hours
- Working week 5 days
- Annual production 750,000 t
- Product sizes 0–64 mm.

Figure 6.4 shows the main process flow.

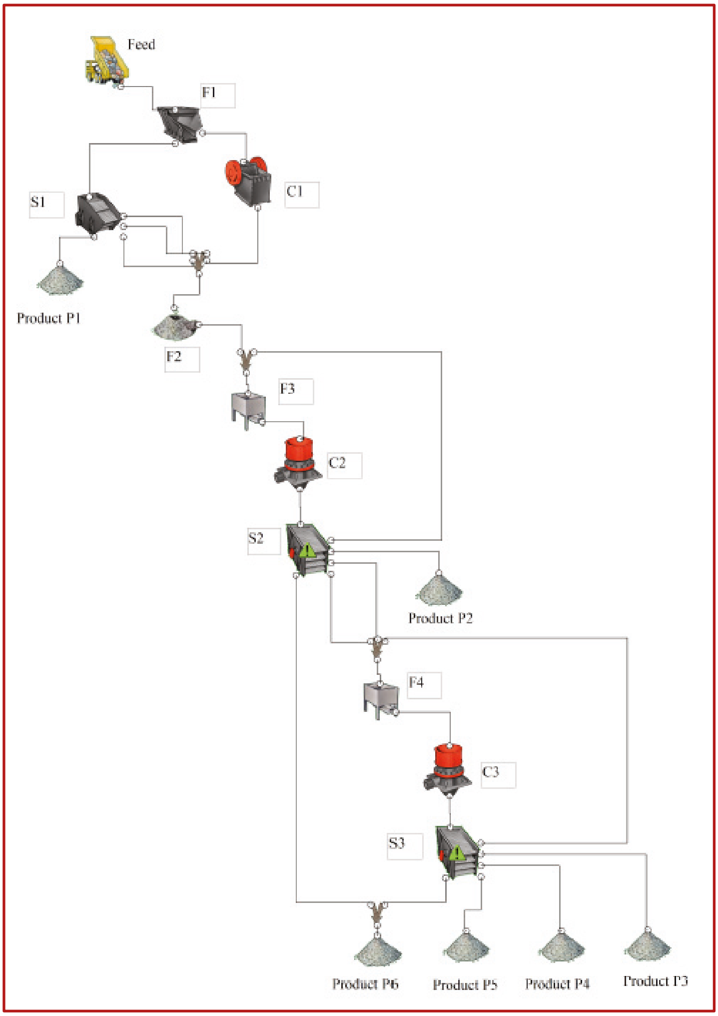

Figure 6.4 *The flowsheet of the fixed C&S plant (CSP 6).*

The blasted rock is loaded into the feed hopper of the grizzly feeder by 50 ton trucks. The blasted rock is separated into coarse and fines by the grizzly screen deck. The fines are conveyed to a screen, S1, that removes the quarry fines and intermediate material. Quarry fines are conveyed to a stockpile as product P1. The coarse material from the grizzly screen deck is crushed in the crusher C1. This crushed product is added to the intermediate material from S1 and conveyed to a surge pile with tunnel feeder. From the surge pile the material is transported conveyor to a surge bin with feeder, ahead of the crusher C2. C2 runs in closed circuit with a four-deck screen, S2. The coarse material from deck 1 is re-crushed in C2. The material from deck 2 is conveyed to a stockpile as product P2. The intermediate material from S2 is conveyed to a surge bin with feeder ahead of crusher C3. The fines from S2 are transported directly to the stockpile for product P6. C3 runs in closed circuit with a four-deck screen, S3. The coarse material from deck 1 is re-crushed in C3. All the other materials from the S3 are conveyed to their own stockpile as products P3, P4, and P5. The fines from S3 are conveyed to the same stockpile as the fines from S2, product P6.

6.5.1 Given production costs for plant CSP 5

Table 6.7 shows the compiled and structured data. The figures are based on actual production data costs, coming mainly from the customer and also from Sandvik's plant information database [25].

Table 6.7 *Actual product costs according to customer and Sandvik [25].*

Item	**Cost** (€/ton)	**Remarks**
Equipment	0.51	(*)
Dynamic product costs	0.48	
Salary	0.40	
Total	1.39	Excluding auxiliary costs

(*) Information from the customer's financial department. However, I think this capital cost is the depreciation cost that they use in the annual report. I have divided this cost by the annual C&S plant production to determine the cost per ton produced.

6.5.2 Calculated production costs

The production costs calculated using the PCCM are shown in **Table 6.8**. In this case products will be extracted from the different C&S stages of the plant using appropriate allocation keys.

Table 6.8 *Calculated product costs based on PCCM (Appendix F6).*

Item	**Cost** (€/ton)	**Remarks**
Equipment	0.63	Interest rate 2.0 % (*)
Dynamic product costs	0.51	
Salary	0.38	
Total	1.52	Excluding auxiliary costs

(*) The selection of 2 % comes from 2019 in the country where the C&S plant is located [80].

The conformity between actual costs and PCCM based costs can be calculated as:

$$\boxed{CF = 1.52/\ 1.39 = 1.10}$$

In this case, the discrepancy between actual and estimated costs can be attributed primarily to equipment costs.

6.6 C&S plant 200 MTPH with four products

This C&S plant is in South Asia producing four construction aggregate products P1–P4 with annual production of 450,000 t in the range 0–19 mm [22, 25, 65, 66, 67, 68, 69]. The operating time per year is 3,000 h, on an extended shift of 12 h/working day. The C&S plant process flow sheet is shown in **Figure 6.5**.

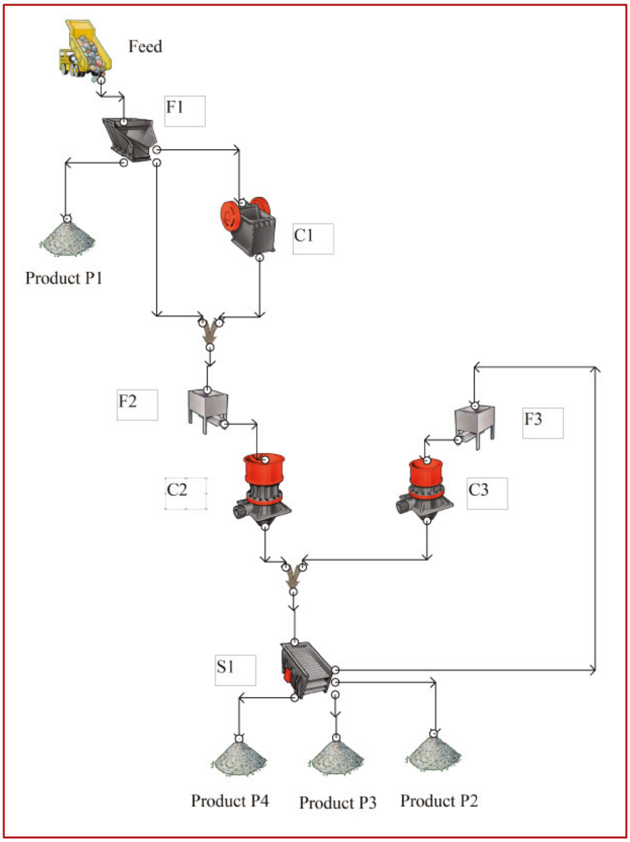

***Figure 6.5** The flowsheet of the C&S plant (CSP 7).*

The blasted rock is transported from the quarry face to the C&S plant by dumpers. The rock is fed into the grizzly feed hopper. The grizzly feeder has two decks to separate the blasted rock. The top deck is a grizzly where coarse material is passed over. The fines that fall through the grizzly are then separated into two products, intermediate and quarry fines on the second deck of the grizzly feeder. The coarse material from the grizzly deck is crushed in crusher C1. The intermediate material bypasses the crusher C1 and combines with the product from crusher C1. The quarry fines from the second deck are conveyed to a stockpile as product P1. The intermediate material and the product from C1 are conveyed to a surge bin with a feeder that supplies crusher C2 which runs in open circuit. Product from C2 is conveyed to the three-deck screen S1. The coarse material from the top deck is crushed in closed circuit in crusher C3. The product from C3 is conveyed back to screen S1. The coarse material from deck number two is conveyed to a stockpile as product P2. The material that passes over deck three is conveyed to a stockpile as product P3<. The material that passes through deck number 3 is conveyed to a stockpile as product P4.

6.6.1 Given production costs for plant CSP 7

The facts and figures for the actual production data costs come mainly from the customer and tests. Some additional information has been drawn from [25].

***Table 6.9** Actual product costs according to customer and Sandvik [25].*

Item	**Cost** ($/ton)	**Remarks**
Equipment	0.4	Estimated and calculated by information from customer
Dynamic product costs	0.8	Estimated and calculated by information from customer
Salary	0.3	Estimated and calculated by information from customer
Total	1.5	Excluding auxiliary costs

6.6.2 Calculated production costs

Table 6. shows the production costs using the PCCM. In this case products are extracted from the different C&S stages of the plant, using different allocation keys.

***Table 6.10** Calculated product costs based on PCCM (Appendix F7).*

Item	**Cost** ($/ton)	**Remarks**
Equipment	0.60	Interest rate 5 % (*)
Dynamic product costs	0.88	
Salary	0.31	
Total	1.79	Excluding auxiliary costs

(*) The selection of 5 % comes from 2019 in the country where the C&S plant is located [80].

In this case the conformity could be calculated as:

$$\boxed{CF = 1.79/ 1.5 = 1.19}$$

Even in this case the main discrepancy between actual and estimated costs can be attributed primarily to equipment costs.

As the actual production costs were estimated using information from the customer, these values are less accurate than the actual cost values from the other C&S plants. Accordingly, not too many conclusions should be drawn regarding production costs from this C&S plant.

6.7 Applications related to selection of C&S plant

Finally, this chapter shows an example of a simulated C&S plant with two alternatives where PCCM is used to determine which process alternative gives the lowest production costs [22, 24, 65, 66, 67, 68, 69].

Properties:

- Pre-crushed copper ore – 40 mm
- Product 0–10 mm
- Design capacity 400 MTPH

In this case we consider only the machines/equipment that are different, mainly the crushers and the feeders. The two flowsheets are shown in **Figure 6.6**.

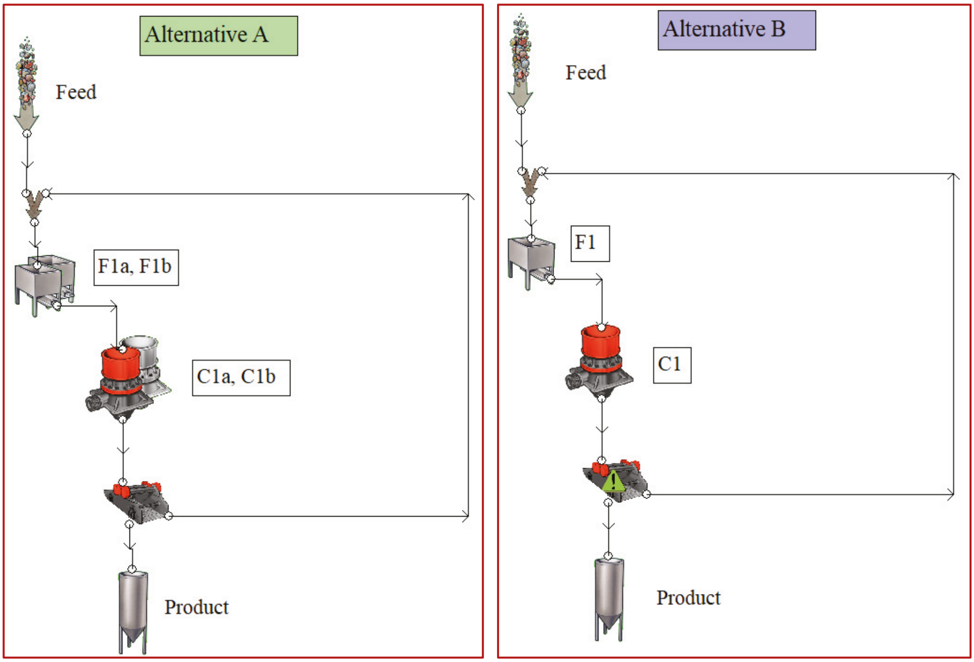

***Figure 6.6** The two flowsheets for alternative A and B (CSP 8).*

The pre-crushed ore is fed into the surge bin(s) with feeder(s). The feeder(s) feed the crusher(s) that run in closed circuit with a one-deck vibrating screen. The coarse material from the screen is fed back to be re-crushed, while the fines are transported to the product silo.

6.7.1 Production costs for alternatives A and B, special cost

Alternative B with one larger crusher is a little more cost effective than alternative A with two smaller crushers. An annual saving of approximately 50,000 USD is indicated when producing 1.25 million ton per year. This is mainly because the operating cost for the big machine is less than operating the two smaller parallel running crushers, as shown in **Table 6.**.

***Table 6.10** Calculated special product costs for alternative A and B.*

Item	**Product Cost** ($/t) **Alternative A**	**Product Cost ($/t) Alternative B**	**Remarks**
Equipment	0.45	0.46	Interest rate 5 % (*)
Dynamic product costs	0.55	0.50	
Total special product cost	1.00	0.96	

(*) The selection of 5% interest rate comes from the country where the C&S equipment will be located and is valid for the application year 2019 [80].

In this example PCCM is used as a rapid economic evaluation of two equivalent technical alternative solutions. The joint costs were excluded and only the specific costs for the alternatives were used in the evaluation to find the alternative with the lowest product costs.

6.8 Conclusions from the case studies conducted

Calculations made with PCCM consistently provide a higher cost than data obtained from the customers concerned and Sandvik's database [25], that is, conformity CF > 1.0. This result can be explained by the fact that PCCM considers more cost items than the other sources do. Another factor contributing to deviations is that PCCM considers initial equipment costs K_0 over the entire lifetime of the equipment, including renovations. Many customers base their cost calculations on accounting depreciation costs. Recognizing this should lead to a reduction in the differences between costs and result in a better calculated conformity.

The interest rate p on the cost of capital can vary greatly between companies and regions. As a result, the cost of capital can contribute to large differences between different applications even if the conditions are similar.

The case studies show how difficult it can be to compare calculated production costs and calculated or measured input parameters. This result also shows how important it is to have a complete and detailed cost model with well-defined inputs for the PCCM. The model enables a secure cost comparison between different equipment choices and different applications.

The actual production costs that are reported and delivered by the customers depend on the customers' willingness to share and report their production costs. In this dissertation, I have reported as actual production costs what the customers have reported to me. I have not validated the facts obtained from the customers.

7. Discussion and Conclusions

This chapter discusses the results achieved by using the PCCM. Conclusions are drawn, and then the two research questions are answered.

7.1 Development

The production cost calculation model PCCM consists of four main parts:

Production costs = Production costs during uptime
+ Production costs during downtime
+ Salary costs
+ Auxiliary costs

that is,

$$k_{Pi} = k_{CP,pi} + k_{CS,Pi} + k_{D,Pi} + k_{aux,Pi} \qquad \textit{Equation 7.1}$$

The k_{Pi} result obtained through the PCCM calculation is cost per product per ton of the end product(s), for example, €/t, $/t, SEK/t. Each of these four main parts of the PCCM can contain one or several subcost items, and in each of these there can be one or several underlying minor cost items.

The structure of the cost model developed has maintained the same form as the original standard Ståhl model [28, 35]. This is despite of the fact that most of the cost components are different from the discrete model based on the cycle time t_0.

The main cost items included in the production cost during uptime are:

- Capital costs (utilization, as available time ratio)
- Dynamic production costs such as WP costs, SP costs, TO costs and energy costs

The main cost items included in the production cost during downtime are:

- Capital costs (utilization, as unavailable time ratio)
- Idling energy costs in machines/equipment when the C&S plant or part of it is out of production

The main cost items included in the payroll costs are:

- Cost of operators
- Cost of team managers
- Cost of plant manager and management staff (as part or whole)

- Cost of service and maintenance personnel associated with the C&S plant (as part or whole)
- Cost of additional personnel belonging to or used by the C&S plant (as part or whole)

The main auxiliary costs are:

- Cost of raw material
- Renting costs of land and/or buildings
- Costs for the security and protection of the C&S plant
- Shared costs, common resources used by both the C&S plant and other activities
- Costs of cooling, heating, and lighting
- Environmental costs
- Cost of fees and taxes
- Site preparation and site restoration costs

When the C&S plant produces only one end product, the payroll costs can be distributed, if necessary, using allocation keys associated with each machine. If the C&S plant produces more than one end product, allocation keys AK_{ji} are used to distribute the production costs of uptime and downtime for the machines/equipment, payroll and auxiliary between the end products.

Thus, the refined and revised PCCM model will be based on:

$$k_{CP,Pi} = \frac{k_{0iupt} + k_{CPdyn,Pi}}{T_{plan} \cdot MT_{ph,Pi}} \tag*{Equation 7.2}$$

$$k_{wp,_{Pi}} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{wpj} \tag*{Equation 7.3}$$

$$k_{sp,_{Pi}} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{spj} \tag*{Equation 7.4}$$

$$k_{to,Pi} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{to,j} \tag*{Equation 7.5}$$

$$k_{to,Pi} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot k_{to,j}$$

$$k_{pow,Pi} = \sum_{j=1}^{j=N_m} AK_{j,i} \cdot T_{plan} \cdot k_{en,j} \cdot k_{kwh} \cdot \left(1 - D_j\right) \cdot U_{RP} \tag*{Equation 7.6}$$

and

$$k_{CPdyn,_{Pi}} = k_{wpPi} + k_{spPi} + k_{toPi} + k_{powPi} \tag*{Equation 7.6}$$

then:

$$k_{CS,Pi} = \frac{k_{0idwt}+k_{podtwi}}{T_{plan}\cdot MT_{ph,Pi}} \tag*{Equation 7.7}$$

$$k_{D,_{Pi}} = AK_{gi} \cdot \frac{\sum_{t=0}^{t=T_{plan}} n_{op}\cdot k_D}{T_{plan}\cdot MT_{ph,Pi}} \tag*{Equation 7.8}$$

$$k_{aux,_{Pi}} = AK_{gi} \cdot \frac{K_{aux}}{T_{plan}\cdot MT_{ph,Pi}} \tag*{Equation 7.9}$$

$$k_{Pi} = K_{CP,Pi} + K_{CS,Pi} + k_{D,Pi} + k_{aux,Pi} \tag*{Equation 7.10}$$

Figure 7.1 Showing one example of the distribution of the production costs in C&S.

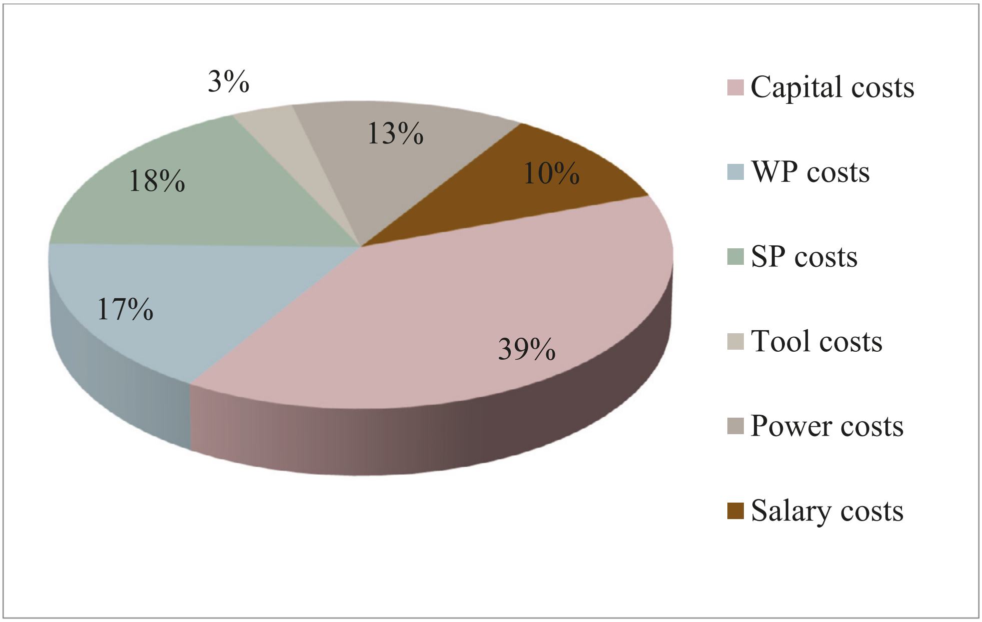

***Figure 7.1** Distribution of the production costs in CSP 3 (Appendix F3).*

One of the main items in the production cost is the cost of capital. According to the results of chapter 6, capital costs are in the range of 30–50 % of the total production cost in a C&S plant, depending of the type of machines, equipment and type of plant operation. The differences in the equipment costs can be attributed to the different technical lifetimes of the machines/equipment, different residual values of the machines/equipment, how heavily the machines/equipment have been loaded during the operation, and differences in interest rates.

In chapter 6 the capital cost is the largest item in the production cost for four of the five plants tested, see Appendices F1–F5.

PCCM contains four main cost items with several subitems in each, see section 7.1.

However, compared to the product cost calculations reviewed, the PCCM covers a much wider area with relevant cost components for calculating production costs as showing in **Table 7.1 and Table 7.2.**

Table 7.1 *Comparison between the reviewed and PCCM product cost calculations.*, part 1.

Ref	**Raw materials cost**	**Personnel cost**	**Equipment cost**	**Capital cost**	**Wear parts costs**	**Spare parts costs**	**Tool costs**	**Maintenance Service cost**	**Power costs**
[28]	X	X	X	X	X	X	X	X	X
[43]		X	X		X	X		X	X
[45]			X	(X)	(X)				X
[46]									
[15]		(X)	X	(X)	X			X	X
[27]		X	X					X	X
[47]		X	X	X	X	X			X
[48]		X	X		X	X			
[49]		X	X						X
[50]		X	X		X	X			X
PCCM	X(*)	X	X	X	X	X	X	X	X

(*) = part in the auxiliary costs

The raw material costs include such items as drilling, blasting, loading, and hauling, that is, all costs to bring the materials to the C&S plant

Table 7.2 *Comparison between the reviewed and PCCM product cost calculations, part 2.*

Model [Ref]	**Fees and taxes**	**Environ-mental costs**	**Land/ building costs**	**Shared costs**	**Allocation keys**	**Site preparation costs**	**Plant Restoration costs**	**Total Production cost**
28								X
43				X	(X)			X
45								X
46								X
15								X
27	X							X
47	X					X		X
48								X
49	X		X					X
50					(X)	X		X
PCCM	X(*)	X(*)	X(*)	X(*)	X	X(*)	X(*)	X

(*) as part in the auxiliary costs

The site preparation costs include all the costs to create a ready-to-run C&S plant. The plant restoration costs are the future costs of restoring the site to its original condition. The reviewed methods do not correctly take into consideration the different technical lifetimes of machines/equipment in a C&S plant. In PCCM, the technical life of the machine/equipment is one of the cornerstones of calculating equipment costs.

The conformity, CF, is in the range of 0.9–1.2 for each of these seven tested C&S plants. Note that the prices used in this thesis for the original machines, equipment, and parts come from suppliers or the actual manufacturer.

Within C&S there are many manufacturers that pirate and falsify both machines and parts. They have different pricing policies for C&S plant owners compared to those of original machines and parts manufacturers. It is very important to understand that these pirates do not have to cover any development costs because they are only trying to copy the original, without really knowing what they are doing [4].

Table 7.*3* shows the conformity, CF, for the C&S plants CSP 1–CSP 7.

***Table** 7.**3** The conformity CF in plants CSP 1–CSP 7.*

C&S plant	**Conformity, CF**	**Remarks**
CSP 1	1.08	Initial model, excluding the raw and capital costs
CSP 2	1.14	Revised model
CSP 3	1.15	Revised model, excluding the capital and auxiliary costs
CSP 4	1.12	Revised model
CSP 5	0.94–1.07	Revised model, excluding salary costs
CSP 6	1.10	Revised model
CSP 7	1.19	Revised model, with estimated actual costs

7.2 Implementation

According to section 4.1 reviewed different industrial manufacturing processes such as

- Metal mining, C&S manufacturing
- Metal metallurgy, casting manufacturing
- Metal machining, cutting manufacturing

The way to manufacture the required end products depends on the type of manufacturing process. A good way to increase understanding of the process and the ability to investigate and control the calculation of product costs is to create a model that follows the manufacturing process as closely as possible, step by step. That has been one of the guiding principles when developing the PCCM. The expression for conformity (CF) in Appendix I provides a good way to check the accuracy of the model.

CF = (Calculated product costs)/(Actual product cost, specified by customer)

The CF provides a new way of checking the results from the product cost calculation compared to the actual product costs in the C&S plant. Although there are many different influencing factors in a C&S plant, the conformity should be in the range of 0.7–1.3 to be accepted as good or good enough.

One of the most important keys to making reliable product cost calculations is knowledge of material flows in the C&S plant, where stream flows often fluctuate. To minimize the effects of this, a longer period of time should be used when measuring production flow. Then the production will approximate the flows in the C&S plant at an almost steady state/stabile operation. By adding the utilization rate of the C&S plant, the annual production can be calculated with high accuracy. Thus the PCCM should be used for product cost calculations during long production runs, and not for making snapshots.

I have chosen to use actual production values and full-scale tests instead of simulated production values to eliminate errors from the simulation program used. Thus the accuracy of the PCCM calculations will depend only on the PCCM itself and not on the accuracy of the combination of the simulation program and the PCCM.

The initial PCCM model (chapter 4) used a black box model approach, using five costs:

- Total production costs
- Total equipment costs
- Total dynamic cost
- Total payroll costs
- Total other costs

This approach created an overview of the production costs.

In chapter 5 the PCCM model was revised and refined, using a discrete model approach, which provides more possibilities:

- Individual and allocated costs
- Individual and allocated equipment costs
- Individual and allocated dynamic costs
- Allocated payroll costs
- Allocated auxiliary costs

By using the refined PCCM model, detailed and individual production costs can be determined for one or for all of the included machines/equipment in the C&S process system. The revised and refined PCCM model will also suit C&S plants that produce only one end product. In that case, the allocation key for the final product is set to 1.

In addition, the refined PCCM in a plant with only one end product will create a detailed production cost structure throughout the C&S plant. This allows different simulated C&S plants with equal technical solutions to be compared to find the alternative with the lowest production cost of the alternatives.

The calculated conformity using PlantDesigner and PCCM shows that in all seven C&S plant examples PCCM normally overestimates the product costs in the range of 10 to 20 %. If better compliance and more accurate calculations are needed, a dynamic C&S plant simulation tool must be used instead of the steady state PlantDesigner.

7.3 How to use the PCCM

The PCCM can be used in many different ways presented below.

7.3.1 In existing C&S plants

The main use of PCCM in a C&S plant is to track the production costs by relating the production costs directly to the actual costs. The total production costs will be calculated by including the capital costs. However, the most valuable way of using the PCCM in existing C&S plants is to track the dynamic production costs continuously. This will be a good tool for monitoring dynamic production costs directly and instantly detecting anomalies.

A more sophisticated possibility would be comparing production costs when using different materials/types of similar WP and/or SP in the same machine. For example, comparing the production costs when using rubber or plastic material as the screen deck element.

7.3.2 In simulated C&S plants

The main goal when using the PCCM in simulated C&S plants is to calculate the production cost or the product costs of the end products. It serves as a helpful tool for evaluating the economics of technically equivalent process solutions. The PCCM will find the alternative that gives the lowest production cost or the lowest costs of the required end products. This could be called C&S **technical-economical minimization**.

The PCCM can also be used to compare different process alternatives either from the total production cost point of view or from the perspective of dynamic costs. Another option is to use the PCCM to identify the best time to replace an existing crusher in an existing C&S plant with a new crusher from the technical-economic point of view.

Finally, the PCCM can be used in simulated C&S plants to compare the dynamic production costs of different almost equivalent process solutions to find the option with the lowest dynamic production cost.

7.3.3 Factors that influence accuracy in the PCCM

Although the conformity (CF) of the seven tested C&S plants (CSP 1–CSP 7) points toward an acceptable accuracy, the following factors must also be taken into account:

- Interest rates affect the capital costs. Normally interest rates change several times per year, depending on the economic situation in each country.

- Changes in the raw material properties, such as feed particle size distribution, moisture, crushability and/or abrasion, may have a large influence on the dynamic production costs during uptime.
- Using original or pirate WP and SP affects the dynamic production costs.
- Variations in exchange rates between the local currency and the currency of equipment suppliers affects both capital and dynamic production costs such as WP and SP. This may also affect the value of any end products are exported. But the effect of exported end products do not make any changes .in the cost calculations but will influence profit of the C&S plant.
- The choice between labor and increased automation and control may also affect costs. An upgrade in existing C&S plants toward increased automation and control may reduce the number of operators and the costs of direct salaries.

1.1

7.4 General conclusions and answer to the research questions

The two research questions formulated were as below

RQ1: How should the necessary information and data be incorporated to perform reliable final product cost analyses in a complete C&S plant?

RQ2A: How to design and populate the product cost calculation platform for the case of an open C&S circuit?

and

RQ2B: How to design and populate the product cost calculation platform for the case of a closed C&S circuit?

A C&S plant has a complex production cost structure, a mix of capital, consumables, salary, and auxiliary costs in different proportions depending on the type of required products and properties, the amount of required products, and the type of machines selected to achieve production.

7.4.1 General conclusion for RQ1

The distribution of the production costs can be divided into four main parts for the seven C&S plants reviewed:

- Production costs during uptime
- Production costs during downtime

- Salary costs
- Auxiliary costs

Each of these items can be further divided into one or several cost items such as capital costs and dynamic production costs. Another sublevel was added to the PCCM to increase its accuracy and the sensitivity. This sublevel of cost items makes the PCCM in C&S plant production costs calculations one of the most advanced methods available today, as shown in **Table 7.4.**

***Table** 7.4 The features incorporated in the PCCM.*

Model	PCCM
Raw material costs	X (*)
Personnel costs	X
Equipment costs	X
Capital costs	X
WP costs	X
SP costs	X
TO costs	X
MS costs	X
Power costs	X

Model	PCCM
Fees and taxation	X (*)
Environmental costs	X (*)
Land/building cost	X (*)
Shared cost	X (*)
Allocation keys	X
Site preparation costs	X (*)
Plant restoration costs	X (*)
Total Production costs	X

(*) = part of the auxiliary costs

In **Table 7.4** the features that are incorporated in the PCCM are marked with an X**.** Even with so many subcost items, the PCCM does not lose the overview of the production costs. **Table 7.5** shows the features in the papers reviewed with an X.

Table 7.5 *Description of the level of detail of input cost items in reported cost models for C&S plants (from section 7.1).*

Model - Reference	**28**	**[44]**	**[45]**	**[46]**	**[15]**	**[27]**	**[47]**	**[48]**	**[49]**	**[50]**
Raw Material costs	X									
Personnel Costs	X	X			(X)	X	X	X	X	X
Equipment Costs	X	X	X		X	X	X	X	X	X
Capital Costs	X		(X)		(X)		X			
WP Costs	X	X	(X)		X		X			X
SP Costs	X	X					X			X
TO Costs	X									
MS Costs	X	X			X	X				
Power Costs	X	(X)	X		X	X	X	X	X	X
Fees and Taxation						X	X		X	
Environmental costs										
Land/Building cost									X	
Shared Cost		X								
Allocation Keys		(X)								(X)
Site Preparation costs							X			X
Plant Restoration cost										
Total Production costs	X	X	X	X	X	X	X	X	X	X

As mentioned earlier, none of the papers reviewed have as many costs' items in the production cost calculations as the PCCM. For example, raw material costs are not included. In an open pit C&S aggregates plant using blasted rock, the cost of the raw material (drilling, blasting, loading, and hauling) may amount to approximately 50 % of the total production cost of the aggregates [4].

In existing C&S plants, normally one can find the total costs for one year operation. But due to that annual equipment costs are of the heavy ones in product cost calculations, sampling of investment costs, age of equipment and type of equipment, one need to make equivalent annual capital costs (EACC, see section 4) to be able to calculate reliable yearly equipment cost. Normally the dynamic operation costs can be found in the C&S plants financial books. But must be allocated according to the material flow in the C&S plant. For multiple end products C&S plants these costs must be allocated also to each end product.

The results in chapter 6 show that the PCCM method appropriately enough describes the variables involved in performing cost analyses of C&S plants when the processes are modeled step by step. By using the CF ratio, one also gets a measurement of the conformity between actual and calculated production costs. As shown in the tables 7.4 the PCCM contains several more main cost items than all the other review. Moreover, the PCCM taken in considerations both the site preparation and restoration cost. The PCCM gives a broader and needed cost items that must be taken in a count when calculating end-product cost. These will be the answers RQ1.

7.4.2 General conclusions related to RQ2A – Open circuit

These comments are based on section 5.3, in which we have an open C&S circuit in which all the rock material flows in a forward direction from the feed point to the end point as in **Figure 7.2** Open C&S circuit.

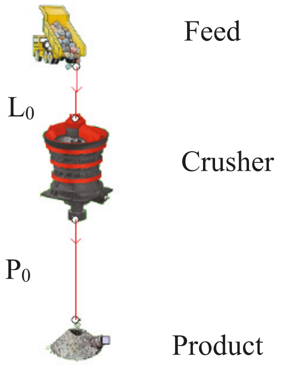

***Figure** 7.2 Open C&S circuit.*

This situation simplifies the production cost calculation because the material passes through the equipment once only. The calculation of the product costs follow the material stream, that is, the proportion in the PSD for each and every stream or substream. $L_0 = P_0$, but may have different PSDs. Thus the product cost calculations are

Uptime:

Capital costs: $k_{0P0upt} = U_{RP} \cdot \sum (a_{fc} \cdot 1 \cdot K_{0c})$

WP costs: $k_{wpP0} = \sum(1 \cdot k_{wpc})$

SP costs: $k_{spP0} = \sum(1 \cdot k_{spc})$

TO costs: $k_{toP0} = \sum(1 \cdot k_{toc})$

Power costs: $k_{powP0} = \sum(1 \cdot (T_{plan} \cdot k_{enc} \cdot k_{kwh} \cdot (1 - D_c) \cdot U_{RP})$

=> $k_{\mathrm{cpP0}} = (\frac{(k_{\mathrm{0P0upt}})+(k_{cpdynP0})}{T_{plan} \cdot MT_{phP0}})$

Downtime:

Capital costs $k_{0POdwt} = (1 - U_{RP}) \cdot \sum(a_{fC} \cdot 1 \cdot K_{0c})$

Dynamic costs. $k_{CSdymP0} = \sum(1 \cdot (T_{plan} \cdot k_{enC} \cdot k_{kwhCd} \cdot (1 - U_{RP}))$

=> $k_{csP0} = (\frac{k_{0P0dwt} + k_{csdynP0}}{T_{plan} \cdot MT_{phP0}})$

Salary costs: $k_{dlP0} = \Sigma$ (salary costs, crusher) / ($T_{plan} \cdot MT_{phP0}$)

Auxiliary costs: $k_{auP0} = \Sigma$ (auxiliary costs, crusher) / ($T_{plan} \cdot MT_{phP0}$)

In these cases, the allocation keys (AK_{gi} and AK_{ji}) are all set to 1. However, if there is more than one end product the allocation keys will be changed to

Allocation keys for general costs $AK_{gi} = P_i/\sum P_i$

and

allocation keys for Auxiliary costs $AK_{ji} = P_i/\sum P_i$

These take into consideration when the product P_i is extracted.

Then the total production costs will be

$$k_{P0} = k_{cpP0} + k_{csP0} + k_{DP0} + k_{auxP0}$$

The section shows how to model in an open circuit, step by step shall be made by the PCCM method. The results given in chapter 6, show that this model meets the requirements, Via the PCCM equations, we get a broad treatment tool for designing, calculating and checking the product costs in open C&S circuits, thus is the answering to RQ2A.

7.4.3 General conclusion for RQ2B - Closed crushing circuit

Figure 5.11 in section 5.3 showed a system that includes a closed crushing circuit.

Figure 7.3 shows the extracted closed circuit. The flow P_{S1} is recirculated to the crusher for further size reduction.

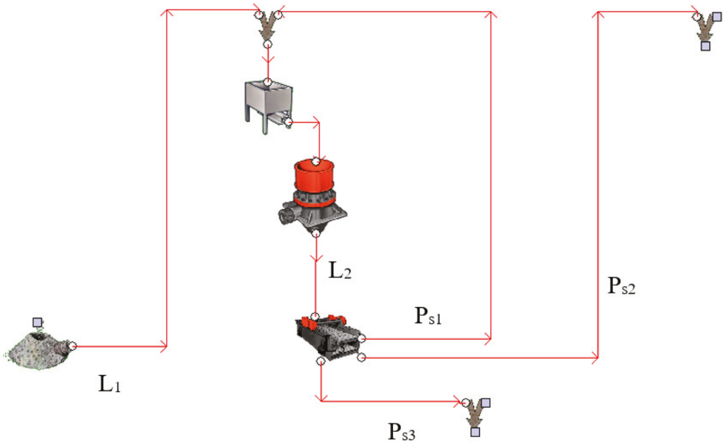

***Figure** 7.3 Closed C&S circuit.*

Using the mass balances in the second station, in steady state conditions

$L_1 = P_{s2} + P_{s3}$

$L_2 = L_3 = P_{s1} + P_{s2} + P_{s3}$

$L_2 = L_1 + P_{s1}$

and leaving the screen

$P_{s3} + P_{s2} + P_{s1} = (pf_{s1ps3} \text{ x } L_3) + (pf_{s1ps2} \text{ x } L_3) + (1 - (pf_{s1ps2} + pf_{s1ps3})) \text{ x } L_3)$

where $pf_{s1ps3} + pf_{s1ps2} + pf_{s1ps1} = 1$

so that $pf_{s1ps1} = 1 - (pf_{s1ps2} + pf_{s1ps3})$

The capital costs for P_{S3} will be:

Uptime:

$$k_{0PS3upt} = U_{RP} \cdot \sum a_{fPS3} \cdot AK_{jPS3} \cdot K_{0j}$$

Downtime:

$$k_{0PS3upt} = (1 - U_{RP}) \cdot \sum a_{fPS3} \cdot AK_{jPS3} \cdot K_{0j}$$

Where the special allocation key AK_{jPS3} will be P_{S3}/L_1

and

the general allocation key $AK_{gPS3} = P_{S3}/(P_{S2} + P_{S3})$

Then total cost k_{PS3} for processing product P_{S3} is

WP: $k_{wpPS3} = \sum(AK_{\mathrm{jPS3}} \cdot k_{wpj})$

SP: $k_{spPS3} = \sum(AK_{\mathrm{jPS3}} \cdot k_{spj})$

TO: $k_{toPS3} = \sum(AK_{\mathrm{jPS3}} \cdot k_{toj})$

Power: $k_{powPS3} = \sum(AK_{\mathrm{jPS3}} \cdot (T_{plan} \cdot k_{enj} \cdot k_{kwh} \cdot (1 - D_j) \cdot U_{RP}))$

The production cost uptime will be

$$k_{\mathrm{cpPS3}} = (\frac{(k_{\mathrm{0PS3upt}}) + (k_{cpdynPS3})}{T_{plan} \cdot MT_{phPS3}})$$

The dynamic production costs during downtime for product P_{S3} will be

$$k_{csdynPS3} = \sum(AK_{\mathrm{jPS3}} \cdot (T_{plan} \cdot k_{enj} \cdot k_{kwhid} \cdot (1 - U_{RP}))$$

The production cost downtime:

$$k_{\mathrm{csPS3}} = (\frac{k_{\mathrm{0PS3dwt}} + k_{\mathrm{csdynPS3}}}{T_{plan} \cdot MT_{phPS3}})$$

The salary cost, k_{DPPS3}, is calculated for product P_{S3} as

$$k_{DPS3} = AKk_{gPS3} \cdot (\frac{(k_D \cdot n_{op})}{T_{plan} \cdot MT_{phPPS3}})$$

The auxiliary k_{auxi} cost is calculated as

$$k_{auxPS3} = AK_{gi} \cdot (\frac{k_{aux}}{T_{plan} \cdot MT_{phPS3}})$$

Then total cost k_{PS3} for processing product P_{S3} is

$$k_{PPS3} = k_{cpPS3} + k_{csPS3} + k_{DPS3} + k_{auxPS3}$$

The production costs for the other products will be equivalent to above procedure and the total production costs in the close circuit, k_{PCC}, will be

$k_{PCC} = \Sigma k_{Pcci}$

By using the procedure for calculation of the product costs in open or closed circuits, the total production costs can be calculated in a complete C&S plant. The philosophy is to divide the flowsheet into two main types of operations, open and closed circuits. Then, all the subtypes are added together in the line of the material flow to calculate the total production cost or the product cost for each end product.

Figure 7.4 shows an example in which the flowsheet is divided into open and closed types of operations.

In construction C&S plants there can be what are called semi-closed/open circuits as a special fraction can be split into two streams. In **Figure 7.5** one stream is a final product and the other stream continues for further treatment. In such cases, the way to calculate the cost follows the principle that the production cost for this semi-closed/open stream is divided according to the proportion of the split.

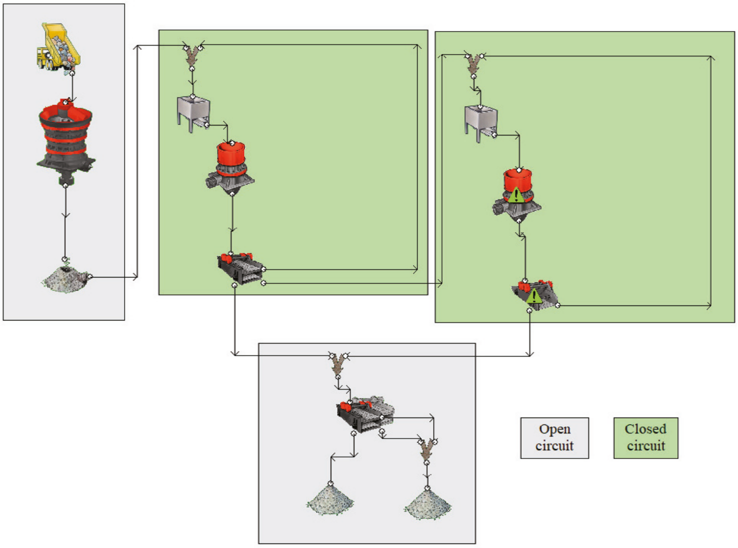

Figure 7.4 Open and closed types of circuits in the flowsheet.

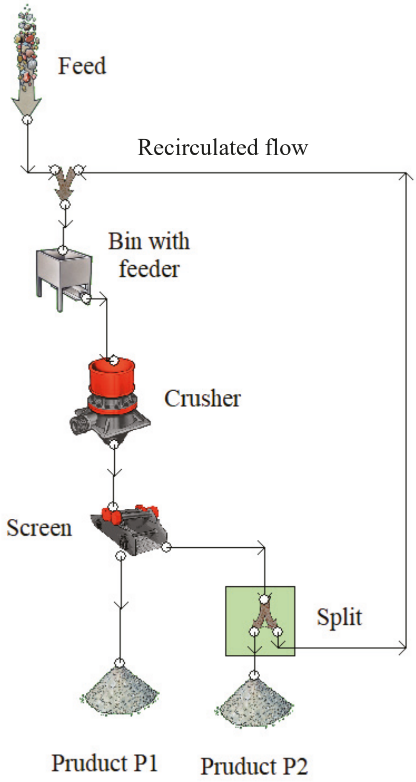

Figure 7.5 *Typical semi-closed/open circuit.*

Careful use of the equations following Figure 7.5 will yield a good model to provide costs analyses of closed and semi-closed/open circuits.

In the closed C&S, material that is coarser than required, is recirculated and sent back for re-crushing. This adds additional complexity due to having to both calculate production costs and take into account the amount of material flowing in the circuit. In PCCM, all production costs, for all material flows in the circuit, can be calculated separately. So, by using the PCCM one can keep track of all cost items within the circuit and by that can easily select the circuit that have "lowest" production cost and will be the section tool when designing/selecting the C&S circuit. This means that PCCM can be used to design, calculate and control closed and/or semi-closed C&S circuits, these will be the answering to RQ2b.

8. Future Research

This chapter identifies possible developments of the PCCM for other size reduction processes such as grinding as well as other sizing processes such as classification.

8.1 PCCM development for other size reduction machines

The PCCM method for making production cost calculations is suitable for both size-reducing and size-sorting machines. In this dissertation PCCM was developed for compression crushers such as jaws and cones, and for size sorting by vibrating screens.

However, there are other size reduction machines used in the construction and mining industries. Limestone occurs in large deposits on the surface of the earth's crust and is a major raw material resource crushed for both aggregates and cement. Milling and grinding are among the most common means of size reduction in mining.

8.1.1 Impact crusher/hammer mills

Impact crushers are dominant in the construction world [4]. Impact crushers can be classified as

- Primary horizontal impact crushers
- Secondary horizontal impact crushers
- Vertical shaft impactors
- Hammer mills

Primary impact crushers can handle big lumps up to 1–2 m in size, producing particle sizes below 200–300 mm in one step. Reduction ratios (Rr) of 10 or more are common. Secondary impact crushers can be fed with stones up to 300 mm in size or less, producing 90 % below 30 mm. Hammer mills have a grid (an arched stationary screen with bars) that prevents oversize particles from leaving the machine before they are ground smaller than the grid opening of the roster. Hammer mills can have a Rr of 20 or more [4.24].

Impactors and hammer mills are mainly used to process raw material with a low abrasion index such limestone. For abrasive rock, impactors and hammer mills are too expensive to run compared with compression crushers. However, one type of impactor, the vertical shaft impactor (VSI), is used in aggregate production with both nonabrasive and abrasive rock. The VSI is a final product crusher for achieving higher shape quality of the aggregates.

Impactors are used in almost the same way as compression crushers, but they use impact, that is, smashing the rock with high energy to create small stones.

The different size reduction methods naturally result in different wear and spare parts consumption than compression crushing.

The PCCM product calculations follow process lines within C&S plants in the mining and construction industries. So, the PCCM can be adapted for use in C&S processes using impactors.

8.1.2 Grinding mills

Grinding mills are generally used in mining and cement plants. There are several types of grinding/milling.

- Rod milling
- Ball milling
- Autogenous milling
    - Semi-autogenous grinding (SAG)
- Other type of grinding/milling
    - Jet-milling
    - Vibrating milling
    - Roller milling

Grinding mills are normally the next step in mining to reduce the size of the rock in order to liberate the metal minerals from the gangue matrix. Milling/grinding produces much finer product sizes than crushing. Grinding/milling can be done wet or dry, while crushing is usually a dry process [70].

Grinding processes are similar to crushing processes, and so the PCCM method can be modified to fit the grinding process. The consumption of WP and SP must be adapted to the grinding/milling process.

8.2 PCCM development for other size-sorting machines

In addition to the vibrating screens discussed in this dissertation, there are other size-sorting machines such as classifiers, cyclones, and visual methods that are mainly used in mining.

8.2.1 Classifiers and cyclones

A vibrating screen separates particle based on differences in size. The equivalent spherical diameter (ESD) of an irregularly shaped object is the diameter of a sphere of equivalent volume [71]. Classifiers separate the particles using an equivalent diameter, that is, by taking into consideration both size and density. A hematite particle of equivalent spherical diameter to a gangue particle will be smaller because hematite is denser than the gangue [82]. Classifiers separate ESDs in a similar process to the way screens separate absolute sizes.

As the processes are equivalent, the PCCM calculation model for screens can be upgraded to fulfill the product cost calculations for classifiers and cyclones.

8.3 Summary

If and when the PCCM is upgraded for grinding/milling and classifying, the PCCM will be become an excellent evaluation tool for size reduction and size sorting in mining and mineral applications. By using the PCCM together with mining and mineral process simulation programs, the equivalent process alternative with the total lowest product costs can be calculated. The lowest dynamic production costs can also be identified.

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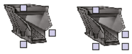
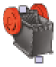
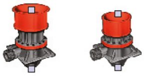
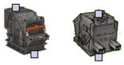
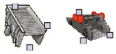
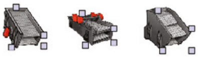
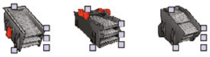
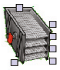
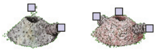
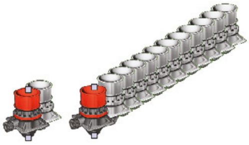
Appendix A-I

Appendix A – Flowchart icons.

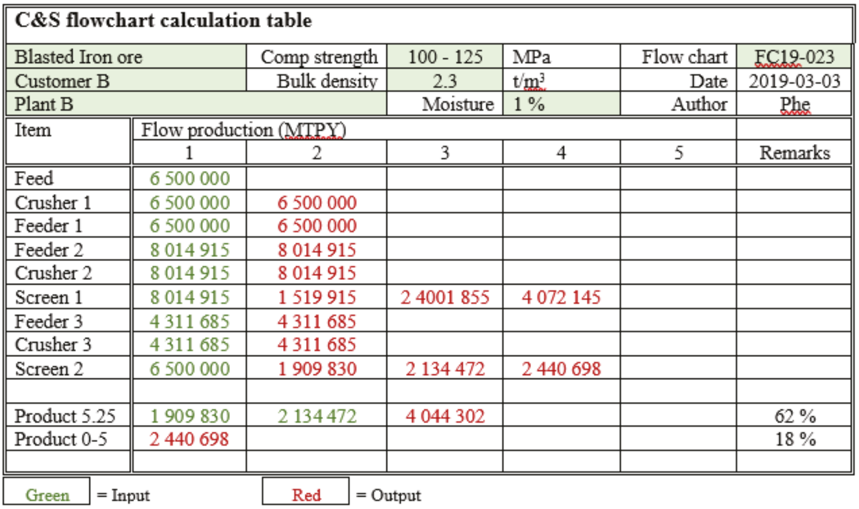
Explanation of the icons used in the flowcharts [22]

Icons	Explanation
	Feed, as alluvial, blasted, pre-crushed or screened stone
	Grizzly feeders, one and two decks
	Jaw crusher
	Cone crushers
	Gyratory crusher
	Horizontal shaft impactors (HSI)
	Vertical shaft impactor (VSI)
	Screens, 1 deck
	Screens, 2 decks
	Screens, 3 decks
	Screen, 4 decks

	Surge pile with one feeder or two feeders
	Bin with one feeder or two feeders
	Stock-pile
⟶	Material flow and flow direction
	Split of one material flow, into two or three new material flows
	Add of two, three or four material flows, into one new material flow
	Multiple identical parallel machines, from 2 up to 12 units
	Mobile units, jaw, cone and screen

Created by Sandvik's PlantDesigner

How to read the flow chart calculation table:



C&S flowchart calculation table

Blasted Iron ore		Comp strength	100 - 125	MPa	Flow chart	FC19-023
Customer B		Bulk density	2.3	t/m^3	Date	2019-03-03
Plant B			Moisture	1 %	Author	Phe
Item	Flow production (MTPY)					
	1	2	3	4	5	Remarks
Feed	6 500 000					
Crusher 1	6 500 000	6 500 000				
Feeder 1	6 500 000	6 500 000				
Feeder 2	8 014 915	8 014 915				
Crusher 2	8 014 915	8 014 915				
Screen 1	8 014 915	1 519 915	2 4001 855	4 072 145		
Feeder 3	4 311 685	4 311 685				
Crusher 3	4 311 685	4 311 685				
Screen 2	6 500 000	1 909 830	2 134 472	2 440 698		
Product 5.25	1 909 830	2 134 472	4 044 302			62 %
Product 0-5	2 440 698					18 %

Green = Input Red = Output

The properties for the calculation are listed in the yellow cells at the top of the table. The column “Item” lists the main flow chain machines.

The flow production columns (1–5) show the annual material flows. Green is shows that material enters the machine. If there are several green inputs to the same machine, the machine is fed from different sources. Red is used to show that the material is leaving the machine. Several red outputs from the same machine show there are different outflows.

Appendix B -- Simulation models and programs.

Simulation of crushing and screening processes are used as mathematical or logical representation of the processes.

Furthermore, simulation can be used to train persons using a virtual environment that would otherwise be difficult or expensive to produce.

There are several types of simulations in crushing and screening, but there are two main principles [72]:

1. **Continuous simulation** (steady state) in which the simulation continuously tracks the system dynamics over time. Instead of being event-based, this is called an activity-based simulation; time is broken up into small time slices and the system state is updated according to the set of activities happening in the time slice. A steady state simulation does not consider the effects of time. It assumes that the plant has reached steady operating conditions

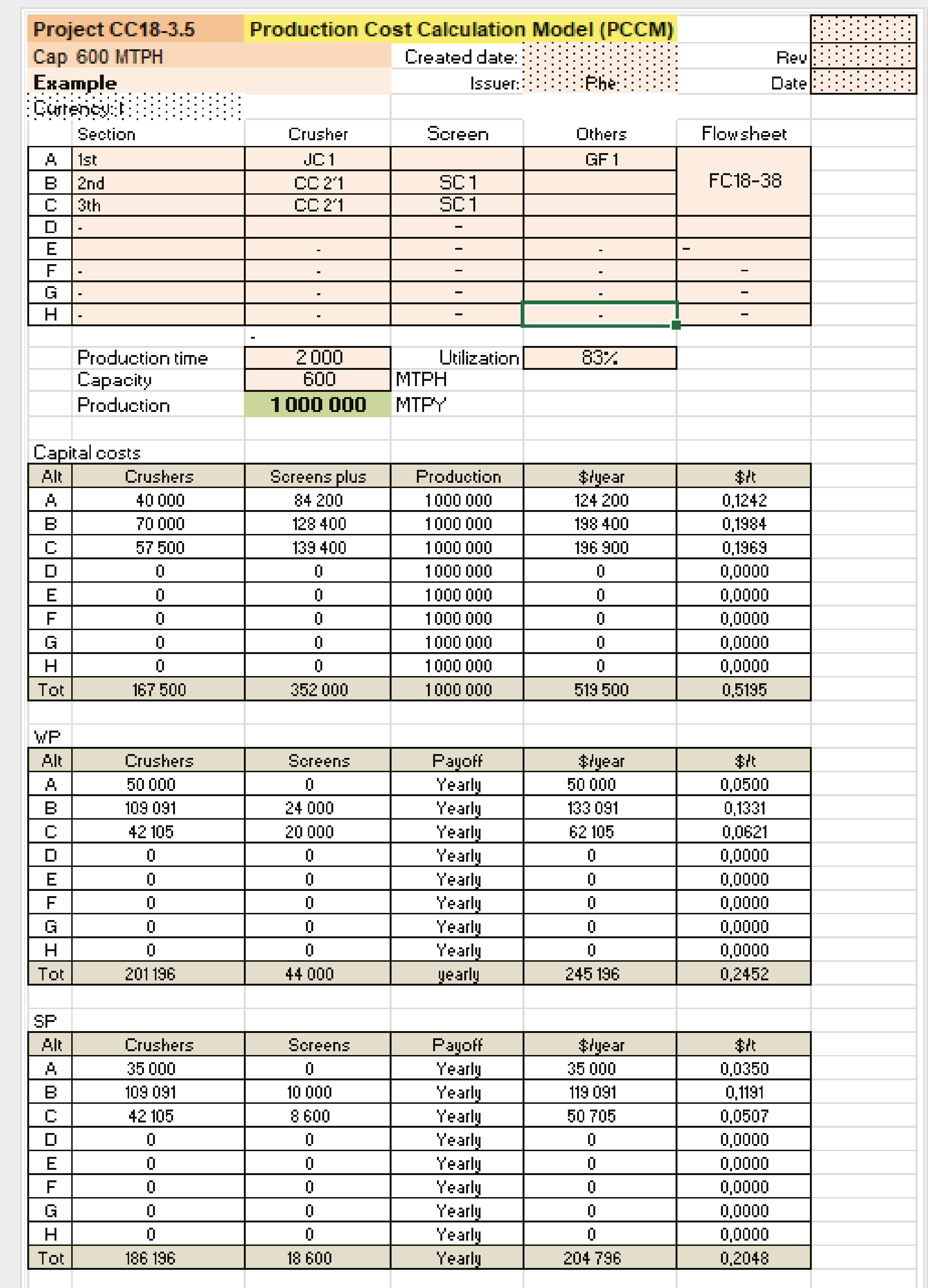
2. **Discrete event simulation** (DES) models the operation of a system as a discrete sequence of events in time as a dynamic simulation. Each event occurs at a particular instant in time and marks a change of state in the system. Between consecutive events, no change in the system is assumed to occur; thus the simulation can directly jump in time from one event to the next. A dynamic simulation does consider the effects of time. It assumes that the plant is in a state of change during the operation.

Some examples of simulation programs that can be used for C&S processes (24):

Simulation type	Program
Continuous	PlantDesigner (Sandvik)
	Bruno (Metso)
	AggFlow (Bedrock)
Discrete-event (DES)	ExtendSim (Imagine That)
	GoldSim (GTG)
	Plant Simulation (Siemens)

To improve the comparison between calculated and actual production costs the simulation of the C&S process must be accurate. While using continuous simulation the PCCM accuracy can reach 65 – 70 %, using DES instead allows accuracy to reach 80 – 85 %.

Appendix C – Spreadsheet [69]



Project CC18-3.5 Production Cost Calculation Model (PCCM)

Cap 600 MTPH — Created date: — Rev

Example — Issuer: Phe — Date

Currency: I

	Section	Crusher	Screen	Others	Flowsheet
A	1st	JC 1		GF 1	FC18-38
B	2nd	CC 2'1	SC 1		
C	3th	CC 2'1	SC 1		
D	-		-		
E		-	-	-	-
F	-	-	-	-	-
G	-	-	-	-	-
H	-	-	-	-	-

Production time	2 000	Utilization	83%
Capacity	600	MTPH	
Production	**1 000 000**	MTPY	

Capital costs

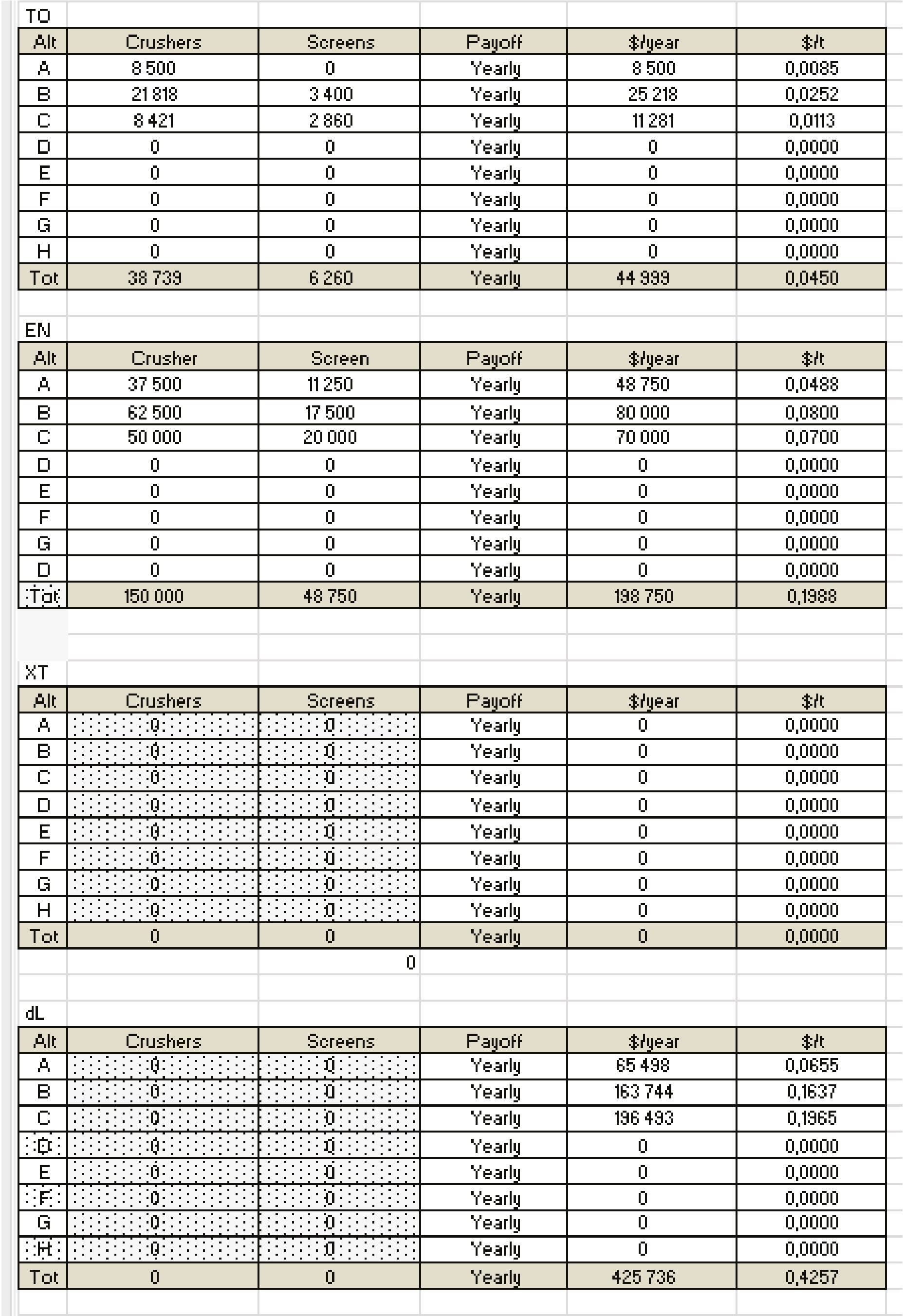
Alt	Crushers	Screens plus	Production	$/year	$/t
A	40 000	84 200	1 000 000	124 200	0,1242
B	70 000	128 400	1 000 000	198 400	0,1984
C	57 500	139 400	1 000 000	196 900	0,1969
D	0	0	1 000 000	0	0,0000
E	0	0	1 000 000	0	0,0000
F	0	0	1 000 000	0	0,0000
G	0	0	1 000 000	0	0,0000
H	0	0	1 000 000	0	0,0000
Tot	167 500	352 000	1 000 000	519 500	0,5195

WP

Alt	Crushers	Screens	Payoff	$/year	$/t
A	50 000	0	Yearly	50 000	0,0500
B	109 091	24 000	Yearly	133 091	0,1331
C	42 105	20 000	Yearly	62 105	0,0621
D	0	0	Yearly	0	0,0000
E	0	0	Yearly	0	0,0000
F	0	0	Yearly	0	0,0000
G	0	0	Yearly	0	0,0000
H	0	0	Yearly	0	0,0000
Tot	201 196	44 000	yearly	245 196	0,2452

SP

Alt	Crushers	Screens	Payoff	$/year	$/t
A	35 000	0	Yearly	35 000	0,0350
B	109 091	10 000	Yearly	119 091	0,1191
C	42 105	8 600	Yearly	50 705	0,0507
D	0	0	Yearly	0	0,0000
E	0	0	Yearly	0	0,0000
F	0	0	Yearly	0	0,0000
G	0	0	Yearly	0	0,0000
H	0	0	Yearly	0	0,0000
Tot	186 196	18 600	Yearly	204 796	0,2048



TO

Alt	Crushers	Screens	Payoff	$/year	$/t
A	8 500	0	Yearly	8 500	0,0085
B	21 818	3 400	Yearly	25 218	0,0252
C	8 421	2 860	Yearly	11 281	0,0113
D	0	0	Yearly	0	0,0000
E	0	0	Yearly	0	0,0000
F	0	0	Yearly	0	0,0000
G	0	0	Yearly	0	0,0000
H	0	0	Yearly	0	0,0000
Tot	38 739	6 260	Yearly	44 999	0,0450

EN

Alt	Crusher	Screen	Payoff	$/year	$/t
A	37 500	11 250	Yearly	48 750	0,0488
B	62 500	17 500	Yearly	80 000	0,0800
C	50 000	20 000	Yearly	70 000	0,0700
D	0	0	Yearly	0	0,0000
E	0	0	Yearly	0	0,0000
F	0	0	Yearly	0	0,0000
G	0	0	Yearly	0	0,0000
D	0	0	Yearly	0	0,0000
Tot	150 000	48 750	Yearly	198 750	0,1988

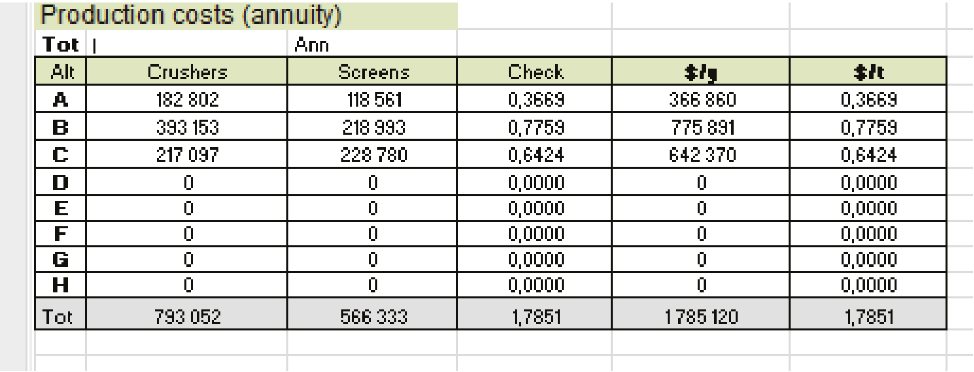
XT

Alt	Crushers	Screens	Payoff	$/year	$/t
A	0	0	Yearly	0	0,0000
B	0	0	Yearly	0	0,0000
C	0	0	Yearly	0	0,0000
D	0	0	Yearly	0	0,0000
E	0	0	Yearly	0	0,0000
F	0	0	Yearly	0	0,0000
G	0	0	Yearly	0	0,0000
H	0	0	Yearly	0	0,0000
Tot	0	0	Yearly	0	0,0000

0

dL

Alt	Crushers	Screens	Payoff	$/year	$/t
A	0	0	Yearly	65 498	0,0655
B	0	0	Yearly	163 744	0,1637
C	0	0	Yearly	196 493	0,1965
D	0	0	Yearly	0	0,0000
E	0	0	Yearly	0	0,0000
F	0	0	Yearly	0	0,0000
G	0	0	Yearly	0	0,0000
H	0	0	Yearly	0	0,0000
Tot	0	0	Yearly	425 736	0,4257

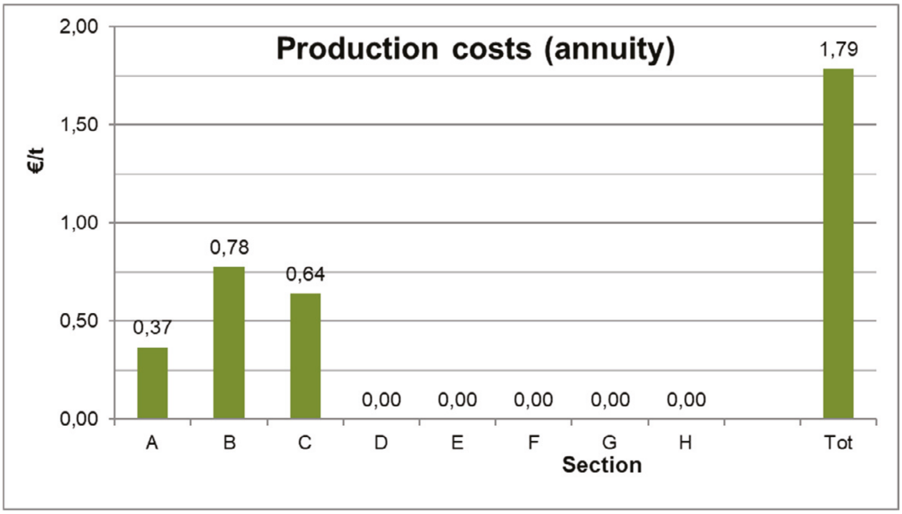


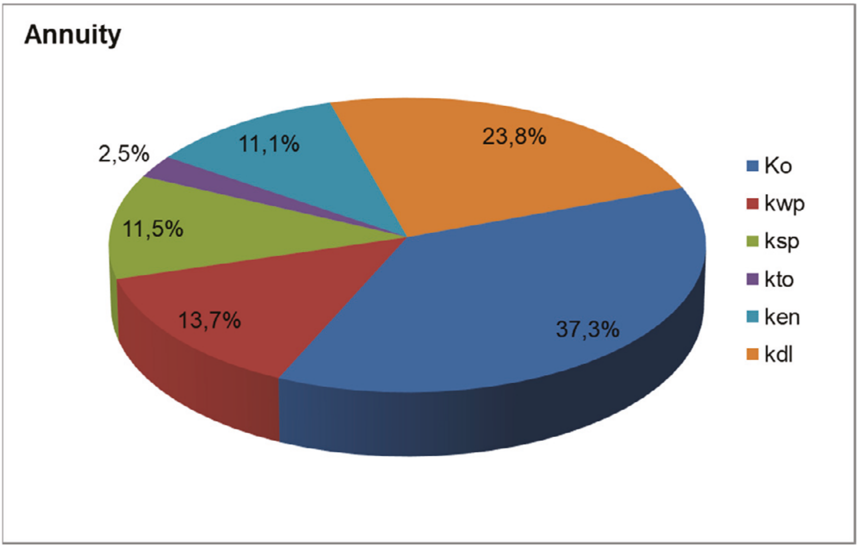
Production costs (annuity)

Tot | Ann

Alt	Crushers	Screens	Check	$/y	$/t
A	182 802	118 561	0,3669	366 860	0,3669
B	393 153	218 993	0,7759	775 891	0,7759
C	217 097	228 780	0,6424	642 370	0,6424
D	0	0	0,0000	0	0,0000
E	0	0	0,0000	0	0,0000
F	0	0	0,0000	0	0,0000
G	0	0	0,0000	0	0,0000
H	0	0	0,0000	0	0,0000
Tot	793 052	566 333	1,7851	1 785 120	1,7851

Remark Production Cost are the annual costs.




Annuity
2,5%
11,1%
23,8%
11,5%
13,7%
37,3%
Ko
kwp
ksp
kto
ken
kdl

Appendix D – Plant Performance Guarantee [73]

All process guarantees are unique and they are adapted to the offered process solution by Sandvik

Appendix No.: ____________
Contract No.: ____________
Dated.: ____________

1. Performance Guarantee

Internal information	
PG No.	PGM11111-1
Project No.	M11111
Opportunity No.	[XXXXXXXXXX]
Goods	[Primary crushing station]
Certified Issuer	xxx

1. DEFINITIONS

For the purposes of this Performance Guarantee the following terms and definitions apply.

"**Bond Impact Work Index (WI)**" means the result derived from measuring the Feed Material resistance to crushing and grinding as determined using the Bond grindability test in the Xxx laboratory.

"**Capacity**" means the sum of all Feed Material processed by the Goods according to the formula:

Capacity = (Weight of Feed Material x Belt Speed x (3600/1000)) / Length of belt cut)

where capacity shall be in MTPH, Weight of Material in kg, Belt Speed in m/s and Length of belt cut in meter.

"**Choke Fed**" means that the Goods shall be fed with the Feed Material in level or above the top of the spider cap for cone crushers CH, CS, CG/in level or above the top of the wear plates for jaw crushers CJ, for sufficient amount of time to collect a representative sample according to Addendum 3 - Xxx Test Procedure.

'"**Consequential Loss**" means any punitive, exemplary, indirect, incidental, special, or consequential, cost, loss, or damage; and any economic loss; loss of actual or anticipated profit or revenue; loss of existing or anticipated business or custom; loss of actual or anticipated savings; loss of contract or opportunity; loss of production; loss arising from an interruption or shut down; loss of use; cost of sourcing alternate supply or a substitute for the products; loss of property; increased operating costs; increased costs of finance; loss of goodwill or reputation; loss of information or data; and loss of ratings, licenses or permits.

"**Continuous Feed Rate"** means that the Goods shall be fed with the Feed Material at a continuous feed rate according to capacities in Clause 4.1

"**Contract**" means the agreement for supply of the Goods entered into by Xxx and the Customer.

"**Customer**" means the person who orders the Goods from Xxx pursuant to the Contract and includes any permitted transferee.

"**Delivery Terms**" means the delivery terms specified in the Contract.

"**Evenly Spread Feed**" means when the screen deck is fed with equal amount of material over its width.

"**Feed Material"** means the raw material provided by the Customer to be fed into the Goods for the purposes of carrying out the Acceptance Tests, which satisfies the characteristics specified in Section 3.3.

"**Fine-tune**" means to modify, adjust, repair, revise or replace parts of the Goods.

"**Fraction length**" means the ratio between the upper and lower separation size on the screen. When lower separation size is zero (0), the Fraction length is greater than two (2).

Ex. Sep 16

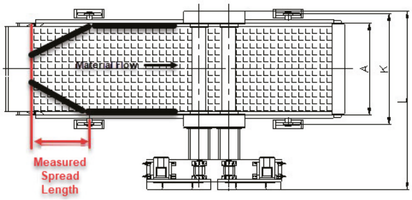
Sep 8

$$Fraction\ length = \frac{16}{8} = 2$$

"**Goods**" means the goods specified in the Contract (including any embedded or standalone software) which Xxx agrees to provide and whose performance is covered by this Performance Guarantee.

"**Grading**" means Particle Size Distribution expressed as the percentages by mass passing a specified set of sieves

"**Measured Spread Length**" means the distance between beginning of screening media to where the material has spread to the full width of screen. Measured Spread Length is valid on the side with the longest measurement.



"**Minimum Performance Criteria**" means performance of the Goods in accordance with the standards set out in Clause 4.

"**Net Capacity**" means the Capacity excluding removed natural fines or gangue mineral.

"Nominal Spread Length" is calculated according to below formula

$$\frac{width\ of\ screen(m) - 0{,}5}{2}$$

"**Order Acceptance**" means Xxx's acceptance of the Order and consequent agreement to the Contract by either delivering the Goods or issuing the Customer with a document named 'Order Acceptance' (or similar).

"**Particle Shape**" means the ratio between length and/or width and/or thickness according to relevant norm.

"Performance Guarantee Acceptance Certificate" means the certificate issued by Xxx on completion of the Performance Guarantee Acceptance Test or at the end of the Performance Guarantee Test Period in the form provided in Addendum 1 and 2

"**Performance Guarantee Acceptance Test**" means the test procedure initiated by Xxx and used to measure the performance of the Goods, as described in this document.

"**Performance Guarantee Acceptance Test Period**" means 1 month from when Xxx has given notice that the Goods are ready for Performance Guarantee Acceptance Test or within 6 months from the passing of the risk according to the Delivery Terms.

"**Performance Guarantee Acceptance Test Report Screens**" means the report generated by Xxx containing the results of the Performance Guarantee Acceptance Test.

"**Process**" means the process of crushing and screening the Feed Material using the Goods.

"**Product**" means the material produced by crushing and screening the Feed Material using the Process.

"**Product Size**" means the designation of Product in terms of lower and upper laboratory sieve sizes accepting that some particles will be retained on the upper laboratory sieve (oversized) and some will pass through the lower laboratory sieve (undersized).

"**Segregated Feed**" means unevenly feeding the Goods with material that has larger or smaller particle size on one side

“**Spread Length**” means the difference between Measured Spread Length and Nominal Spread Length.

“**Third Party Equipment**” means any equipment not being a part of the Goods which in any way affects, is part of the Process or is connected to the Goods.

“**Unsafe**” means unacceptable actual or potential hazards and incidents relating to safety, health or the environment.

2. COMPLIANCE WITH MINIMUM PERFORMANCE CRITERIA

Xxx agrees with the Customer that the Goods will meet the Minimum Performance Criteria provided that the Customer meets its obligations and strictly adheres to the terms and conditions specified in this Performance Guarantee.

3. CONDITIONS

3.1 Installation

The Goods shall be installed in accordance with the process flow described in:

Flow-sheet drawing(s) No.:	FM11111-1, dated 2022-02-01
Layout drawing(s) No.:	LM11111-1, dated 2022-02-01

The parties agree that any parameters given in the above mentioned flow-sheet(s) and layout(s) related to the Goods are default values. At Xxx’s sole discretion these parameters may be changed to achieve the Minimum Performance Criteria.

3.2 Third Party Equipment

The Customer is responsible for ensuring that any Third Party Equipment is fully operational and designed to handle the maximum peak flow capacities based on the flowsheet(s) specified in Clause 3.1, with a minimum safety margin 25 %.

3.3 Feed Material

This Performance Guarantee is conditional upon the Feed Material complying with the specifications below:

- The Feed Material to be processed shall be [insert description of Feed Material] with a specific gravity in the range [insert range] metric t/m^3.

- Feed Material entering the Goods, shall be well blended with a Grading according to the table below.
  The test method for sizes up to 125 mm is described in the European norm.

Size (mm)	Cumulative % passing (by weight)
750	100
500	70 – 80
250	55 – 65
125	35 – 45
63	20 – 30
31.5	10 – 20
16	0 – 10

- The Bond Impact Work Index (WI) must be in the range of [update for each guarantee].

- The Feed Material shall be free from contamination. Examples of contamination are non-minerals (wood, soil etc.) and uncrushable materials (tramp metal, reinforcement bars, steel etc.).

- The Feed Material clay content shall be in accordance with the table below.

Particle Size (mm)	Moisture content (% by weight)
0 - 8 mm	Max 0,5%
> 8 mm	0%

- The Feed Material moisture content shall not exceed 1 % (by weight).

Alternative to above moisture content

- The Feed Material moisture content shall be in accordance with the table below.

Particle Size (mm)	Moisture content (% by weight)
0 - 8 mm	Max 10%
>8 mm	Max 1%

3.4 Test Material

When Customer has provided Xxx with sample Feed Material to determine its characteristics in connection with the sale of the Goods, the Performance Guarantee is conditional upon the Feed Material being consistent with the sample Feed Material provided.

3.5 Installation and Operation

This Performance Guarantee is conditional upon:

a) The Goods shall be installed, erected and operated in accordance with Xxx's recommendations and in accordance with any applicable Xxx Manual or Xxx Warranty including the use of Xxx original proprietary spare parts and any repairs being performed by Xxx qualified personnel.
b) The Goods must be operated in accordance with the Xxx Operator & Maintenance Manuals unless the Supplier or its

Personnel instructs the Customer to operate the Goods otherwise.

c) The Goods shall be fed continuously with the Feed Material meeting the specifications in Clause 3.3 and in accordance with the flow-sheet and layout specified in Clause 3.1.
d) Installation shall not be carried out in unhealthy or Unsafe surroundings. All the necessary safety and precautionary measures shall be taken before and during installation, and shall be maintained throughout operation of the Goods.
e) If the Goods are CG, CS and/or CH crushers, ASRi or ACS must be installed and in use during the Acceptance Test.
f) All crushing chamber parts or screening media, included in the test shall have minimum 60% remaining Life time during the Acceptance Test.
g) If the Goods include screens, the screening media must be approved by Xxx. Xxx reserves the right to change screening media to meet Minimum Performance Criteria.
h) The Measured Spread Length shall be continuously less than Nominal Spread Length + 0,5 m
i) The Goods shall not be fed with Segregated Feed.
j) The Goods shall be fed with Evenly Spread Feed.
k) If the Goods are CG, CJ, CS and/or CH crushers, it shall be Choke fed.
l) If the Goods are CI crushers, it shall be a Continuous Feed Rate

4. MINIMUM PERFORMANCE CRITERIA

4.1 Capacity

Minimum capacity: [XXX MTPH] of Product complying with the requirements of Clause 4.2.

4.2 Product Grading

The test method is described in the European norm EN 933-1.

Particle Size (mm)	Distribution (%)
< 200	Min 98
< 125	Min 80
< 90	Min 50

Alternative table

Size (mm)	Cumulative % passing (by weight)
32	98
22	70 – 80
16	55 – 65
11.2	35 – 45
8	20 – 30
4	10 – 20
0.5	0 – 10

Alternative table

Grading specifies the allowable undersize and oversize content of the Product.

Product Size (mm)	Grading according to European Norm (EN)	Oversize/Undersize (%)
0 – 4	Gf85	15 / -
4 – 8	Gc90/15	10 / 15
8 – 11.2	Gc85/15	15 / 15
11.2 – 16	Gc90/15	10 / 15
16 – 22	Gc90/15	10 / 15

4.3 Product Size Distribution

Product Size (mm)	Distribution (%)
0 – 4	25 – 35
4 – 8	25 – 35
8 – 11.2	10 – 15
11.2 – 16	10 – 15
16 – 22	10 – 15

4.4 Particle shape – Flakiness Index (FI)

The test method to determine Particle shape of the Product is described in the European norm EN 933-3.

Product Size (mm)	Flakiness Index (FI) according to EN 933-3
5 - 8	≤ 20%
8 – 12.5	≤ 20%
12.5 – 16	≤ 15%
16 – 20	≤ 15%

Alternative

4.5 Particle shape – Shape Index (SI)

Particle shape of the Product. The test method is described in the European norm EN 933-4.

Product Size (mm)	Shape Index (SI) according to EN 933-4
5 - 8	≤ 20%
8 – 11.2	≤ 20%
11.2 – 16	≤ 15%
16 – 22	≤ 15%

Alternative

4.6 Particle shape – Flakiness Index according to British standard

Particle shape of the Product. The test method is described in the norm British standard BS 812 Section 105.1.

Product Size (mm)	Flakiness Index according to BS 812 Section 105.1
6.3 - 10	≤ 25%
10 – 14	≤ 25%
14 – 20	≤ 25%
20 – 28	≤ 25%

Alternative

4.7 Particle shape – Elongation Index according to British standard

Particle shape of the Product. The test method is described in the norm British standard BS 812 Section 105.2.

Product Size (mm)	Elongation Index according to BS 812 Section 105.2
6.3 - 10	≤ 25%
10 – 14	≤ 25%
14 – 20	≤ 25%
20 – 28	≤ 25%

5. **PERFORMANCE VERIFICATION**

5.1. Time for Performance Guarantee Acceptance Test

The Performance Guarantee Acceptance Test shall be carried out immediately after the Goods have been erected, commissioned and Fine-tuned for operation and Xxx has given notice that the Goods are ready for the Performance Guarantee Acceptance Test.

The parties agree that the performance of the Goods shall be verified as a momentary test of the Goods utilizing the Xxx Test Procedure contained in Addendum 3.

If, for reasons not attributable to Xxx, the Performance Guarantee Acceptance Test has not taken place within the Performance Guarantee Acceptance Test Period, the Goods shall be considered to be accepted by the Customer. Such acceptance is to be documented in the Performance Guarantee Acceptance Certificate contained in Addendum 2.

5.2. Performance Guarantee Acceptance Testing

The Customer shall perform the Performance Guarantee Acceptance Test. Xxx will supervise to ensure that the Performance Guarantee Acceptance Test is correctly performed.

The Customer shall bear all costs of the Performance Guarantee Acceptance Test with the exception of the cost of Xxx’s employees and independent contractors engaged by Xxx which shall be borne by Xxx.

The Customer shall provide free of charge any operating personnel, power, lubricants, water, fuel, raw materials and other materials required for the tests and for final adjustments in preparing for these tests. The Customer shall also supply and install free of charge any additional equipment required to perform the Performance Guarantee Acceptance Test (such as mobile cranes, ladders etc) and provide any labor or other assistance necessary for carrying out the tests.

The Customer shall provide laboratory facilities including personnel, sampling equipment in accordance with the Xxx Test Procedure, according to Addendum 3 and laboratory screens with suitable hole sizes.

Samples shall be collected in accordance with the Xxx Test Procedure, according to Addendum 3, when the Goods are operated under full load and have reached the situation of steady flow.

Xxx has the right to observe and participate when the samples are analyzed.

The Performance Guarantee Acceptance Test results shall be documented immediately in the Performance Guarantee Acceptance Test Report in Addendum 4. The Performance Guarantee Acceptance Test Report shall clearly state the conditions under which the Performance Guarantee Acceptance Test was conducted, the performance achieved by the Goods and whether or not the Minimum Performance Criteria was achieved.

5.3. Feed Material Verification – Bond Impact Work Index (WI)

For every individual test, a sample of the run of quarry/run of mine consisting of 20 stones in size passing 75 mm square hole and retaining on a 55 mm square hole sieve shall be collected from the run of quarry/run of mine. This Feed Material sample is to be immediately packed and marked with the test No. and reference and be kept available for WI test at Xxx's laboratory.

Customer agrees that Xxx may take Feed Material samples at the loading point of the Goods to determine/analyze the Feed Material specifications according to Clause 3.3.

Two samples shall be taken for each test, one immediately before and one immediately after each test operation.

On request by Xxx, the Customer shall send the Feed Material verification samples to Xxx SRP AB in Sweden for WI test(s).

5.4. Sampling positions

Sample(s) shall be collected from the sampling positions(s) shown on the Flow-sheet drawing(s) specified in Clause 3.1.

If samplings positions are not shown on Flow-sheet samples shall be collected from below sampling positions. Capacity and grading, sample(s) shall be collected from the belt conveyor immediate after the Goods which is covered by the guarantee.

Feed grading, sample(s) shall be collected from the Feed Material conveyor immediate before the Goods which is covered by the guarantee.

5.5. Determination of Capacity

Capacity sample(s) shall be collected using belt cuts as set out in the Xxx Test Procedure, according to Addendum 3, at the sampling positions specified by Xxx in Clause 5.4.

The conveyor(s) shall be stopped and the Product on a representative one-meter length of the conveyor(s) shall be collected. Capacity is determined as a function of the belt speed and the sampled material's weight.

The result shall be compared with the Minimum Performance Criteria in Clause 4.

Alternative

5.6. Determination of Product Grading

Sample(s) shall be collected using belt cuts as set out in the Xxx Test Procedure, according to Addendum 3, at the sampling positions specified by Xxx in Clause 5.4.

The sample shall be sieved on lab screens with suitable hole size(s) to determine the Product Grading.

The result shall be compared with the Minimum Performance Criteria in Clause 4.

Alternative

5.7. Determination of Product Size Distribution

Sample(s) shall be collected using belt cuts as set out in the Xxx Test Procedure, according to Addendum 3, at the sampling positions specified by Xxx in Clause 5.4.

The sample(s) collected shall be used to determine the Product Size Distribution. The guaranteed range in each product size is expressed as percentage of the total amount of material in the different guaranteed product sizes.

The result shall be compared with the Minimum Performance Criteria in Clause 4.

Alternative

5.8. Determination of Particle Shape

Sample(s) shall be collected using belt cuts as set out in the Xxx Test Procedure, according to Addendum 3, at the sampling positions specified by Xxx in Clause 5.4.

The sample(s) collected shall be screened on lab screens and respectively Particle Shape shall be determined according to the norm specified in Clause 4.

The result shall be compared with the Minimum Performance Criteria in Clause 4.

6. PERFORMANCE GUARANTEE ACCEPTANCE TEST RESULTS

6.1. The Performance Guarantee Acceptance Test results meet the Minimum Performance Criteria

Performance Guarantee Acceptance Test results that meet the Minimum Performance Criteria stated in Clause 4 shall immediately be documented in the Performance Guarantee Acceptance Test Report. The Customer shall accept the Goods that meet the Minimum Performance Criteria.

Acceptance is evidenced by the Performance Guarantee Acceptance Certificate issued by Xxx, signed by the Customer and sent to Xxx. If Customer does not sign and return the Performance Guarantee Acceptance Certificate within 30 days after Performance Guarantee Acceptance Test is performed, Acceptance will be deemed. No further tests are required and the Customer waives any and all claims in relation to the Goods meeting the Minimum Performance Criteria.

6.2. The Performance Guarantee Acceptance Test results do not meet the Minimum Performance Criteria for reasons not attributable to Xxx

If the Goods fail to comply with the Minimum Performance Criteria, for reasons not attributable to Xxx, the Customer, at its cost, shall be responsible for bringing the Goods into compliance according to Clause 3 before further Performance Guarantee Acceptance Tests can be carried out

Additional Performance Guarantee Acceptance Tests shall be done within a mutually agreed timeframe. If the Goods fail to meet the Minimum Performance Criteria in two (2) additional tests, for reasons not attributable to Xxx, Xxx may, at its option, cease further Performance Guarantee Acceptance Tests and the Goods shall be deemed to be accepted by the Customer

Deemed Acceptance shall be evidenced by a Performance Guarantee Acceptance Certificate issued by Xxx, signed by the Customer and sent to Xxx. If Customer does not sign and return the Performance Guarantee Acceptance Certificate within 30 days after Performance Guarantee Acceptance Test is performed, Acceptance will be deemed**.** No further tests are required and the Customer waives any and all claims in relation to the Goods meeting the Minimum Performance Criteria.

Examples of reasons for failure not attributable to Xxx include but are not limited to: Failure of power supply, lack of Feed Material and/or Feed Material not according to Clause 3.3, extreme weather conditions, or operating personnel strike.

6.3. The Performance Guarantee Acceptance Test results do not meet the Minimum Performance Criteria solely due to Xxx

If the Goods fail to meet the Minimum Performance Criteria for reasons solely attributable to Xxx, Xxx reserves the right, to Fine-tune the Goods to enable them to meet the Minimum Performance Criteria before further Performance Guarantee Acceptance Tests are conducted.

The cost for to modify, adjust, repair, revise or replace parts of the Goods in this instance shall be paid according to following guidelines:

Cranes	First time paid by the Customer. Thereafter by Xxx.
Labour	The Customer pay for his personnel and Xxx for his.
Spare parts	Paid by Xxx.
Wear parts	Paid by Xxx if original configuration is changed and cannot be used by customer.

The Customer shall be responsible for ensuring that all other parts of the Goods (not Fine-tuned) and any other equipment which in any way affects or is part of the process, meet the requirements of Clause 3, before further Performance Guarantee Acceptance Tests can be carried out.

Additional Performance Guarantee Acceptance Tests shall be done within a mutually agreed timeframe. If the Goods fail to meet the Minimum Performance Criteria in three (3) additional tests, for reasons solely attributable to Xxx, Xxx may, at its option, cease further Performance Guarantee Acceptance Tests and Clause 6.4 will apply.

6.4. <u>The Performance Guarantee Acceptance Test results do not meet the Minimum Performance Criteria solely due to Goods</u>

If the Goods fail to meet the Minimum Performance Criteria after Xxx has Fine-tuned the Goods in accordance with Clause 6.3 for reasons solely attributable to Xxx, the Customer is entitled to liquidated damages limited to an amount equal to 1/2 (= 0.5) % of the Ex Works price of the Goods for each one (1.0) % that the Goods fail to meet the Minimum Performance Criteria. Where the Goods comprise of more than one machine the liquidated damages will be calculated on the price of the machine which fails to meet the Minimum Performance Criteria.

Notwithstanding any other clause in the Contract, or any other representation or agreement to the contrary, the maximum aggregated amount of liquidated damages Xxx shall be liable for in connection with this Performance Guarantee shall be no greater than five (5.0) % of the non-performing Goods’ Ex Works price

Examples of the liquidated damages calculation

1. If the Ex Works price of the Goods/machine is EUR.500 000, Capacity Minimum Performance Criteria is 100 tons and actual Capacity is 97 tons, the liquidated damages are calculated as follows: failure = (100-97)/100 = 3%. LD = 500 000 x 0,005 = 2500 Euro / % failure, 3% failure = 3 x 2500 = 7 500 Euro

2. If the Ex Works price of the Goods/machine is EUR.500 000, if guaranteed Minimum Performance Criteria is 10% and actual is 22%, the liquidated damages are calculated as follows: failure = 22-10 = 12%, LD = 500 000 x 0,005 = 2500 Euro / % failure, 12% failure = 12 x 2500 = 30 000 Euro. Liquidated damages is limited to 5% which gives the amount of liquidated damages to 500 000 x 0,05 = 25 000 Euro.

The Customer shall forfeit its right to compensation for failure of the Goods to meet the Minimum Performance Criteria if it has not lodged a claim in writing for such compensation within six months after the final Performance Guarantee Acceptance Test has taken place.

The liquidated damages stated in Clause 6.4 shall be the sole remedy the Customer has in connection with the Xxx's failure to comply with this Performance Guarantee and the liquidated damages shall be deemed to be full compensation for such failure. Xxx shall not be liable to pay any other direct or indirect costs or Consequential Loss or other compensation.

ADDENDUMS

Addendum 1:	Performance Guarantee Acceptance Certificate templates 1
Addendum 2:	Performance Guarantee Acceptance Certificate templates 2
Addendum 3:	Flow-sheet drawing(s) No.: FM11111-1, dated 2022-06-18, as per Clause 3.1.
Addendum 4:	Layout drawing(s) No.: LM11111-1, dated 2022-06-18, as per Clause 3.1.
Addendum 5:	Raw Material Test Summery, report #: xxxxxxx

Appendix E – Contribution to published paper

This doctoral dissertation has its roots in the following publications and presentations.

Paper I [62]
Lindström, A., Rading-Heyman, E., Hedvall, P., Schultheiss, F., Ståhl, J-E., Cost analysis for crushing & screening: Development of methodology for determination of production costs for product fractions. SPS 14, Gothenburg, Sweden.

Hedvall initiated the paper, developed the basic plan for the study and wrote the paper together with Lindström and Rading-Heyman. Hedvall also presented the paper at the conference SPS14.

Paper II [74]
Hedvall, P., Fägerlind, J., Schultheiss, F., Ståhl, J-E., The new improved industrial way, making product cost calculations in crushing & screening, ESCC 2015, PID 61, Gothenburg, Sweden.
Hedvall developed the basic plan of the study together with Fägerlind.

Hedvall also carried out a major part of the experimental work, the data analysis, and wrote the paper with the assistance of the other coauthors. Hedvall also presented the paper at the conference ESCC 2015.

Paper III [63]
Hedvall, P., Ståhl, J-E., Product cost calculation model for crushing & screening operations, SPS 16, ID 53, Lund, Sweden.
Hedvall developed the basic plan.

Hedvall carried out a major part of the experimental work, the data analysis, and wrote the paper with the assistance of the other coauthors. Hedvall also presented the paper at the conference SPS16.

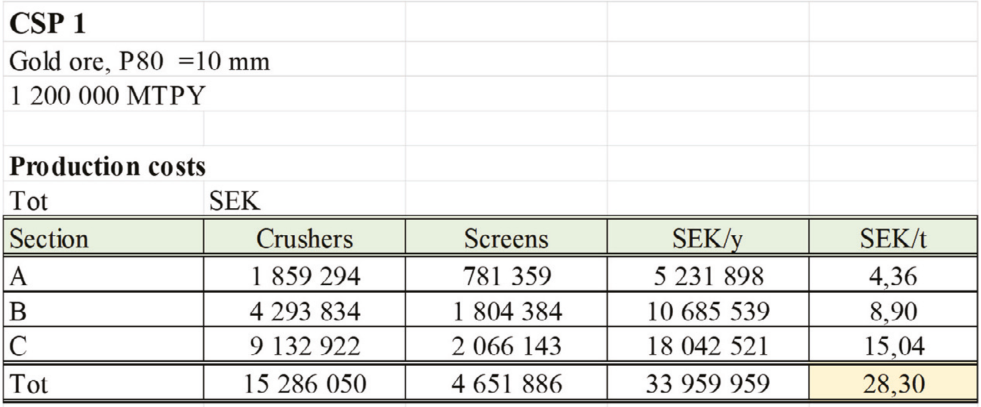
Paper IV [64]
Hedvall, P., Ståhl, J-E., The industrial way to make the production cost calculations in crushing & screening, IMPC 2016, ID 218, Quebec, Canada.

Hedvall developed the basic plan. Hedvall carried out a major part of the testing, experimental work, the data analysis, and wrote the paper with the assistance of the other coauthors. Hedvall also presented the paper at the conference IMPC 2016.

Appendix F – Case study of full-scale plants.

Appendix	C&S plant	Chapter
F1	CSP 1, Gold ore, 400 MTPH, P80 = 10 mm	4
F2	CSP 2: Iron ore, 6,500.000 MTPY, products 0–5 mm & 5–20 mm	5
F3	CSP 3: Iron ore, 500 MTPH, 0–16 mm	6
F4	CSP 4: Copper ore, 1000 MTPH, P80 = 6 mm	6
F5	CSP 5: Mobile C&S plant for construction aggregate, flexible capacities, and end products	6
F6	CSP 6: Stationary C&S plant for construction aggregates, 500 MTPH, 6 end products	6
F7	CSP 7: Stationary C&S plant for construction aggregates, 200 MTPH, 4 end products	6
F8	CSP 8: Production Costs for applications of alternative C&S solutions, 400 MTPH	6

Appendix F1 – Gold ore



CSP 1

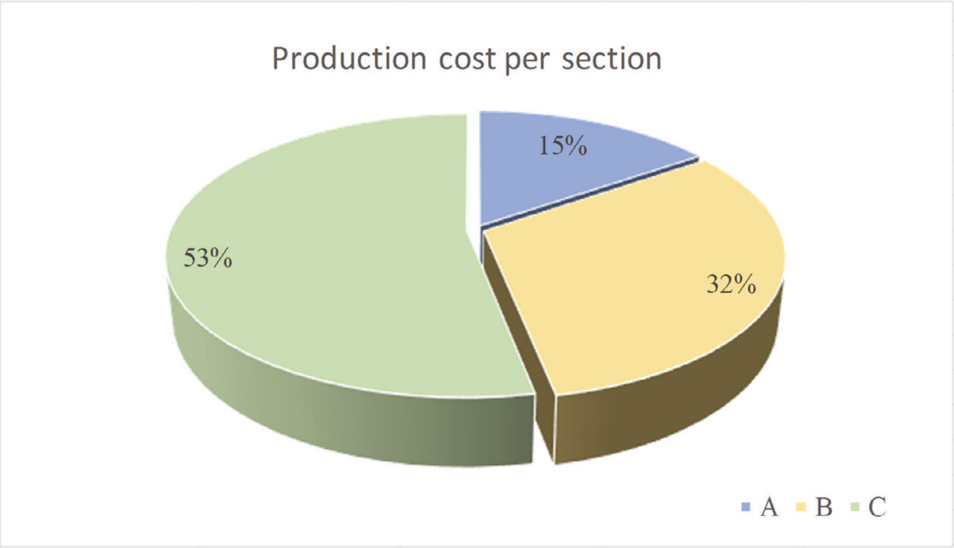
Gold ore, P80 =10 mm

1 200 000 MTPY

Production costs

Tot SEK

Section	Crushers	Screens	SEK/y	SEK/t
A	1 859 294	781 359	5 231 898	4,36
B	4 293 834	1 804 384	10 685 539	8,90
C	9 132 922	2 066 143	18 042 521	15,04
Tot	15 286 050	4 651 886	33 959 959	28,30



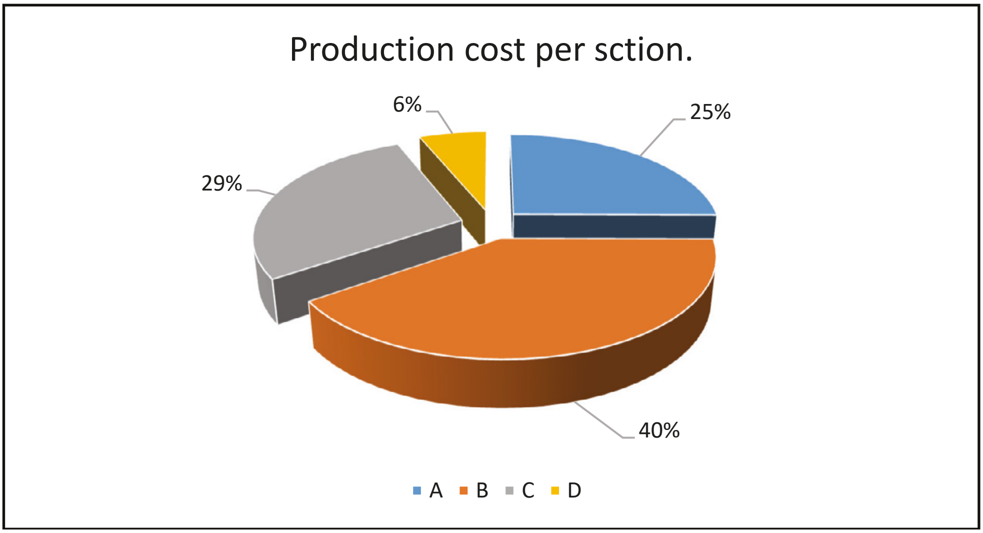
Appendix F2 – Iron ore (Magnetite)

CSP2

Iron ore, 6 500 0000 MTPY

Product P_1 = 5 - 20 mm
Product P_2 = 0 - 5 mm

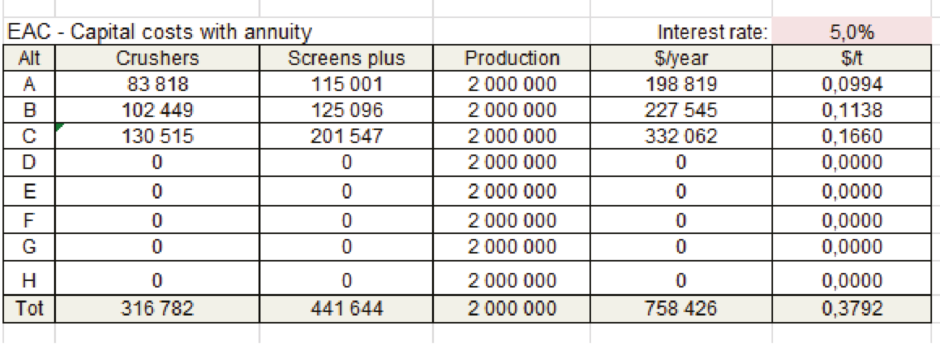
Section	$/y	$/t	P1	P2
A	1 344 516	0,21	853 095	491 421
B	2 157 836	0,33	1 369 147	788 689
C	1 519 816	0,23	964 324	555 493
D	333 338	0,05	211 503	121 835
Tot	5 355 507	0,82	3 398 069	1 957 438



Appendix F3 – Iron ore (Magnetite and hematite).

CSP 3: PCCM calculations: C&S plant producing 0–16 mm

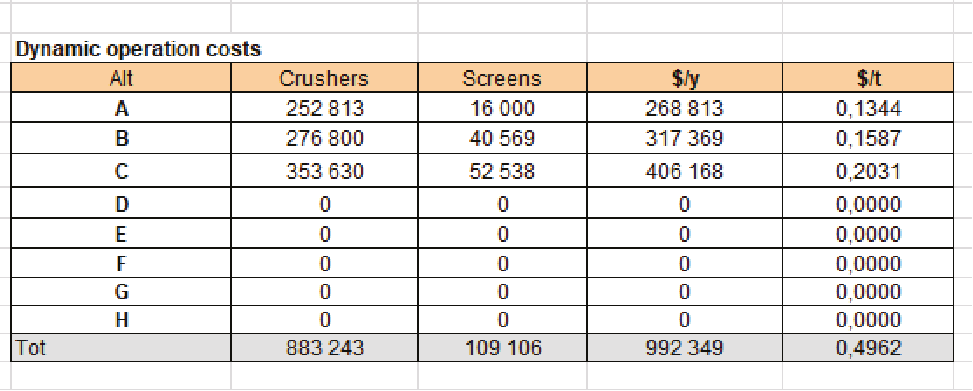
1. Capital costs



EAC - Capital costs with annuity — Interest rate: 5,0%

Alt	Crushers	Screens plus	Production	$/year	$/t
A	83 818	115 001	2 000 000	198 819	0,0994
B	102 449	125 096	2 000 000	227 545	0,1138
C	130 515	201 547	2 000 000	332 062	0,1660
D	0	0	2 000 000	0	0,0000
E	0	0	2 000 000	0	0,0000
F	0	0	2 000 000	0	0,0000
G	0	0	2 000 000	0	0,0000
H	0	0	2 000 000	0	0,0000
Tot	316 782	441 644	2 000 000	758 426	0,3792

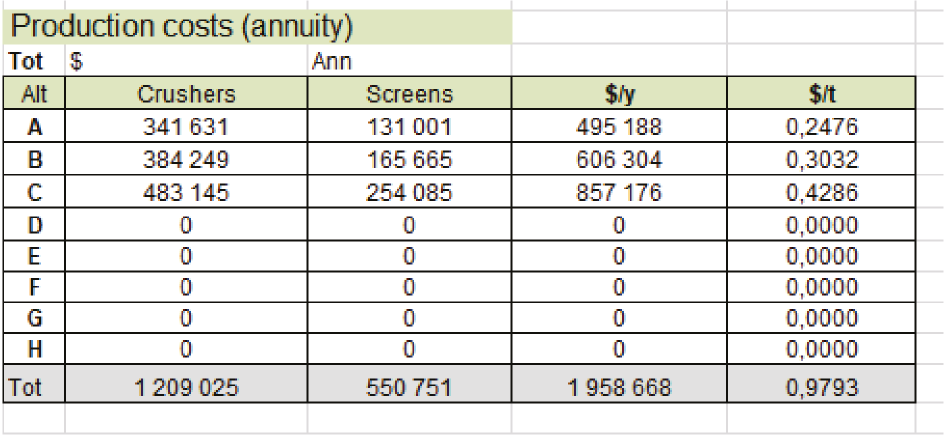
2. Dynamic costs



Dynamic operation costs

Alt	Crushers	Screens	**$/y**	**$/t**
A	252 813	16 000	268 813	0,1344
B	276 800	40 569	317 369	0,1587
C	353 630	52 538	406 168	0,2031
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	883 243	109 106	992 349	0,4962

3. Total costs (annual)

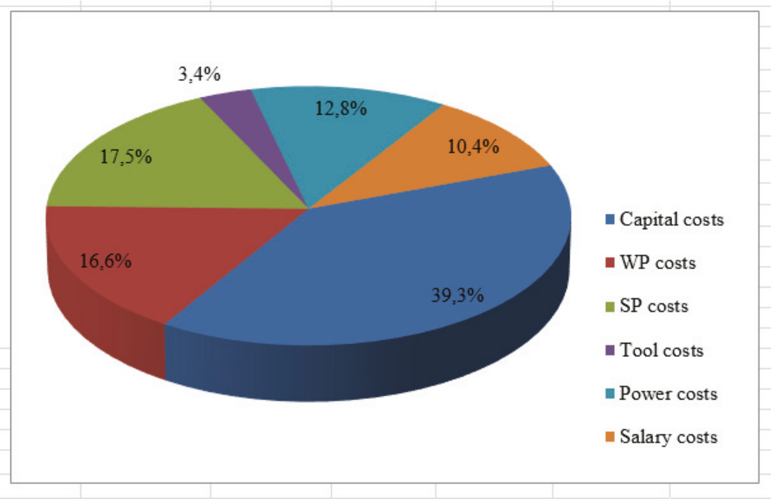


Production costs (annuity)

Tot $ Ann

Alt	Crushers	Screens	$/y	$/t
A	341 631	131 001	495 188	0,2476
B	384 249	165 665	606 304	0,3032
C	483 145	254 085	857 176	0,4286
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	1 209 025	550 751	1 958 668	0,9793

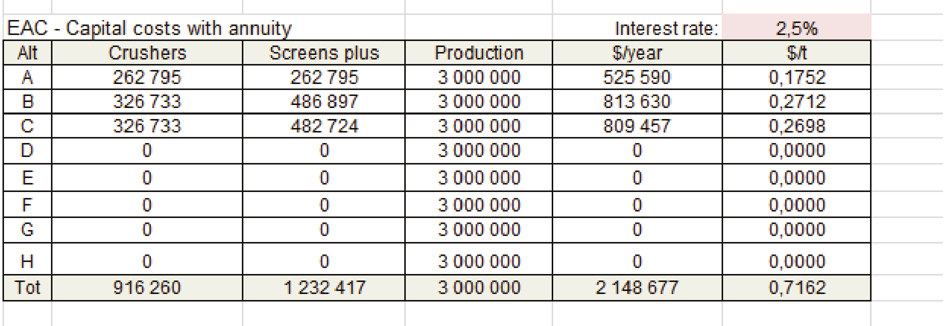
4. Cost distribution diagram



Appendix F4 – Copper ore.

CSP 4: PCCM calculations: C&S plant producing 0–¼”

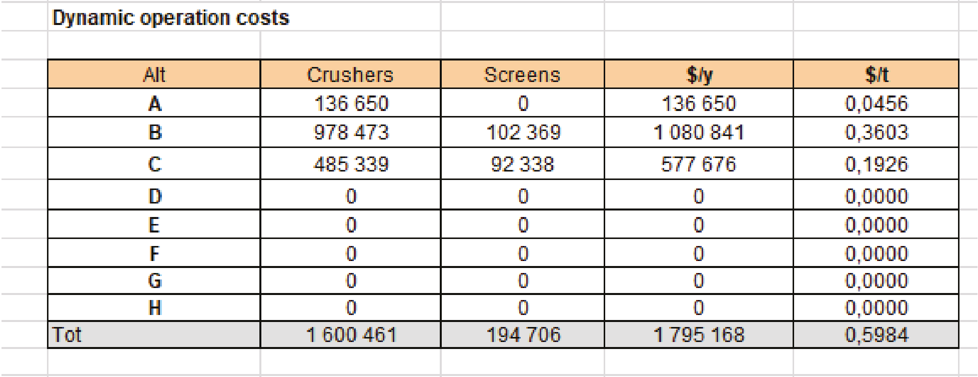
1. Capital costs



EAC - Capital costs with annuity — Interest rate: 2,5%

Alt	Crushers	Screens plus	Production	$/year	$/t
A	262 795	262 795	3 000 000	525 590	0,1752
B	326 733	486 897	3 000 000	813 630	0,2712
C	326 733	482 724	3 000 000	809 457	0,2698
D	0	0	3 000 000	0	0,0000
E	0	0	3 000 000	0	0,0000
F	0	0	3 000 000	0	0,0000
G	0	0	3 000 000	0	0,0000
H	0	0	3 000 000	0	0,0000
Tot	916 260	1 232 417	3 000 000	2 148 677	0,7162

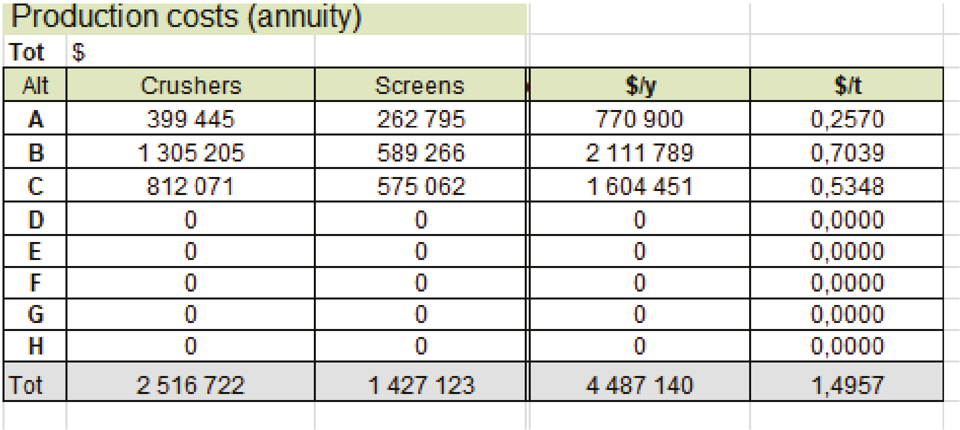
2. Dynamic costs



Dynamic operation costs

Alt	Crushers	Screens	$/y	$/t
A	136 650	0	136 650	0,0456
B	978 473	102 369	1 080 841	0,3603
C	485 339	92 338	577 676	0,1926
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	1 600 461	194 706	1 795 168	0,5984

3. Total costs (annual)

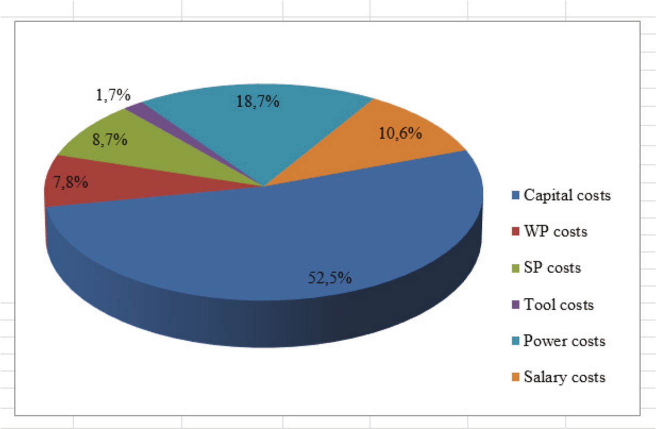


Production costs (annuity)

Tot $

Alt	Crushers	Screens	$/y	$/t
A	399 445	262 795	770 900	0,2570
B	1 305 205	589 266	2 111 789	0,7039
C	812 071	575 062	1 604 451	0,5348
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	2 516 722	1 427 123	4 487 140	1,4957

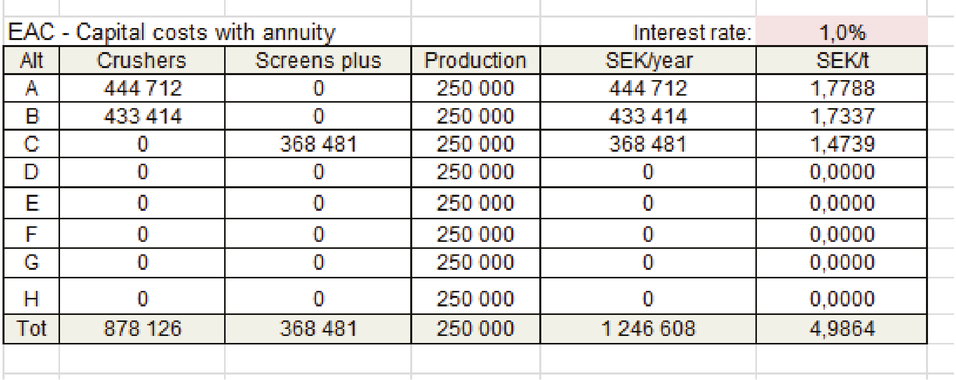
4. Cost distribution diagram



Appendix F5 – Mobile C&S plant

CSP 5: PCCM calculations: Mobile C&S circuit

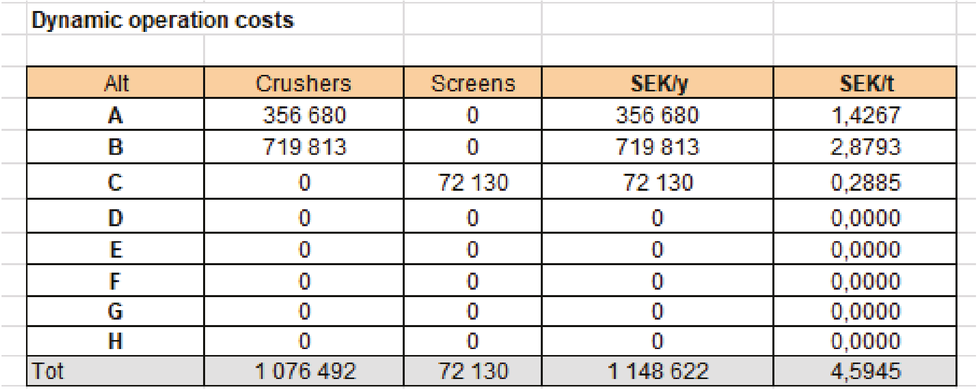
1. Capital costs



EAC - Capital costs with annuity — Interest rate: 1,0%

Alt	Crushers	Screens plus	Production	SEK/year	SEK/t
A	444 712	0	250 000	444 712	1,7788
B	433 414	0	250 000	433 414	1,7337
C	0	368 481	250 000	368 481	1,4739
D	0	0	250 000	0	0,0000
E	0	0	250 000	0	0,0000
F	0	0	250 000	0	0,0000
G	0	0	250 000	0	0,0000
H	0	0	250 000	0	0,0000
Tot	878 126	368 481	250 000	1 246 608	4,9864

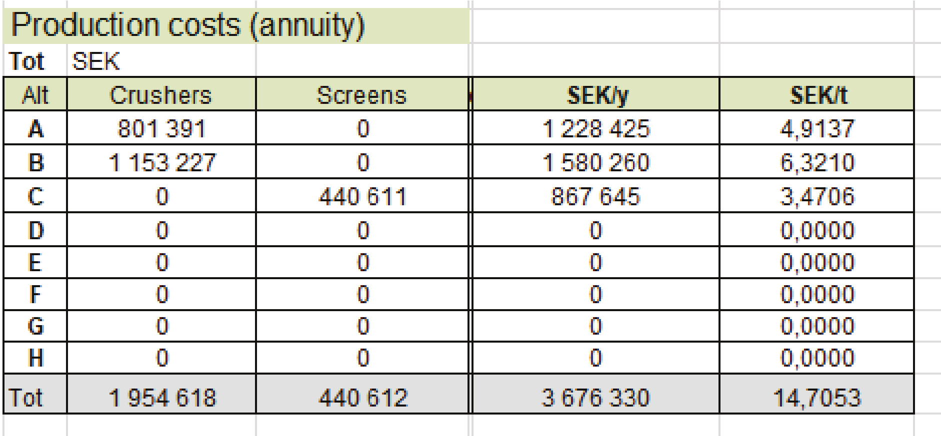
2. Dynamic costs



Dynamic operation costs

Alt	Crushers	Screens	SEK/y	SEK/t
A	356 680	0	356 680	1,4267
B	719 813	0	719 813	2,8793
C	0	72 130	72 130	0,2885
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	1 076 492	72 130	1 148 622	4,5945

3. Total costs

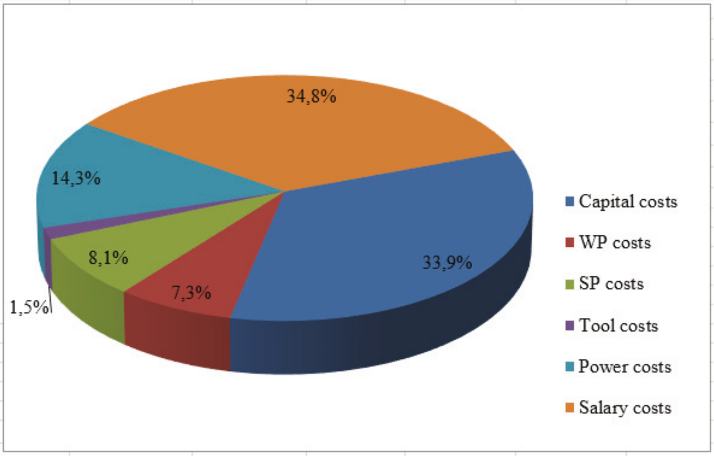


Production costs (annuity)

Tot SEK

Alt	Crushers	Screens	SEK/y	SEK/t
A	801 391	0	1 228 425	4,9137
B	1 153 227	0	1 580 260	6,3210
C	0	440 611	867 645	3,4706
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	1 954 618	440 612	3 676 330	14,7053

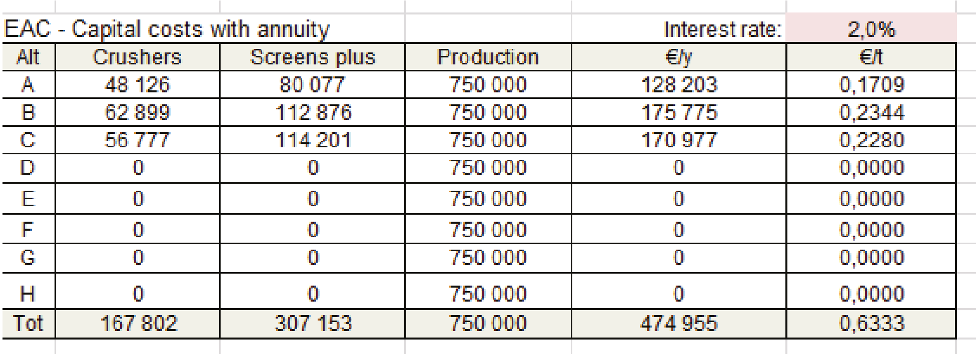
4. Cost distribution diagram



Appendix F6 – Fix quarry C&S plant.

CSP 6: PCCM calculations: Stationary C&S plant

1. Capital costs

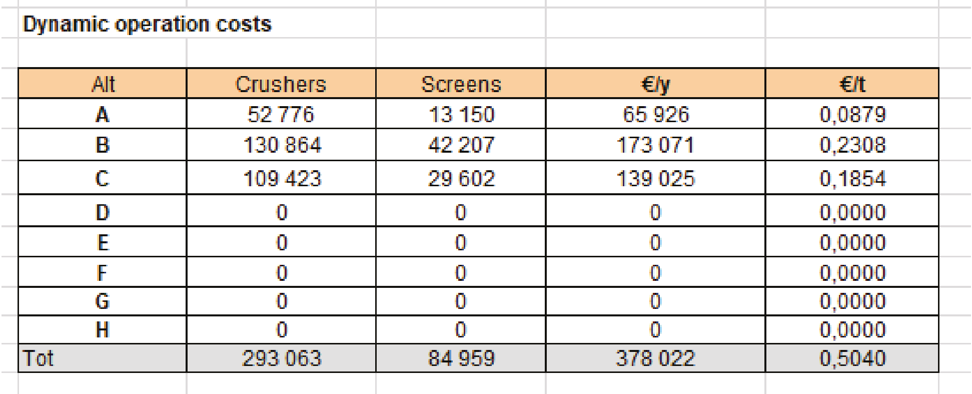


EAC - Capital costs with annuity

Interest rate: 2,0%

Alt	Crushers	Screens plus	Production	€/y	€/t
A	48 126	80 077	750 000	128 203	0,1709
B	62 899	112 876	750 000	175 775	0,2344
C	56 777	114 201	750 000	170 977	0,2280
D	0	0	750 000	0	0,0000
E	0	0	750 000	0	0,0000
F	0	0	750 000	0	0,0000
G	0	0	750 000	0	0,0000
H	0	0	750 000	0	0,0000
Tot	167 802	307 153	750 000	474 955	0,6333

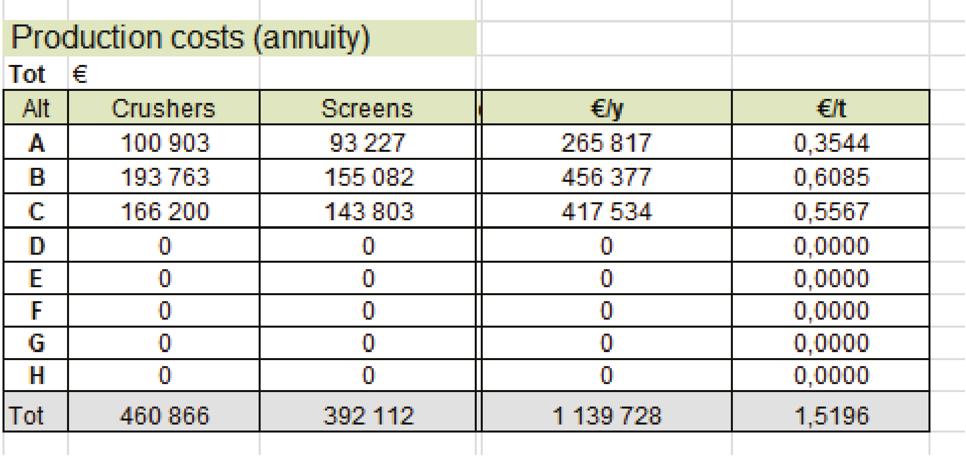
2. Dynamic costs



Dynamic operation costs

Alt	Crushers	Screens	€/y	€/t
A	52 776	13 150	65 926	0,0879
B	130 864	42 207	173 071	0,2308
C	109 423	29 602	139 025	0,1854
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	293 063	84 959	378 022	0,5040

3. Total costs (annual)

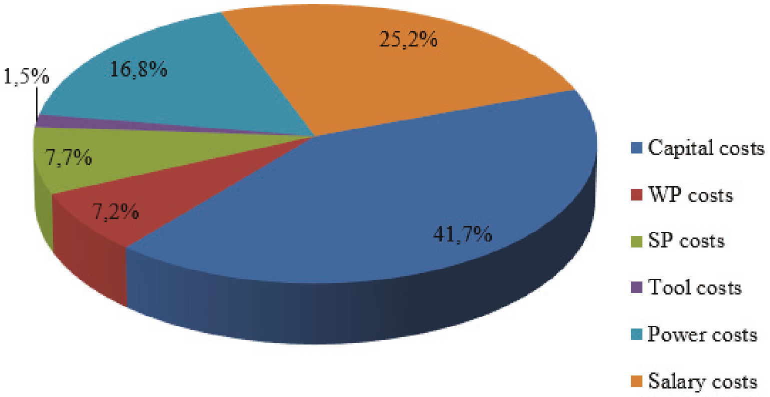


Production costs (annuity)

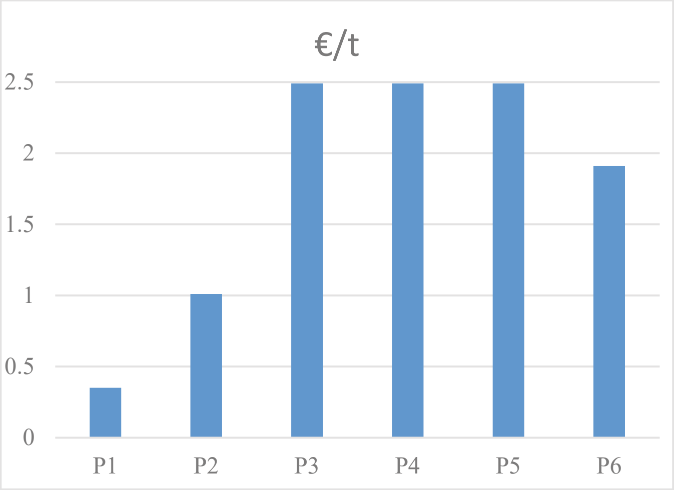
Tot €

Alt	Crushers	Screens	€/y	€/t
A	100 903	93 227	265 817	0,3544
B	193 763	155 082	456 377	0,6085
C	166 200	143 803	417 534	0,5567
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	460 866	392 112	1 139 728	1,5196

4. Cost distribution diagram



5. Costs of end products

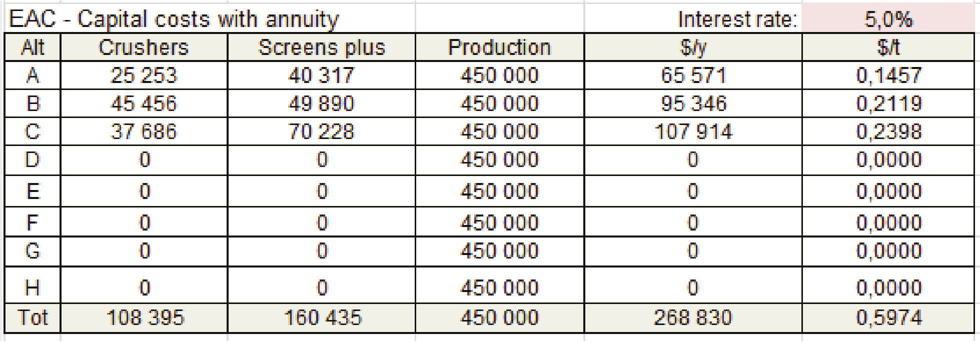


The lower production cost for product P6 is because it will be produced in both the second and third crushing stages, while products P3 – P5 are produced only in the third C&S stage.

Appendix F7 – Fix C&S plant (quarry)

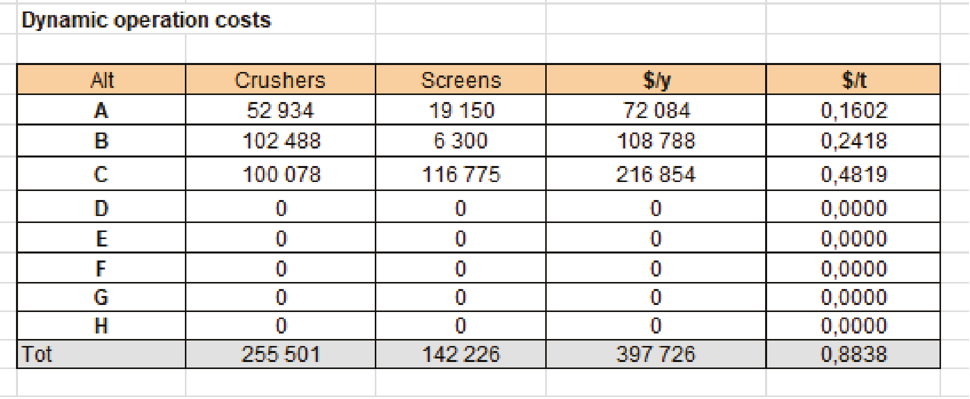
CSP 7: PCCM calculations: 200 MTPH

1. Capital costs (annual)



EAC - Capital costs with annuity				Interest rate:	5,0%
Alt	Crushers	Screens plus	Production	$/y	$/t
A	25 253	40 317	450 000	65 571	0,1457
B	45 456	49 890	450 000	95 346	0,2119
C	37 686	70 228	450 000	107 914	0,2398
D	0	0	450 000	0	0,0000
E	0	0	450 000	0	0,0000
F	0	0	450 000	0	0,0000
G	0	0	450 000	0	0,0000
H	0	0	450 000	0	0,0000
Tot	108 395	160 435	450 000	268 830	0,5974

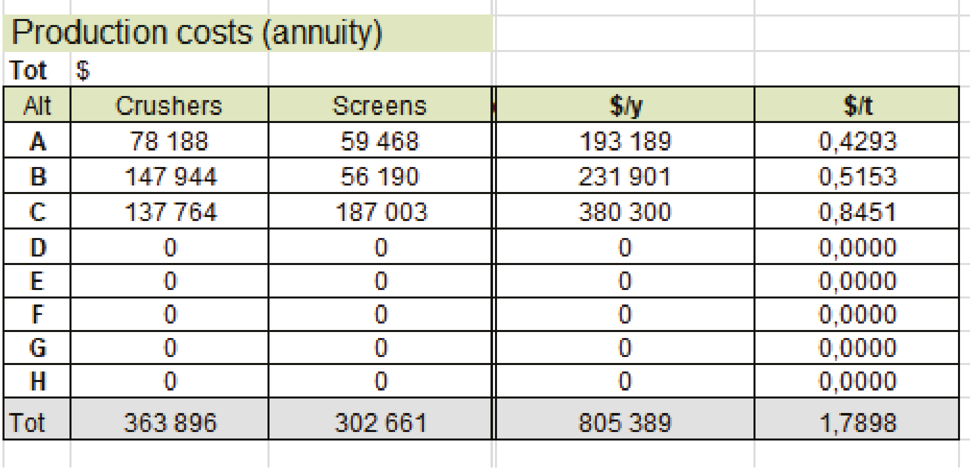
2. Dynamic costs



Dynamic operation costs

Alt	Crushers	Screens	$/y	$/t
A	52 934	19 150	72 084	0,1602
B	102 488	6 300	108 788	0,2418
C	100 078	116 775	216 854	0,4819
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	255 501	142 226	397 726	0,8838

3. Total costs (annual)

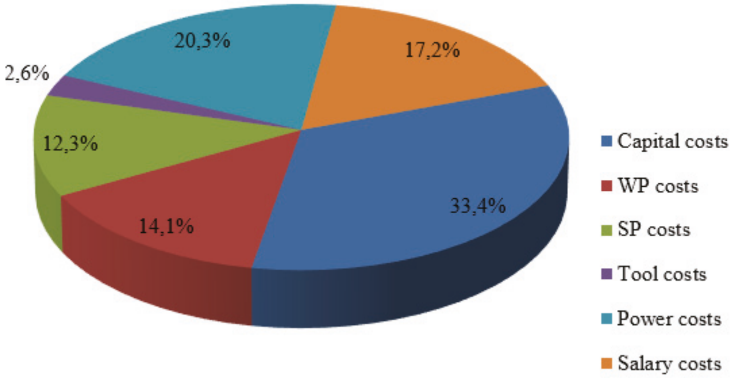


Production costs (annuity)

Tot $

Alt	Crushers	Screens	$/y	$/t
A	78 188	59 468	193 189	0,4293
B	147 944	56 190	231 901	0,5153
C	137 764	187 003	380 300	0,8451
D	0	0	0	0,0000
E	0	0	0	0,0000
F	0	0	0	0,0000
G	0	0	0	0,0000
H	0	0	0	0,0000
Tot	363 896	302 661	805 389	1,7898

4. Cost distribution diagram



Appendix F8 – Invest analysis of replacement.

CSP 8: PCCM calculations: 400 MTPH crushing plant.

Alt	Crusher	Others	Flowsheet	Calculation no.
A	2 x C1a&b	2 x F1a&b	FC16-032a	cc16-32a
B	1 x C1	1 x F1B	FC16-032b	cc16-32a

Capital costs (US$ and Interest rate 5 %)

Alt	Crusher	Others	$/y	$/t
A	278,874	286,489	565,243	0.45
B	284,910	294,706	579,616	0.46

Dynamic costs (US$)

Alt	Crusher	Others	$/y	$/t
A	682,015	4,130	686,145	0.55
B	615,313	4,125	619,438	0.50

Production costs (US$)

Alt	Crusher	Others	$/y	$/t
A	960,800	290,589	1,251,452	1.00
B	900,223	298,831	1,199,054	0.95

Appendix G -- Environment, Health, and Safety.

G.1 Environment.

The environment can be divided into two main focuses, nearby and surrounding. “Nearby” deals with the environment inside the C&S plant itself, while the “surroundings” relate to the environment outside the C&S plant.

The near environment focus is dust, noise, vibrations, and leakage. Most manufacturers of equipment for C&S plants have goals to minimize the dust discharge from each machine/equipment. It is essential to service and maintain the dust covers and de-dusting equipment, to keep the specified protection levels.

Noise and vibration are problems within C&S plants as size reduction and size sorting machines generate noise and vibration. All manufacturers of crushers and screens try to minimize noise and vibration levels in the design phase of the machines. When designing the C&S plant, one key to minimizing noise and vibration is to use rubber and plastic as covers in chutes, on feeders, and in screening media. Vibrations from machines can be reduced by rubber dampers between the machine and the supporting steel structure.

Leakage to the environment may occur as wastewater, through spillage water from process water, or by leaching of the products/fractions due to precipitation. Different types of raw materials processed will give different types of environmental tailings through leakage. The focus is on reduce/remove ions of metals, sulfur and sulfur compounds, and other hazardous substances in the wastewater before reaching the groundwater system.

The surrounding environment is more or less sensitive depending on how close the neighbors are living to the C&S plant.

People living near C&S plants are exposed to dust and noise more than vibration, where the noise and dust come from the equipment in the C&S plant and from truck traffic in and out of the C&S plant.

In the USA some construction aggregate producers have moved their C&S plant underground, to what they call stone mines (Figure G.1). As a result, they have received permission to run their C&S plant within crowded cities. This is more common in the USA than in other countries. It may in future become more common in other crowded cities in order to both produce construction aggregates close to construction and building sites and minimize truck traffic in an area that already has very high traffic intensity.

Low costs for restoration may be possible as the "goafs" (quarry rooms) can later be used for valuable/safety storage, cold storage room, car parking, offices, arenas, malls, or shelters.

Figure G.1 *Underground installation of primary crusher and grizzly feeder [75].*

In some developing countries there are unauthorized C&S plants that utilize/extract natural sand and/or natural gravel. These illegal C&S operations have a large impact on the environment and can cause major destruction of the environment around them.

G.2 Health

The main goal for health is reduce the number of work-related injuries, illnesses, and other incidents. A way to increase health in C&S plants is to give all employees access to work health and wellbeing programs. Silicosis was one of the most infamous work-related diseases within crushing and screening. This work-related disease is now almost eliminated by good dust control/protection in crushing and screening plants.

In many countries there are laws and regulation in these areas. For example, in Australia section 19 of the Work Health and Safety Act 2011 specifies that a person conducting a business or undertaking must ensure the health and safety of workers at work in the business or undertaking, so far as is reasonably practicable. Additionally, section 19 requires that the employer ensure that the health and safety of other persons is not put at risk from work carried out as part of the conduct of the business or undertaking, so far as is reasonably practicable. [76].

The Luxembourg Declaration on Workplace Health Promotion (WHP) in the European Union (2007) describes WHP as "the combined efforts of employers, employees and society to improve the health and wellbeing of people at work. This can be achieved through a combination of improving the work organization and working environment, promoting active participation, [and] encouraging personal development." The European Agency for Safety and Health at Work (2010) has added "enabling healthy choices" as a fourth action. [77].

G.3 Safety

Safety one can be divided into two main categories, personal and general.

The basic level in personal safety is a safety helmet, safety shoes/boots, and a visible safety vest/jacket, see Figure G2. For mobile C & S plants/equipment nearby or on roads, the operators must also have visible work pants. These three safety items are mandatory for humans working at or visiting a C & S plant.

Figure G.2 *Safety helmet, safety shoes/boots, and visible safety west/jacket.*

The next level in personal safety is ear defenders/ear plugs, protective gloves, overalls, protection goggles, and a dust mask or respirator. These five safe items are strongly recommended for people working at or visiting a C&S plant [78].

The general safety in a C&S plant includes

- Education and training for personal safety and security
- Emergency stops suitably placed, working correctly, and needing to be manually reset after an emergency stop
- Proper lifting devices
- Guarded moving parts on machines and equipment
- Easy and safe access to all equipment and machines through walkways, stairways, platforms, or ladders with guardrails
- Marked "roads" for trucks and wheel loaders
- Marked escape routes and assembly points for the C&S plant
- Fenced C&S plants with lockable gates with in/out passage control

Workers should be prohibited from removing guards while machinery is in use, and guards should not create an additional hazard.

An effective lock-out program/system should be in place to ensure that workers can completely turn off the machines/equipment when performing maintenance and/or service. It should not be possible to start the machine/equipment while working on the machine/equipment.

G.4 Remarks

Within EHS, one can say that there are two main levels, namely the determination level and the comfort level [79].

The determination level is what the laws and regulations stipulate in each country.

The comfort level relates to levels that feel pleasant. However, the comfort level (≈ experience or feeling) is not the same for different people, meaning that this level is not defined in the same way as the determination level.

Table G.1 shows that signs at a C&S plant are in four colors.

Table G. 1 *Color on signs in a C&S plant [79].*

Color	Meaning
Blue circles	Show you what you **MUST do**
Green signs	Indicate safety
Yellow signs	Warn of hazardous situations
Red circles	Show you what **must NOT do**

Good ways to improve safety and security in C&S plants include

- Keeping all walkways, stairways, and platforms free from wear parts, spare parts, tools, waste, and debris
- Cleaning under and next to the equipment and machines for better access for maintenance, service, control, and monitoring.

Last but not at least, all C&S plants will be shut down sooner or later and will need to be restored after production has closed.

Restoration ecology is the scientific study supporting the practice of ecological restoration, which is the practice of renewing and restoring degraded, damaged, or ecosystems and habitats in the environment destroyed by active C&S plants.

Restoration ecology tries to recreate an environment that is equivalent or nearly equivalent to the situation before the start of the quarry or mining plant [79].

For surface C&S plants, restoration usually requires more work and more costs than for underground plants. There are considerably more surface plants than underground plants. As earlier stated, the goafs (mining or quarry rooms) can later be used by society for other purposes.

The most important environmental issue, and the great challenge for the future for mining and construction and us all, is to be able to run, manage, and sustainably develop these industries in a balanced way, because we will need both metals and building materials for many, many, many generations to come [80].

Appendix H – Production analysis, input sheet

This data sheet can be used to sample and record the production costs in existing C&S plants.

Data sheet - Sampling roduction costs			Date				
Oeration							
Plant							
Folwsheet							
Item	Machine/Equipment	Flow in	Flow out 1	Flow out 2	Flow out 3	Flow out 4	Flow out 5

Currency					Page	
Customer						
Quation						
Investment	Tech life	WP costs	SP costs	TO costs	Power	Load (x)

Appendix I -- Analyses of simulation results

In simulation, one creates mathematical model(s) of system or processes and explores the behaviors and results of the models by running simulations.

As simulation results should be close to the actual results, one needs to have tools to determine the accuracy of the simulation. One needs to be able to summarize and analyze the results in a way that will give maximum insight and help in later decision-making. It is very useful to create charts to visualize results, for example frequency charts and cumulative frequency charts [81]. This can be done when one has many actual results and many corresponding calculated simulations.

However, in my dissertation I have a limited number of actual tests with corresponding simulations, so I need a simpler method, but still with enough accuracy, to evaluate my PCCM simulation model.

With the above in mind, I have created an evaluation tool to compare the results of the simulation with actual results, called conformity (CF).

CF = (Calculated Production Costs)/(Actual Production Costs, specified by customer**)**

Remember that the ***Actual Production Costs*** *are the ones* ***specified by the customers*** *themselves.*

In this dissertation, I have reported what the customers have reported to me, as actual production costs. I have not separately validated the facts obtained from the customers.

Using the CF provides a ratio of how good the simulation is in comparison with the actual results. As C&S plants have many different input parameters and many affecting factors, I think that CF should be $0.7 \leq CF \leq 1.30$, to be regarded as good enough.